Sustainable Chemistry and Pharmacy 36 (2023) 101330

Contents lists available at ScienceDirect

Sustainable Chemistry and Pharmacy

journal homepage: www.elsevier.com/locate/scp

Measuring Circularity: Tools for monitoring a smooth transition to Circular Economy

Iliana Papamichael[a,*], Irene Voukkali[a], Pantelitsa Loizia[a], Marinos Stylianou[a], Florentios Economou[a], Ioannis Vardopoulos[a,b], Eleftheria E. Klontza[c], Demetris F. Lekkas[c], Antonis A. Zorpas[a,**]

[a] *Laboratory of Chemical Engineering and Engineering Sustainability, Faculty of Pure and Applied Sciences, Open University of Cyprus, Giannou Kranitiodi 89, 2231, Latsia, Nicosia, Cyprus*

[b] *Department of Economics and Sustainable Development, School of Environment, Geography and Applied Economics, Harokopio University, 70 Eleftheriou Venizelou Avenue, 17676, Kallithea, Attica, Greece*

[c] *Waste Management Laboratory, Department of the Environment, University of the Aegean, 81100, Mytilene, Greece*

ARTICLE INFO

Handling Editor: Klaus Kümmerer

Keywords:
Circular economy
KPIs
Monitoring
SWOT analysis

ABSTRACT

The linear economy of today's society conflicts with many environmental, social, and economic challenges. Therefore, the implementation of the Circular Economy model is prioritized by policymakers and the research community. The European Union is in accord with the smooth transition towards a Circular Economy through the Circular Economy Strategy, The European Green Deal (carbon neutrality by 2050) as well as the Sustainable Development Goals (SDGs) of the United Nations. Replacing the conventional business models with circular business models entails a change in technological aspects involving the R strategies (refuse, reduce, recycle, etc.). For a beneficial transition, Circular Economy should be monitored to give out quantitative measurable data. Quantifying Circular Economy can be achieved through the use of Key Performance Indicators, Life Cycle Analysis, Material Flow Analysis as well as the use and development of quality protocols (ISO/TC 323). Such tools will aid with measuring Circular Economy performance (urban or industrial), support decision-making (policymakers, CEOs, etc.) and highlight strengths, weaknesses, blind spots and opportunities regarding circularity. This research analyses the use of monitoring of three main monitoring tools in the framework of Circular Economy using SWOT analysis (Strengths, Weaknesses, Opportunities, Threats) to provide a collective understanding on the implementation of Circular Economy in different settings (urban, industrial, domestic) and provide a clearer pathway towards this transition. The three tools analysed were Key Performance Indicators, quality protocols and digitalization while a hybrid approach was proposed to tackle the shortcomings and utilize the strengths of each of the three methods. The results of the study are expected to provide context to policy makers, academics, the industry, economists and other key players into the synergies necessary for circular economy implementation as well as the necessity of data collection and continuous monitoring for a smooth transition towards circularity.

* Corresponding author.
** Corresponding author.
E-mail addresses: iliana.papamichael@gmail.com (I. Papamichael), antoniszorpas@yahoo.com, antonis.zorpas@ouc.ac.cy (A.A. Zorpas).

https://doi.org/10.1016/j.scp.2023.101330
Received 5 July 2023; Received in revised form 20 October 2023; Accepted 28 October 2023
Available online 7 November 2023

1. Introduction

Adequate waste management has been in the spotlight of the last decade as recent media attention highlights the tragic impacts caused by anthropogenic activity on the environment (Vardopoulos et al., 2021). Due to industrial and economic activities as well as the ever-rising population growth worldwide (Vinci et al., 2023), the amount of waste accumulated rises as well in all classifications: domestic, industrial, municipal, agricultural, commercial, *etc*. (Okedu et al., 2022). According to Statista (2022), the average global annual municipal solid waste generation has reached 2 billion metric tons in 2022, with the leading country being the United States, and is expected to rise to 6.5 billion tons by 2025 (Okedu et al., 2022).

In this regard, the Circular Economy concept has gained increasing momentum in urban and business settings, while the public, policymakers, and members of the research community have given Circular Economy significant attention (Kirchherr et al., 2018). Many governments are engaging with the Circular Economy concept as, according to the Ellen MacArthur Foundation (2015), it can cut emissions by 48%, generate 1.8 trillion euros in economic benefits and 2 million new employments by 2030, as well as increase profit margins for businesses who use it (Kirchherr et al., 2017). The Circular Economy concept constitutes a system that tackles global challenges (*i.e.* climate change, waste, pollution, *etc*.) and is based on three main principles: (i) elimination of waste and pollution, (ii) circulation of products and materials in their highest value form and (iii) regeneration of the natural environment. Main goal is decoupling economic activities from consumption patterns of limited resources. Circular Economy constitutes a resilient system striving to leave nobody behind (Ellen MacArthur Foundation, 2021).

Furthermore, to tackle growing sustainability challenges on all three pillars (*i.e.* environment, society, economy) the European Union (EU) has proposed several action plans including European Green Deal (EGD), Sustainable Development Goals (SDGs), Waste Framework Directive (WFD) and strategies regarding chemicals, plastics, industrial emissions safety, textiles waste etc (European Commission, 2020; Voukkali et al., 2023). According to the EGD, carbon neutrality should be achieved by 2050 along with a gradual decrease in emissions (55% fewer greenhouse gasses (GHGs) emissions by 2030 relative to the measurements of 1990) to prevent this human catastrophe (Loizia et al., 2021). Baseline of the EGD are the SDGs of the United Nations (UN). Adopted by 193 countries in 2015, the SDGs provide a pathway towards eliminating extreme poverty, reducing inequalities, and protecting the planet by 2030. 17 main interconnected SDGs were proposed, each analysed concisely for implementation. Specifically, the Agenda strives towards affordable and clean energy (SDG 7) with an increasing share of renewable energy sources along with economic growth and decent work opportunities (SDG 8). At the same time, through industry and innovation (SDG 9) sustainable cities and communities will be formed (SDG 11) while responsible consumption and production (SDG 12) should be in place to minimize waste accumulation and the effects waste production has on sustainability (United Nations, 2015). Furthermore, the WFD 2008/98/EC aims at reducing waste without endangering human and environmental health, without adverse effects on air, soil, biodiversity, and water but also without causing pests through noise and odors. The WFD focuses on monitoring the development of national end-of-waste criteria in Member States and the assessment for the development of Union criteria regarding end-of-life and end-of-waste management while honoring the waste hierarchy (prevention, reuse, recycling, recovery, and disposal) (Official Journal of the European Union, 2008).

One of the main areas that the EGD embraces is the Circular Economy Action Plan (CEAP), aiming to accelerate the shift to sustainable and circular economy (European Commission, 2020; Voukkali et al., 2023). Main goal of the CEAP is the transfer of knowledge to consumers for vigilance on product origin, sustainability, and decoding of green claims to make sustainable products the new norm. In order to achieve this, the focus should be on the whole of the value chain to pinpoint where circularity principles could be implemented. Main principle of the Circular Economy is the implementation of the ‘R strategies’ of circularity (i.e. reduce, reuse, recycle, remanufacture, refurbish, redesign, *etc*.) which have the potential to provide innovation on different stages of the supply chain (Moustairas et al., 2021). Therefore, a clear vision and new strategy development are proposed by the scientific community which includes the involvement of customers, businesses, and policymakers, driven by the promotion of circular economy through knowledge exchange, education, as well as regulatory relief measures for a synergistic transition towards the circularity in urban settings (Borg et al., 2020; D'Adamo et al., 2022; Georgitsoyanni et al., 2013; Kasavan et al., 2021).

However, there is still a disconnect between the theoretical benefits of Circular Economy and their actual application in the urban and industrial sectors (Bianchini et al., 2019). The lack of data availability along with the quantification, monitoring, and identification of possible optimization points in a production line or system, are crucial first steps regarding the smooth implementation of circular economy (Papamichael et al., 2023a). To gauge the extent of progress in implementing the circular economy model concerning circular economy, various techniques and instruments have been suggested by the academic community (Papamichael et al., 2023b). These include the establishment of Key Performance Indicators (KPIs), the application of digitalization (for instance, Life Cycle Assessment (LCA), the utilization of the big data approach, and other relevant methodologies. (Jiang et al., 2023; Niyommaneerat et al., 2023).

According to Kirchherr et al. (2017), there are four main types of interconnected barriers causing circularity delay: (i) social barriers involving consumer behavior and awareness, but also alteration of existing business culture, *etc*., (ii) technological barriers including circular design, complexity of the supply chain, lack of technical “know how”, complexity of industrial symbiosis, *etc*., (iii) regulatory barriers including laws and regulatory obstacles but also lack of global collaboration and (iv) market barriers like high investment costs, risks of investments, funding, *etc*. (Araujo Galvão et al., 2018; Jaeger and Upadhyay, 2020; Kirchherr et al., 2017). While Jaeger and Upadhyay (2020) claim that waste reduction and recycling alone have very little influence on Circular Economy compared to high-impact actions (i.e. repair and maintenance etc.) manufacturing firms still focus on these practices. If the economy and enterprises continue to operate under the "business as usual” scenario, Circular Economy could fail due to the relevance and interdependence of these four categories of barriers (Kirchherr et al., 2017).

Therefore, without quantifiable information flow of circular economy activities, the transition from linear to circular supply chains and business models will be stifled due to a lack of measurable proof of circularity (Kirchherr et al., 2017). This is because according to Loizia et al. (2021), without quantification and measurable data, one's endeavor is to "*measure something that is not there*". In context this implies that lack of data on waste streams, life cycle of production lines and services and other key elements, there cannot be a targeted and smooth transition towards circular economy (Luoma et al., 2022). The existence of clear metrics and standards from key players in circular economy implementation in all sectors (*i.e.* businesses -like fashion industry, private sector etc.-, urban setting -urban planning and development-, national -circular cities and national strategies-, etc.), is vital for the progression of circular thinking into adequate alterations of everyday life (Araujo Galvão et al., 2018; D'Adamo et al., 2022; Voukkali and Zorpas, 2022).

Common tools for measuring waste management are Key Performance Indicators (KPIs). KPIs are computational sets aiming to quantify, simplify and communicate data that are not easily observed in an unequivocal manner (Loizia et al., 2021). KPIs like Municipal solid waste production (MSW-P), recycling (MSW-R), recovery, *etc*. have been used in the past in urban settings to quantify and measure environmental performance of given sectors (Pappas et al., 2022). Simultaneously, different tools for measuring environmental impacts and resource use like LCA and Material Flow Analysis (MFA) have been used in combination with KPIs in order to produce measurable results in the framework of digital technologies (Bianchini et al., 2019; Haupt and Zschokke, 2017; Loizia et al., 2021; Pappas et al., 2022; Zorpas, 2020).

Standardization in correlation with KPIs removes bias from evaluation especially when a hierarchy is employed to the KPIs for effective quantification and decision making (De la Barrera et al., 2016; Papamichael et al., 2022). According to the Cambridge dictionary (n.d.), standardization is defined as the process of making things of the same type all have the same basic features. Quality protocols are being introduced to ensure the safety, quality and efficiency of services in regard to sustainability (Antoniou and Zorpas, 2019; Kazamias and Zorpas et al., 2021; Yarahmadi et al., 2020). Common protocols used in urban settings include ISO 37101 and ISO 37120, for defining and measuring the implementation of SDGs in urban settings (ISO, 2014, 2016) where KPIs concerning different sections of sustainable development (i.e. education, health, mobility, governance, etc.) are used to improve resource use and other relevant fields. Diverse stakeholders are involved in ISO 37101 (ISO, 2016) which has been designed to aid communities in defining, pursuing, and measuring SDGs (White, 2021). Complementary to ISO 37101, ISO 37120 (ISO, 2014) defines the adequate methodologies for a set of KPIs used by competent authorities to measure the quality of life and community performance. The KPIs involved in ISO 37101, 37120 target education, mobility, health, governance, emergency etc. To outline and best describe the sustainability level of the said community (Papamichael et al., 2023a). Through the KPIs, targets towards improving resource use and environmental preservation are employed while quality of life over time is monitored. Other protocols include ISO 14001 for Environmental Management as well as ISO 14000 family for environmental management (i.e. ISO 14001:2015, ISO 14052:2017, ISO 14031:2021, ISO 14053:2021) concerning different sectors like eco-design, environmental costs and benefits, circulation, material flow cost and other (ISO, n.d.; Papamichael et al., 2022).

Still, due to Industry 4.0 and the 4th industrial revolution linked the technological advancements of today's world, these qualitative and quantitative tools all fall under the umbrella of digitalization (Beliatis et al., 2019; Massoud et al., 2021). The concept of digitalization (Papamichael et al., 2023a) involves the integration of technology into everyday life, aiding in providing real-time results, monitoring, and problem-solving, by eliminating, on a large scale, external and internal errors caused by human intervention (Roy et al., 2021). The promotion of smart system development can aid with addressing shared challenges of circular economy and the development of new and innovative strategies for authorities and policymakers (Vardopoulos et al., 2020). Concepts like the Internet of Things (IoT) (Okedu et al., 2022), agent-based models (Fernandez-Mena et al., 2020), benchmarking, Geographic Information Systems (GIS) (Mondejar et al., 2021), artificial intelligence, and others can catalyze innovation potentials around circular economy and sustainability, while digitalization combined with other concepts (i.e. gamification) could be used to attract the interest of policymakers and competent authorities, in order to be engaged in active actions, in accordance with EU legislation (Kristoffersen et al., 2020; Maranghi et al., 2020; Papamichael et al., 2022; Pappas et al., 2022).

This research paper provides insights into the use of monitoring tools in the framework of Circular Economy using SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis. Purpose of this study is to provide a collective understanding of the barriers standing in the way of the transition towards sustainability but also to give incentives and motivation to different players (*i.e.* competent authorities, engineers, academia, governmental bodies, *etc*.) to use the opportunities and strengths identified. Goal of the study is for the results of the SWOT analysis to be implementable and useable in different sectors (i.e. urban, industrial, domestic).

2. Methodology

2.1. SWOT analysis

A conceptual model of analysis, namely SWOT analysis, was used to study the relations between internal (Strengths (S), Weaknesses (W)) and external (Opportunities (O) and Threats (T)) factors of circular economy tools (Amato et al., 2021; Zorpas et al., 2021). A group of experts from Cyprus and Greece was selected for the SWOT analysis: 5 experts on KPIs (based on their scientific background in the area of waste monitoring approaches from which 2 were academics, 1 policy maker, and 2 consultant engineers who participated and/or developed and/or designed and/or established any waste management strategy e.g. waste prevention strategy etc.), 5 experts on Circular Economy (based on their academic background on Circular Economy from which 2 were academics, 2 were policy makers and 1 from consultant sector), 3 experts on environmental management systems (2 were accredited with ISO14001/EMAS or other similar Environmental Management Systems (EMS) as Lead Auditors and 1 was from a standardization body), and 1 expert on digitalization (based on related research with gamification holding a PhD in the area). The experts were questioned, and the research was carried out in adherence to the legal requirements and institutional standards set by Cyprus. Regarding ethical considerations, a positive ethical approval was obtained from the Cyprus National Bioethics Committee (ΕΕΒΚ ΕΠ, 2022.01.224). All experts consented to take part in the SWOT analysis and the sharing of their responses after receiving comprehensive information about the research's aims and scope, while personal data (apart from occupation) were excluded, as per their knowledge. At the same time, a literature review based on PRISMA statement was carried out to combine the opinions and results of the scientific community with the answers given by the experts for the SWOT analysis. In order to evaluate the circular economy tools used objectively and on an equal basis, specific criteria were used as depicted in Table 1.

2.2. PRISMA statement

In order to cross reference, the results of the SWOT analysis, PRISMA statement for preferred reporting items for systematic reviews and meta-analysis was used to collect data relevant to the research. The PRISMA process, involves 27 routes and encompasses the well-defined stages of a review, including eligibility criteria and relevant information sources, strategy exploration, selection procedure, results and data analysis (Rethlefsen et al., 2021; Voukkali and Zorpas, 2022; Voukkali et al., 2023). The PRISMA 2020 checklist involves seven sections and subjects as well as 27 sub criteria that should be met (Papamichael et al., 2023b). Particular criteria were used in order to eliminate or include different records (i.e. articles, reports, etc.). Specifically, the eligibility criteria for inclusion or exclusion are summarized in Table 2. The keywords used for the recruitment were "circular economy AND X, where X corresponded to: "tools", "key performance indicators", "digitalization", "quality protocols", "ISO", "metrics". The articles collected were from the SCOPUS database. From the 700 records identified, 121 of them were used in the current research. The results of the PRISMA statement are presented in Fig. 1.

3. Result and discussion

Table 3 presents the classification of the results of the literature review divided into the three categories of monitoring tools (KPIs, quality protocols and digitalization). As research and innovation involves synergy of action, many of the records identified can be classified in more than one category. From the 121 records recruited through the PRISMA statement, 34 concerned KPIs, 18 quality protocols and 37 digitalization. The rest were used for relevant parts of the current research.

According to Fig. 2, most case studies used were in the EU (45 case studies), regarding all three tools. Asia was second with 10 total case studies found and the remaining locations had one case study, regarding the references used in the current study. According to OECD, (n.d.), the reason for the EU 's leading role regarding monitoring in the context of Circular economy as well as the monitoring tools individually, is the European Commissions' increasing activity regarding matters of circular economy and sustainability. All CEAP, EGD and SDGs of the UN as well as other major legislations, policies and strategies are either crafted by the European Commission itself or adopted in a major and substantial role in legislation and everyday activities (European Commission 2018, 2020). Euro-

Table 1
Criteria used for the SWOT analysis and elaboration.

Criterion	Explanation
Acceptance	Acceptance of the tool from the scientific community, industrial sector, consultant engineers and the policy makers.
Adaptation	Adaption of the tool with EGD, SDGs and other similar policies. Each tool was assessed on the level of implementation with different adopted strategies and/or policies and/or legislations in place.
Data accuracy	Accuracy of data outputs from the tool in terms of validity and error.
Data availability	Availability of data needed in order for the tool to operate to produce valid and useable results.
Interconnectivity	The degree in which the tool can be used simultaneously with other monitoring tools e.g digitalization, LCA etc.
Application	The degree of applicability the tool has in different environments (e.g urban, marine, megacities, etc.) and sectors (i.e. industrial, corporal, agricultural etc.).
International cooperation	The degree in which the tool can be used across the globe in synergies e.g between two countries, different level of industrial sectors, different level on policy recommendations etc.
Standardization	The degree in which the tool is standardized, and specific protocols are in place in order to use and accept the results from all inspections/audits and users. In addition, the level that the tool can be used to assess/monitor/validate/establish etc. in any ISO standard (e.g ISO 14001, EMAS, or other similar EMS) as well as for the new standard on Circular Economy that intend to develop from the ISO organization according to the TC323 (Technical Committee on Circular Economy according to ISO, 14001)
Complexity	The complexity in the use of the tool in terms of implementation in strategic approach and/or to assess any selected area and/or data collection, assumptions etc.
Time consuming	The time consumed for the collection of data and operation of the tool to produce valid results.
Human error	The degree in which human error and intervention place a major/minor role in the operation and results of the tool.
User friendly	The degree in which the tool interface is user friendly, easy to operate and easy to realize the benefits and to utilize the results to be useful to the end user(s) (e.g policy makers, academia, consultant engineers, and other relevant stakeholders)

Table 2
Inclusion and exclusion criteria for the recruitment of records on circular economy tools.

Inclusion criteria	Exclusion criteria
Records in English	Records with irrelevant data
Records focusing on circular economy	Duplicates
Articles from Scopus from 2019 on	Everything not included in the inclusion criteria
Records corresponding to the Keywords	

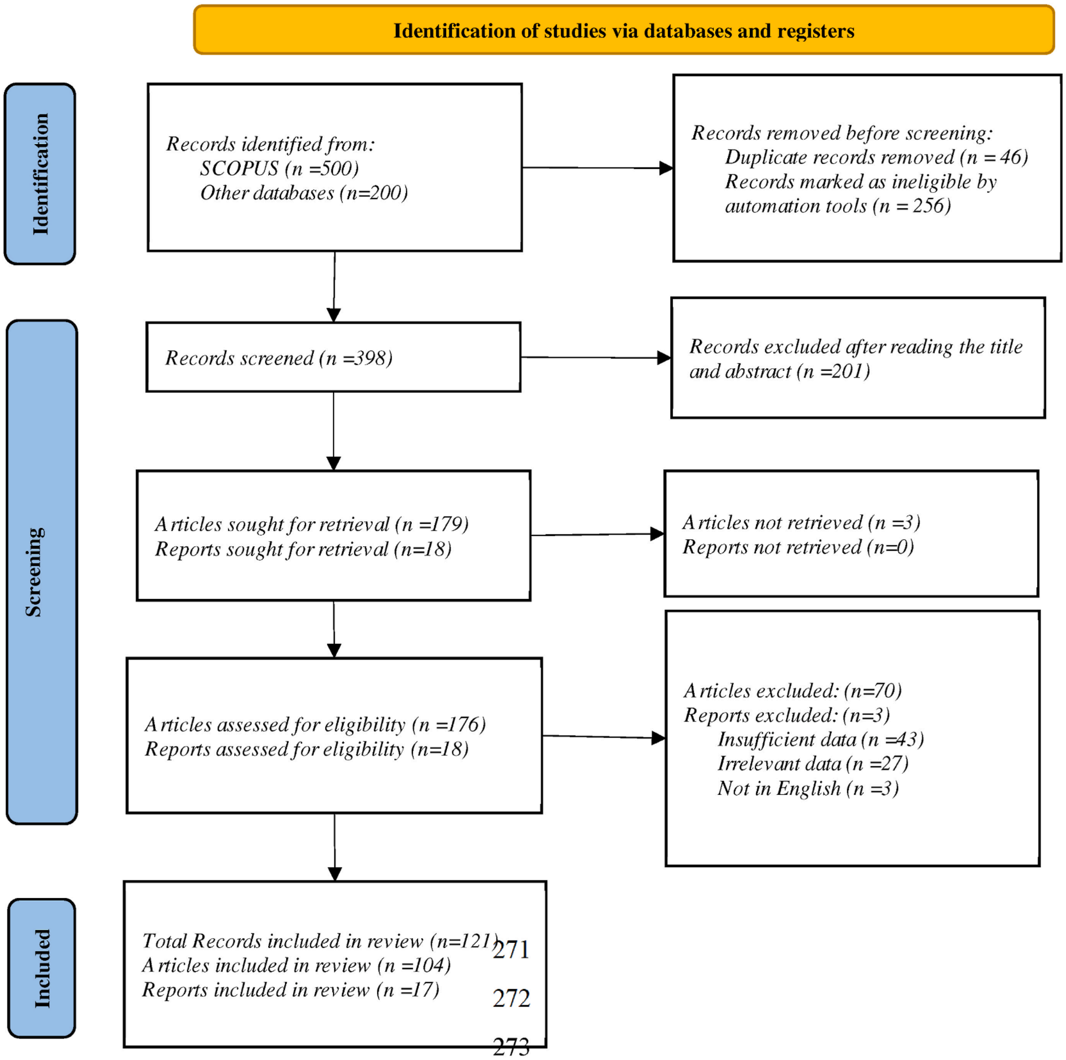

Fig. 1. PRISMA Statement of the current study.

pean-level policies in each nation have been established with their own national set of regulations pertaining to the circular economy, resulting in considerable heterogeneity among member states. While some countries have made significant strides in the adoption of circular economy principles, others are still in the initial stages of this transition (Domenech et al., 2019). Çetin et al. (2022) employed a multi-case analysis approach to gather firsthand data from Dutch social housing agencies implementing circular principles in various aspects such as new construction, renovation, maintenance, and demolition projects. The results of the study indicated that the utilization of artificial intelligence, digital twins, and scanning technologies aids in the collection, assimilation, and interpretation of data to support strategies for prolonging the life cycles (such as maintenance). Similarly, Nocca and Angrisano (2022) introduced a comprehensive assessment structure designed for the evaluation of cultural heritage restoration and repurposing endeavors, using as a foundation for the development of the assessment framework the Level(s) tool established by the European Commission, for the area of Naples in Italy. Building upon critical insights, the tool incorporated criteria and indicators derived from prior studies and other authorized resources addressing similar issues, including those from the Green Building Council and Heritage Impact Assessment tools.

Table 4 presents the SWOT analysis for the evaluation of circular economy monitoring tools based on the literature review and the feedback of the experts. From the results it is illustrated that all three of the tools present acceptance form the scientific community and adaptation to EU legislation. Many researchers showcase this as KPIs have been used in the past not only for Circular Economy concepts but also for sustainable development and climate change mitigation in general (Bianchini and Rossi, 2021; Loizia et al., 2021; Ngan et al., 2019; Shanmugam et al., 2022; Velasco-Muñoz et al., 2021). Furthermore, KPIs are integrated by default in EU legislation like EU monitoring framework for Circular Economy (European Commission, 2018), in order to provide quantifiable and measurable targets for member states to follow. Additionally, the unequivocal design of KPIs provide major data accuracy, as they are computational sets based on real life data and not results based on experience (Kravchenko et al., 2019). Still, KPIs are

Table 3
Related circular economy records from Scopus database (articles) and other trustworthy reports.

Circular Economy monitoring tools	No.	Research involving aspects of Circular Economy
KPIs	34	(Antwi-Afari et al., 2022; Aravossis et al., 2019; Barón Dorado et al., 2022; Belay et al., 2022; Bertanza et al., 2021; Bianchini and Rossi, 2021; Chatziparaskeva et al., 2022; Deus et al., 2022; Díaz-Ramírez et al., 2020; Dwivedi et al., 2022; European Commission, 2018; González et al., 2021; Kaiser et al., 2022; Karakutuk et al., 2021; Kravchenko et al., 2019; Loizia et al., 2021; Mantalovas and Di Mino, 2020; Maranghi et al., 2020; Ngan et al., 2019; Paletto et al., 2021; Pauer et al., 2019; Pollard et al., 2022; Prifti et al., 2021; Saavedra del Oso et al., 2022; Saidani et al., 2019; Shanmugam et al., 2022, 2021; Silvestri et al., 2020; Steuer, 2021; Tercero Espinoza, 2021; Velasco-Muñoz et al., 2021; Wang et al., 2021; Wani and Mishra, 2022; Zaytsev et al., 2021)
Quality Protocols	18	(Barón Dorado et al., 2022; Beuron et al., 2020; Gaballo et al., 2021; International Organization for Standardization (ISO), 2018, n.d.; ISO 14000; Khadim et al., 2022; Khan and Abonyi, 2022; Marrucci et al., 2022a, 2022b; Mignacca and Locatelli, 2021; Mulhall et al., 2022; Rajić et al., 2022; Schischke et al., 2022; Velasco-Muñoz et al., 2021; Wang et al., 2022; White, 2021; Yarahmadi et al., 2020)
Digitalization	37	(Alonso et al., 2021; Antwi-Afari et al., 2022; Appolloni et al., 2022; Aravossis et al., 2019; Barteková and Börkey, 2022; Beliatis et al., 2019; Bianchini and Rossi, 2021; Çetin et al., 2022; Claim Project, 2018; I D'Adamo et al., 2022; Díaz-Ramírez et al., 2020; Doh Dinga and Wen, 2021; Domenech et al., 2019; Dwivedi et al., 2022; European Environment Agency (EEA), 2021; Fernandez-Mena et al., 2020; García-Muiña et al., 2021; Glavič, 2021; González et al., 2021; Hernandez Marquina et al., 2021; Kurniawan et al., 2022; Luoma et al., 2022; Maranghi et al., 2020; Massoud et al., 2021; Melinte et al., 2020; Mondejar et al., 2021; Nika et al., 2020; NKS, 2017; Nocca and Angrisano, 2022; Papamichael et al., 2022; Pappas et al., 2022; Pauer et al., 2019; Prifti et al., 2021; Roy et al., 2021; Saavedra del Oso et al., 2022; Utrilla et al., 2020; Yeğin and Ikram, 2022)

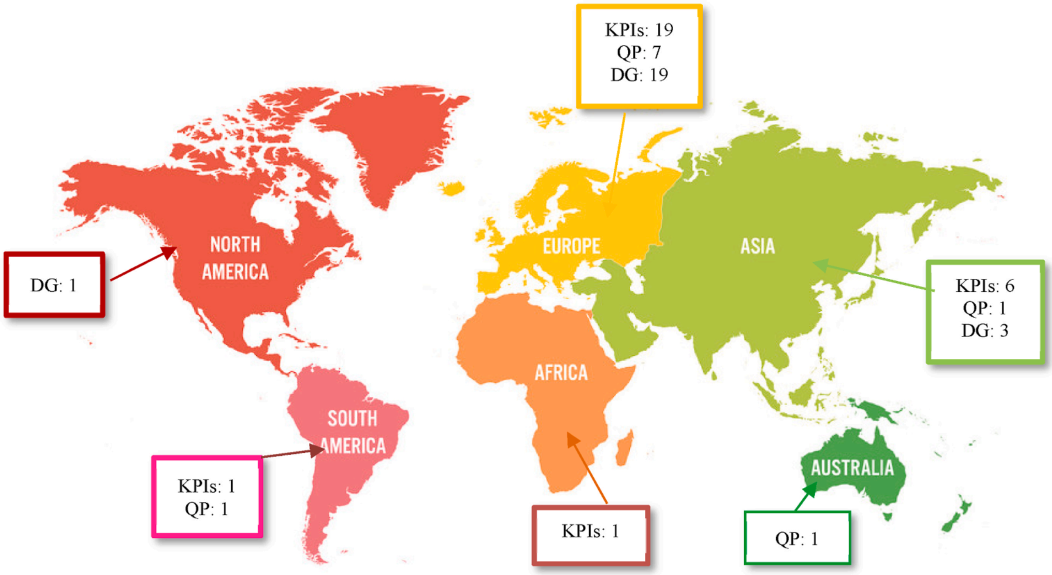

Fig. 2. Map indicating the geographical location of the research case studies about KPIs, Quality Protocols (QP) and digitalization (DG). The remaining articles of Table 3 (7 for KPIs, 8 for QP and 14 for DG) could not be categorized as they were reviews or other studies not specific to a geographical location.

deeply interconnected with other monitoring and assessing tools like quality protocols. ISO 37120 for Sustainable Development of Communities includes over 100 different indicators across 17 different sectors (i.e. economy, education, energy, governance, mobility etc.) (ISO, 2014). They have been used in different sectors (i.e. urban, industrial) concerning circular economy practices like end-of-life management, fashion, plastic manufacturing etc. (Chatziparaskeva et al., 2022; Ellen MacArthur Foundation, 2017). Still, one of the challenges of working with many KPIs, is the lack of available data to be processed but also the increasing complexity and time needed for interconnecting different KPIs (Kravchenko et al., 2019; Loizia et al., 2021). Also, human intervention may result in decreased data accuracy. Still, such implication cannot halt the use of KPIs for monitoring circular economy, especially for the purposes of creating international cooperation and access to data on a global scale for a holistic approach to raw material usage (Glavič, 2021).

At the same time, quality protocols like ISO 37120 for sustainable development of communities are trying to be in line with EU legislations and other strategies, for instance SDG 11 for sustainable cities and communities (ISO, 2014). Simultaneously, the insertion of data in digitalized tool is being used for monitoring the progress towards EU targets. D'Adamo et al. (2021) used multicriteria decision analysis (MCDA) to measure the current performance of Italy regarding SDGs using 175 indicators. The input data was obtained from the Italian National Institute of Statistics (ISTAT) which engaged in the production of statistical tools to measure the progress towards the establishment of the 17 SDGs. Quality protocols especially in the form of environmental management systems require data from the user, therefore data are always available but not always accurate. Still, quality protocols provide standardiza-

Table 4
SWOT Analysis of the Circular Economy tools.

		Strengths	Weaknesses
INTERNAL	**KPIs**	**1-Acceptance:** Accepted and used from the scientific community **2-Adaptation:** Quantified targets set by EGD, SDGs, etc. **3- Data Accuracy:** Quantifiable data result in more accurate results **5-Interconnectivity:** Easily used with other methods (i.e. with ISO) **6-Application:** Applied in different sectors/supply chains **12-User friendly:** Simple to use & easy to understand	**4-Data availability:** Lack of data to be used **9- Complexity:** Too many KPIs are complex to interconnect **10-Time consuming:** Collection of data can be time consuming **11-Human error:** Human intervention may result in false results
	Quality protocols	**1-Acceptance:** Accepted on an international level **2- Adaptation:** can be adapted to EU legislation **4- Data availability:** Data are usually available from the system under study **8-Standardization:** Quality protocols are standardized, providing smooth procedures and internationality **9-Complexity:** Quality protocols are usually straight forward in their demands **12-User friendly:** Results are easily understood	**3-Data accuracy:** Alteration of data from staff **5-Interconnectivity:** Lack of interconnection with different tools apart from KPIs. **10-Time consuming:** Collection of data and training of staff can be time consuming **11- Human error:** Human intervention may result in false results **6- Application:** Quality protocols must be investigated to be used in different sectors/different standardization procedures need to be followed
	Digitalization	**1- Acceptance:** Digital tools used are widely accepted (i.e. LCA) **2- Adaptation:** Saves time in achieving target set EU legislation **3- Data Accuracy:** Quantifiable data & min human intervention **5- Interconnectivity:** Includes most monitoring methods **6- Application:** Digitalization can be applied in many sectors **10- Time consuming:** Automation of work and real time data **11- Human error:** Automation results in less human intervention **12- User friendly:** Simple to use due to user friendly interfaces	**4-Data availability:** Lack of data to be used **9-Complexity:** Too many data harden the creation of a tool
		Opportunities	**Threats**
EXTERNAL	**KPIs**	**7-International cooperation:** used as a common approach across the globe	**8-Standardization:** Lack of standardization
	Quality protocols	**2- Adaptation:** Quality protocols could be analysed further to abide by legislation and action plans (i.e. EGD, SDGs, CES) **5-Interconnectivity:** Further investigation of quality protocols for interconnectivity with other tools **7-International cooperation:** Promotion of standardization for optimization of results	**5-Interconnectivity:** Lack of attention from governmental bodies
	Digitalization	**7-International cooperation:** Strengthened through data communication	**8-Standardization:** Lack of standardization thus acceptance

tion and internationality to their implementation, creating a sense of universality and harmonization when it comes to monitoring (Beuron et al., 2020). Although, the implementation of quality protocols can be time consuming and their application in different sectors usually requires different analysis of results. Lastly, human error due to human intervention (*i.e.* changing results) can lead to inaccurate data and thus decrease the level of quality management for circular economy practices (ISO, n.d. 2015). When it comes to digitalization, the SWOT analysis reveals great potential in monitoring Circular Economy. This is expected as digitalization has been a major beacon of development of the century due to Industry 4.0 and the technological development (García-Muiña et al., 2021; Kurniawan et al., 2022). Weaknesses of digitalization include data availability which largely correlates with user data inputs and complexity in terms of creating the tools for monitoring (Mulhall et al., 2022). At the same time, main threat of digitalization is the standardization of methodologies to create universal cooperation and homogeneity regarding the digital tools to be used (Barón Dorado et al., 2022).

According to the results of the SWOT analysis, along with experts' opinion regarding the comparison of the three tools, hybrid approaches in quantifying circular economy need to be addressed in order for the tools to be complementary (Papamichael et al., 2023a). In other words, the shortcomings of one tool can be fulfilled by the standards and characteristics of another. For instance, the use of many digitalization tools is neither standardized nor accepted broadly by the scientific community and other stakeholder. The combination however of digital tools with standards (EMS etc.) can be beneficial in creating a synergy for the quantification of circular characteristics and data collection (Pappas et al., 2022).

Even so, the introduction of digitalization has a potential to reduce resource use as it creates automation and real time monitoring which can aid in integrating circular economy into everyday activities (Melinte et al., 2020). According to Varaniūtė et al. (2022), digitalization, circular economy and sustainable development could be defined as guidelines for the management of the uncertainty in product development processes. At the same time, digitalization is used in many companies and enterprises in accounting management to create informed decision making.

Alonso et al. (2021) demonstrated how using deep learning techniques through convolutional neural networks can aid in identifying and classifying materials through images for automating recycling procedures. By inputting pictures, these networks were able to distinguish between different materials through locating specific features. At the same time, existing tools like TRashNet or MobileNet V2 can classify materials through the use of datasets and achieve 97% accuracy in their classifications (Melinte et al., 2020). Similarly, VGG16, GoogleNet and other networks achieves 97.86% accuracy in specific material classifications (i.e. paper, plastic, glass, metal etc.) (Alonso et al., 2021).

Apart from promoting circular economy initiatives on a private and industrial sector, digital transformation can also be used by policymakers in order to improve sustainability and economy (Barteková and Börkey, 2022). Example of this is the "MarineLitterWatch" mobile app of the European Environmental Agency (EEA) (European Environment Agency (EEA), 2021). The application is combined with online platforms and databases to connect marine litter on beaches reported by citizens and communities. The data are then used for the development of measures to tackle the specific waste streams of each area. Aiming specifically at the Mediterranean and Baltic Sea, the Horizon 2020 funded project "CLAIM" was used to generate datasets on plastic litter for the modelling of pathways and accumulation areas for the use of policymakers (Claim Project, 2018). Furthermore, GIS along with social networks (i.e. mobile phones) could be used for modelling urban areas to assess natural resources depletion and use to give access to better urban planning. Also, several cities are implementing smart waste management solutions (i.e. Pay as you throw with the sue of code bars). Specifically, Prague introduced a zero-waste plan called "Smart Prague 2030" while in Slovakia, new digitally enhanced and large capacity bins were introduced in order to improve waste management, optimize cost, improve quality of services and the overall quality of life for citizens (NKS, 2017; Smart, 2019).

However, to the author's knowledge, there is only one hybrid approach introduced on this matter. In the concept of KPIs, quality protocols and digitalization, Pappas et al. (2022), developed a gamified waste management tool, in order to model urban settings in the concept of sustainable development, waste management, legislation and other. The tool has the form of a virtual city, where the user could insert data to several KPIs (waste accumulation index, municipal solid waste recycling, recovery, generation, clean coats index, mobility, renewable energy sources etc.) to obtain real life and real time data on the situation of the virtual city in terms of waste management, EU legislation and EMS like ISO 37101, 37120, and ISO 14000 family (Papamichael et al., 2022). A gamification approach was used in order to engage the users to a more user-friendly environment and in the concept of "serious" game playing. As the pilot version of the tool was developed for educational purposed, a new pilot version of the tool was developed called "Stakeholders" edition, where an advanced user interface was developed to aid policy and decision makers in strategic planning of their urban environments (Papamichael et al., 2022; Pappas et al., 2022).

The interconnection of different tools to measure circular economy could provide a more optimized pathway towards circularity. As the tools and methods are already interconnected in a large degree (i.e. use of KPIs with digitalization, use of KPIs with quality protocols- ISO 37120 etc.), a targeted hybrid approach would be able to tackle different barriers of the transition towards circularity by eliminating the threats and weaknesses of the tools and take advantage of the strengths and opportunities provided by each three main categories (KPIs, quality protocols and digitalization) (ISO, 2014, 2016; Papamichael et al., 2022).

4. Conclusion

The research focuses on the comparison of different tools to measure and monitor circular economy-namely KPIs, quality protocols like environmental management systems (e.g ISO) and digitalization through a SWOT analysis. Through this analysis, the strengths, weaknesses, opportunities and threats of each of the three tools were identified while digitalization seemed to provide the fewer threats and weaknesses and the largest share of strengths and opportunities. As digital technologies (i.e. Artificial Intelligence, blockchain, IoT etc.) can aid to overcome obstacles and barriers to the transition of circular economy, at the same time, it has an enormous influence to consumption and production patterns of today's society. The utilization of the benefits arising from Industry 4.0 could have several and enormous positive effects on the sustainability pillars (environment, society, economy). At the same time, the interconnection of the different tools in one hybrid approach could provide a better understanding and monitoring of circular economy- and other similar concepts-in order to achieve a holistic solution to quantify circularity transition in different sectors. Still, the level of accomplishment of all waste management practices, adoption of circular economy and adherence to legislation can only be increased by the level of interest and action by policy makers and governments. Furthermore, concepts like gamification, as well as the promotion of circularity through campaigns and other marketing strategies will have to be used in order to influence the public into a more circular and sustainable way of life. Therefore, monitoring alone will not be sufficient for a smooth circular transition, but the involvement of all different players and actors of society is, urgent as circularity is interconnected with everything. Future work will have to include the promotion of hybrid approaches to monitoring circular economy combined with citizen engagement and public awareness for improving the quality of life and mitigate the anthropogenic effect of our kind onto the planet.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Research involving human participants

Favorable ethical opinion was obtained from Cyprus National Bioethics Committee (ΕΕΒΚ ΕΠ, 2022.01.224).

Authors' contribution

Iliana Papamichael: Conceptualization, methodology, software, validation, formal analysis, investigation, data curation, Writing-Original draft preparation, writing-review & editing, visualization. Irene Voukkali: Conceptualization, Methodology, software, validation, formal analysis, Writing-review & editing, visualization, supervision. Pantelitsa Loizia: Conceptualization, Validation, Formal analysis, Investigation, Data curation, Writing-Review & Editing, Visualization, Investigation. Marinos Stylianou: Conceptualization, Methodology, software, validation, formal analysis, Writing-review & editing, visualization, supervision. Florentios Economou: Conceptualization, Validation, Formal analysis, Investigation, Data curation, Writing-Review & Editing, Visualization, Investigation. Ioannis Vardopoulos: Formal analysis, Data Curation, Writing-Review & Editing, Visualization. Eleftheria Klontza: Formal analysis, Data Curation, Writing-Review & Editing, Visualization. Demetris F. Lekkas: Formal analysis, Data Curation, Writing-Review & Editing, Visualization. Antonis A. Zorpas: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data Curation, Writing-Original Draft, Writing-Review & Editing, Visualization, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

The authors would like to acknowledge the Laboratory of Chemical Engineering and Engineering Sustainability of the Open University of Cyprus, the Waste Management Laboratory of the Department of the Environment from the University of the Aegean as well as the Department of Economics and Sustainable Development, School of Environment, Geography and Applied Economics for supporting this research.

References

Alonso, S.L.N., Forradellas, R.F.R., Morell, O.P., Jorge-Vazquez, J., 2021. Digitalization, circular economy and environmental sustainability: the application of artificial intelligence in the efficient self-management of waste. Sustain. Times 13, 1–20. https://doi.org/10.3390/su13042092.

Amato, A., Andreoli, M., Rovai, M., 2021. Adaptive reuse of a historic building by introducing new functions: a scenario evaluation based on participatory mca applied to a former carthusian monastery in tuscany. Italy. Sustain. https://doi.org/10.3390/su13042335.

Antoniou, N.A., Zorpas, A.A., 2019. Quality protocol and procedure development to define end-of-waste criteria for tire pyrolysis oil in the framework of circular economy strategy. Waste Manag. 95, 161–170. https://doi.org/10.1016/j.wasman.2019.05.035.

Antwi-Afari, P., Ng, S.T., Chen, J., 2022. Developing an integrative method and design guidelines for achieving systemic circularity in the construction industry. J. Clean. Prod. 354. https://doi.org/10.1016/j.jclepro.2022.131752.

Appolloni, A., Chiappetta Jabbour, C.J., D'Adamo, I., Gastaldi, M., Settembre-Blundo, D., 2022. Green recovery in the mature manufacturing industry: the role of the green-circular premium and sustainability certification in innovative efforts. Ecol. Econ. 193, 107311. https://doi.org/10.1016/j.ecolecon.2021.107311.

Araujo Galvão, G.D., de Nadae, J., Clemente, D.H., Chinen, G., de Carvalho, M.M., 2018. Circular economy: overview of barriers. Procedia CIRP 73, 79–85. https://doi.org/10.1016/j.procir.2018.04.011.

Aravossis, K.G., Kapsalis, V.C., Kyriakopoulos, G.L., Xouleis, T.G., 2019. Development of a holistic assessment framework for industrial organizations. Sustain. Times. https://doi.org/10.3390/su11143946.

Barón Dorado, A., Giménez Leal, G., de Castro Vila, R., 2022. EMAS environmental statements as a measuring tool in the transition of industry towards a circular economy. J. Clean. Prod. 369. https://doi.org/10.1016/j.jclepro.2022.133213.

Barteková, E., Börkey, P., 2022. Digitalisation for the transition to a resource efficient and circular economy. OECD Environ. Work. Pap. https://doi.org/10.1787/19970900.

Belay, S., Goedert, J., Woldesenbet, A., Rokooei, S., 2022. AHP based multi criteria decision analysis of success factors to enhance decision making in infrastructure construction projects. Cogent Eng 9, 2043996. https://doi.org/10.1080/23311916.2022.2043996.

Beliatis, M.J., Lohacharoenvanich, N., Aagaard, A.A., Acharya, K.S., Presser, M.A., 2019. Internet of things for a sustainable food packaging ecosystem insights from a business perspective. In: Global IoT Summit, GIoTS 2019 - Proceedings. https://doi.org/10.1109/GIOTS.2019.8766378.

Bertanza, G., Mazzotti, S., Gómez, F.H., Nenci, M., Vaccari, M., Zetera, S.F., 2021. Implementation of circular economy in the management of municipal solid waste in an Italian medium-sized city: a 30-years lasting history. Waste Manag. 126, 821–831. https://doi.org/10.1016/j.wasman.2021.04.017.

Beuron, T.A., Madruga, L.R., da, R.G., Garlet, V., Avila, L.V., Guarda, F.G.K., Terra, C.C. de F., Balsan, L.A.G., 2020. Contributions of an environmental management system for sustainable development at a Brazilian university. Environ. Qual. Manag. 29, 103–113. https://doi.org/10.1002/tqem.21697.

Bianchini, A., Rossi, J., 2021. Design, implementation and assessment of a more sustainable model to manage plastic waste at sport events. J. Clean. Prod. 281, 125345. https://doi.org/10.1016/j.jclepro.2020.125345.

Bianchini, A., Rossi, J., Pellegrini, M., 2019. Overcoming the Main Barriers of Circular Economy Implementation through a New Visualization Tool for Circular Business Models. https://doi.org/10.3390/su11236614. Sustain.

Borg, D., Mont, O., Schoonover, H., 2020. Consumer acceptance and value in use-oriented product-service systems: lessons from Swedish consumer goods companies. Sustain. Times. https://doi.org/10.3390/su12198079.

Çetin, S., Gruis, V., Straub, A., 2022. Digitalization for a circular economy in the building industry: multiple-case study of Dutch social housing organizations. Resour. Conserv. Recycl. Adv. 15. https://doi.org/10.1016/j.rcradv.2022.200110.

Chatziparaskeva, G., Papamichael, I., Voukkali, I., Loizia, P., Sourkouni, G., Argirusis, C., Zorpas, A.A., 2022. End-of-Life of composite materials in the framework of the circular economy. Microplastics. https://doi.org/10.3390/microplastics1030028.

Claim Project, 2018. Claim work packages. Available online: https://www.claim-h2020project.eu/work-packages/. 11.22.22.

De la Barrera, F., Reyes-Paecke, S., Banzhaf, E., 2016. Indicators for green spaces in contrasting urban settings. Ecol. Indicat. 62, 212–219. https://doi.org/10.1016/j.ecolind.2015.10.027.
Deus, R.M., Esguícero, F.J., Battistelle, R.A.G., Jugend, D., 2022. Drivers and barriers to successful solid waste management: assessing through an aggregated indicator. J. Mater. Cycles Waste Manag. 24, 1476–1484. https://doi.org/10.1007/s10163-022-01396-8.
Díaz-Ramírez, M.C., Ferreira, V.J., García-Armingol, T., López-Sabirón, A.M., Ferreira, G., 2020. Battery manufacturing resource assessment to minimise component production environmental impacts. Sustain. Times 12. https://doi.org/10.3390/SU12176840.
Dictionary, Cambridge. no date. Standardization. Available online: https://dictionary.cambridge.org/dictionary/english/standardization. (Accessed 19 October 2023).
Doh Dinga, C., Wen, Z., 2021. Many-objective optimization of energy conservation and emission reduction in China's cement industry. Appl. Energy 304. https://doi.org/10.1016/j.apenergy.2021.117714.
Domenech, T., Bleischwitz, R., Doranova, A., Panayotopoulos, D., Roman, L., 2019. Mapping industrial symbiosis development in europe_ typologies of networks, characteristics, performance and contribution to the circular economy. Resour. Conserv. Recycl. 141, 76–98. https://doi.org/10.1016/j.resconrec.2018.09.016.
Dwivedi, A., Madaan, J., Santibanez Gonzalez, E.D.R., Moktadir, M.A., 2022. A two-phase approach to efficiently support product recovery systems in a circular economy context. Manag. Decis. 60, 2060–2091. https://doi.org/10.1108/MD-01-2021-0030.
D'Adamo, I., Gastaldi, M., Imbriani, C., Morone, P., 2021. Assessing regional performance for the sustainable development goals in Italy. Sci. Rep. 11, 24117. https://doi.org/10.1038/s41598-021-03635-8.
D'Adamo, Idiano, Lupi, G., Morone, P., Settembre-Blundo, D., 2022. Towards the circular economy in the fashion industry: the second-hand market as a best practice of sustainable responsibility for businesses and consumers. Environ. Sci. Pollut. Res. https://doi.org/10.1007/s11356-022-19255-2.
D'Adamo, I., Mazzanti, M., Morone, P., Rosa, P., 2022. Assessing the relation between waste management policies and circular economy goals. Waste Manag. 154, 27–35. https://doi.org/10.1016/j.wasman.2022.09.031.
Ellen MacArthur Foundation, 2015. Towards a circular economy: business rationale for an accelerated transition. Available online: https://emf.thirdlight.com/link/ip2fh05h21it-6nvypm/@/preview/1?o. 3.27.22.
Ellen MacArthur Foundation, 2017. A new textiles economy: redesigning fashion's future. Available online: https://www.ellenmacarthurfoundation.org/assets/downloads/publications/A-New-Textiles-Economy_Full-Report_Updated_1-12-17.pdf. 1.23.22.
Ellen MacArthur Foundation, 2021. Circular business models: redefining growth for a thriving fashion industry. Available online: https://emf.thirdlight.com/link/circular-business-models-exec-summ/@/preview/1?o. 2.18.22.
European Commission, 2018. Communication from the commission to the European Parliament, the council, the European Economic and Social committee and the committee of the regions on a monitoring framework for the circular economy. Available online: https://ec.europa.eu/environment/circular-economy/pdf/monitoring-framework.pdf. 11.15.22.
European Commission, 2020. Communication from the commission to the European parliament, the council, the European economic and social committee and the committee of the regions A new circular economy action plan. In: Ommunication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions A New Circular Economy Action Plan New Circular Economy Action Plan for a Cleaner and More. Competitive Eu, Brussels, pp. 1–27.
European Environment Agency (EEA), 2021. Marine LitterWatch in a nutshell. Available online: https://www.eea.europa.eu/themes/water/europes-seas-and-coasts/assessments/marine-litterwatch/at-a-glance/marine-litterwatch-in-a-nutshell. 11.22.22.
Fernandez-Mena, H., Gaudou, B., Pellerin, S., MacDonald, G.K., Nesme, T., 2020. Flows in Agro-food Networks (FAN): an agent-based model to simulate local agricultural material flows. Agric. Syst. 180. https://doi.org/10.1016/j.agsy.2019.102718.
Gaballo, M., Mecca, B., Abastante, F., 2021. Adaptive reuse and sustainability protocols in Italy: relationship with circular economy. Sustain. Times 13. https://doi.org/10.3390/su13148077.
García-Muiña, F., Medina-Salgado, M.S., González-Sánchez, R., Huertas-Valdivia, I., Ferrari, A.M., Settembre-Blundo, D., 2021. Industry 4.0-based dynamic Social Organizational Life Cycle Assessment to target the social circular economy in manufacturing. J. Clean. Prod. 327. https://doi.org/10.1016/j.jclepro.2021.129439.
Georgitsoyanni, E., Sardianou, E., Lappa, A., Mylona, E., 2013. In: Sklias, P., Tzifakis, N. (Eds.), Prospects for Local Development Based on Cultural Assets/Heritage: the Residents' Perspective BT - Greece's Horizons: Reflecting on the Country's Assets and Capabilities. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 147–160. https://doi.org/10.1007/978-3-642-34534-0_12.
Glavič, P., 2021. Evolution and current challenges of sustainable consumption and production. Sustain. Times. https://doi.org/10.3390/su13169379.
González, A., Sendra, C., Herena, A., Rosquillas, M., Vaz, D., 2021. Methodology to assess the circularity in building construction and refurbishment activities. Resour. Conserv. Recycl. Adv. 12. https://doi.org/10.1016/j.rcradv.2021.200051.
Haupt, M., Zschokke, M., 2017. How can LCA support the circular economy?—63rd discussion forum on life cycle assessment, Zurich, Switzerland, November 30, 2016. Int. J. Life Cycle Assess. 22, 832–837. https://doi.org/10.1007/s11367-017-1267-1.
Hernandez Marquina, M.V., Zwolinski, P., Mangione, F., 2021. Application of Value Stream Mapping tool to improve circular systems. Clean. Eng. Technol. 5. https://doi.org/10.1016/j.clet.2021.100270.
International Organization for Standardization (ISO). n.d. ISO/CD 59004 circular economy – terminology, principles and guidance for implementation. Available online: https://www.iso.org/standard/80648.html. 11.15.22.
International Organization for Standardization (ISO), 2018. ISO/TC 323 circular economy. Available online: https://www.iso.org/committee/7203984.html. 11.15.22.
ISO, Family Environmental Management. n.d. 14000, Available online: https://www.iso.org/iso-14001-environmental-management.html (accessed 8.18.22)..
ISO, 2014. Sustainable Development of Communities-Indicators for City Services and Quality of Life. ISO 37120:2014(E)).
ISO, 2015. Environmental Management Systems: Requirements with Guidance of Use. ISO 14001:2015).
ISO, 2016. Sustainable Cities and Communities. ISO 37101:2016).
Jaeger, B., Upadhyay, A., 2020. Understanding barriers to circular economy: cases from the manufacturing industry. J. Enterprise Inf. Manag. 33, 729–745. https://doi.org/10.1108/JEIM-02-2019-0047.
Jiang, J., Chu, C., Song, L., Gao, X., Huang, B., Zhang, Yufei, Zhang, Yi, Liu, Y., Hou, L., Ju, M., Cao, Z., 2023. From prospecting to mining: a review of enabling technologies, LCAs, and LCCAs for improved construction and demolition waste management. Waste Manag. 159, 12–26. https://doi.org/10.1016/j.wasman.2023.01.017.
Kaiser, S., Gold, S., Bringezu, S., 2022. Environmental and economic assessment of CO2-based value chains for a circular carbon use in consumer products. Resour. Conserv. Recycl. 184. https://doi.org/10.1016/j.resconrec.2022.106422.
Karakutuk, S.S., Akpinar, S., Ornek, M.A., 2021. An application of a circular economy approach to design an energy-efficient heat recovery system. J. Clean. Prod. 320. https://doi.org/10.1016/j.jclepro.2021.128851.
Kasavan, S., Yusoff, S., Guan, N.C., Zaman, N.S.K., Fakri, M.F.R., 2021. Global trends of textile waste research from 2005 to 2020 using bibliometric analysis. Environ. Sci. Pollut. Res. 28, 44780–44794. https://doi.org/10.1007/s11356-021-15303-5.
Kazamias, G., Zorpas, A.A., 2021. Drill cuttings waste management from oil & gas exploitation industries through end-of-waste criteria in the framework of circular economy strategy. J. Clean. Prod. 322, 129098. https://doi.org/10.1016/j.jclepro.2021.129098.
Khadim, N., Agliata, R., Marino, A., Thaheem, M.J., Mollo, L., 2022. Critical review of nano and micro-level building circularity indicators and frameworks. J. Clean. Prod. 357. https://doi.org/10.1016/j.jclepro.2022.131859.
Khan, A.A., Abonyi, J., 2022. Information sharing in supply chains – interoperability in an era of circular economy. Clean. Logist. Supply Chain 5. https://doi.org/10.1016/j.clscn.2022.100074.
Kirchherr, J., Hekkert, M.P., Bour, R., Huijbrechtse-Truijens, A., Kostense-Smit, E., Muller, J., 2017. Breaking the barriers to the circular economy. Available online: https://circulareconomy.europa.eu/platform/sites/default/files/171106_white_paper_breaking_the_barriers_to_the_circular_economy_white_paper_vweb-14021.pdf. 3.27.22.
Kirchherr, J., Piscicelli, L., Bour, R., Kostense-Smit, E., Muller, J., Huibrechtse-Truijens, A., Hekkert, M., 2018. Barriers to the circular economy: evidence from the European union (EU). Ecol. Econ. 150, 264–272. https://doi.org/10.1016/j.ecolecon.2018.04.028.

Kravchenko, M., McAloone, T.C., Pigosso, D.C.A., 2019. Implications of developing a tool for sustainability screening of circular economy initiatives. Procedia CIRP 80, 625–630. https://doi.org/10.1016/j.procir.2019.01.044.

Kristoffersen, E., Blomsma, F., Mikalef, P., Li, J., 2020. The smart circular economy: a digital-enabled circular strategies framework for manufacturing companies. J. Bus. Res. 120, 241–261. https://doi.org/10.1016/j.jbusres.2020.07.044.

Kurniawan, T.A., Maiurova, A., Kustikova, M., Bykovskaia, E., Othman, M.H.D., Goh, H.H., 2022. Accelerating sustainability transition in St. Petersburg (Russia) through digitalization-based circular economy in waste recycling industry: a strategy to promote carbon neutrality in era of Industry 4.0. J. Clean. Prod. 363. https://doi.org/10.1016/j.jclepro.2022.132452.

Loizia, P., Voukkali, I., Zorpas, A.A., Navarro Pedreño, J., Chatziparaskeva, G., Inglezakis, V.J., Vardopoulos, I., Doula, M., 2021. Measuring the level of environmental performance in insular areas, through key performed indicators, in the framework of waste strategy development. Sci. Total Environ. 753, 141974. https://doi.org/10.1016/j.scitotenv.2020.141974.

Luoma, P., Penttinen, E., Tapio, P., Toppinen, A., 2022. Future images of data in circular economy for textiles. Technol. Forecast. Soc. Change 182. https://doi.org/10.1016/j.techfore.2022.121859.

Mantalovas, K., Di Mino, G., 2020. Integrating circularity in the sustainability assessment of asphalt mixtures. Sustain. Times 12. https://doi.org/10.3390/su12020594.

Maranghi, S., Parisi, M.L., Facchini, A., Rubino, A., Kordas, O., Basosi, R., 2020. Integrating urban metabolism and life cycle assessment to analyse urban sustainability. Ecol. Indicat. 112, 106074. https://doi.org/10.1016/j.ecolind.2020.106074.

Marrucci, L., Daddi, T., Iraldo, F., 2022a. The circular economy, environmental performance and environmental management systems: the role of absorptive capacity. J. Knowl. Manag. 26, 2107–2132. https://doi.org/10.1108/JKM-06-2021-0437.

Marrucci, L., Daddi, T., Iraldo, F., 2022b. Do dynamic capabilities matter? A study on environmental performance and the circular economy in European certified organisations. Bus. Strat. Environ. 31, 2641–2657. https://doi.org/10.1002/bse.2997.

Massoud, R., Berta, R., Poslad, S., Gloria, A.D., Bellotti, F., 2021. IoT sensing for reality-enhanced serious games, a fuel-efficient drive use case. Sensors 21. https://doi.org/10.3390/s21103559.

Melinte, D.O., Travediu, A.-M., Dumitriu, D.N., 2020. Deep convolutional neural networks object detector for real-time waste identification. Appl. Sci. https://doi.org/10.3390/app10207301.

Mignacca, B., Locatelli, G., 2021. Modular circular economy in energy infrastructure projects: enabling factors and barriers. J. Manag. Eng. 37. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000949.

Mondejar, M.E., Avtar, R., Diaz, H.L.B., Dubey, R.K., Esteban, J., Gómez-Morales, A., Hallam, B., Mbungu, N.T., Okolo, C.C., Prasad, K.A., She, Q., Garcia-Segura, S., 2021. Digitalization to achieve sustainable development goals: steps towards a smart green planet. Sci. Total Environ. 794. https://doi.org/10.1016/j.scitotenv.2021.148539.

Moustairas, I., Vardopoulos, I., Kavouras, S., Salvati, L., Zorpas, A.A., 2021. Exploring factors that affect public acceptance of establishing an urban environmental education and recycling center. Sustain. Chem. 25, 100605. https://doi.org/10.1016/j.scp.2022.100605.

Mulhall, D., Ayed, A.-C., Schroeder, J., Hansen, K., Wautelet, T., 2022. The product circularity data sheet—a standardized digital fingerprint for circular economy data about products. Energies 15. https://doi.org/10.3390/en15093397.

Ngan, S.L., How, B.S., Teng, S.Y., Promentilla, M.A.B., Yatim, P., Er, A.C., Lam, H.L., 2019. Prioritization of sustainability indicators for promoting the circular economy: the case of developing countries. Renew. Sustain. Energy Rev. 111, 314–331. https://doi.org/10.1016/j.rser.2019.05.001.

Nika, C.E., Vasilaki, V., Expósito, A., Katsou, E., 2020. Water cycle and circular economy: developing a circularity assessment framework for complex water systems. Water Res. 187. https://doi.org/10.1016/j.watres.2020.116423.

Niyommaneerat, W., Suwanteep, K., Chavalparit, O., 2023. Sustainability indicators to achieve a circular economy: a case study of renewable energy and plastic waste recycling corporate social responsibility (CSR) projects in Thailand. J. Clean. Prod. 391, 136203. https://doi.org/10.1016/j.jclepro.2023.136203.

NKS, 2017. Waste management in nitra. Available online: https://www.ceeweb.org/wp-content/uploads/Nitra-Waste-management_V4.pdf. 11.22.22.

Nocca, F., Angrisano, M., 2022. The multidimensional evaluation of cultural heritage regeneration projects: a proposal for integrating level(s) tool—the case study of villa vannucchi in san giorgio a cremano (Italy). Land 11. https://doi.org/10.3390/land11091568.

OECD, n.d. Circular Economy Country Studies. Available online: https://www.oecd.org/environment/waste/circular-economy-country-studies.htm (accessed 10.19.23)..

Official Journal of the European Union, 2008. Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:02008L0098-20180705&from=EN (accessed 5.7.22)..

Okedu, K.E., Barghash, H.F., Al Nadabi, H.A., 2022. Sustainable waste management strategies for effective energy utilization in Oman: a review. Front. Bioeng. Biotechnol. 10. https://doi.org/10.3389/fbioe.2022.825728.

Paletto, A., Becagli, C., Bianchetto, E., Sacchelli, S., de Meo, I., 2021. Measuring and assessing forest-based circular bioeconomy to implement the National Sustainable Development Strategy in Italy. Austrian J. For. Sci. 138, 251–278.

Papamichael, I., Pappas, G., Siegel, J.E., Zorpas, A.A., 2022. Unified waste metrics: a gamified tool in next-generation strategic planning. Sci. Total Environ. 154835. https://doi.org/10.1016/j.scitotenv.2022.154835.

Papamichael, I., Voukkali, I., Loizia, P., Pappas, G., Zorpas, A.A., 2023a. Existing tools used in the framework of environmental performance. Sustain. Chem. Pharm. 32, 101026. https://doi.org/10.1016/j.scp.2023.101026.

Papamichael, I., Voukkali, I., Loizia, P., Zorpas, A.A., 2023b. Construction and demolition waste framework of circular economy: a mini review. Waste Manag. https://doi.org/10.1177/0734242X231190804. Res. 0734242X231190804.

Pappas, G., Papamichael, I., Zorpas, A., Siegel, J.E., Rutkowski, J., Politopoulos, K., 2022. Modelling key performance indicators in a gamified waste management tool. Model. https://doi.org/10.3390/modelling3010003.

Pauer, E., Wohner, B., Heinrich, V., Tacker, M., 2019. Assessing the environmental sustainability of food packaging: an extended life cycle assessment including packaging-related food losses and waste and circularity assessment. Sustain. Times 11. https://doi.org/10.3390/su11030925.

Pollard, J., Osmani, M., Cole, C., Grubnic, S., Colwill, J., Díaz, A.I., 2022. Developing and applying circularity indicators for the electrical and electronic sector: a product lifecycle approach. Sustain. Times 14. https://doi.org/10.3390/su14031154.

Prifti, K., Galeazzi, A., Margarita, I., Papale, A., Miele, S., Bargiacchi, E., Barbieri, M., Petea, M., Manenti, F., 2021. Converting end-of-life plastic waste into methanol: the gasiforming™ process as new, efficient and circular pathway. Environ. Eng. Manag. J. 20, 1629–1636. https://doi.org/10.30638/eemj.2021.151.

Rajić, M., Mančić, M., Kostić, Z., Milosavljević, P., 2022. Model of the circular economy and its application in industry practice: a case study of Serbia. In: Lecture Notes in Networks and Systems. pp. 1083–1092. https://doi.org/10.1007/978-3-031-05230-9_128.

Roy, A., Manna, A., Kim, J., Moon, I., 2021. Integrated planning of IoT-based smart bin allocation and vehicle routing in solid waste management. IFIP Adv. Inf. Commun. Technol. https://doi.org/10.1007/978-3-030-85906-0_55.

Saavedra del Oso, M., Regueira, A., Hospido, A., Mauricio-Iglesias, M., 2022. Fostering the valorization of organic wastes into carboxylates by a computer-aided design tool. Waste Manag. 142, 101–110. https://doi.org/10.1016/j.wasman.2022.02.008.

Saidani, M., Kendall, A., Yannou, B., Leroy, Y., Cluzel, F., 2019. Closing the loop on platinum from catalytic converters: contributions from material flow analysis and circularity indicators. J. Ind. Ecol. 23, 1143–1158. https://doi.org/10.1111/jiec.12852.

Schischke, K., Berwald, A., Dimitrova, G., Rückschloss, J., Nissen, N.F., Schneider-Ramelow, M., 2022. Durability, reparability and recyclability: applying material efficiency standards en 4555x to mobile phones and tablet computers. In: Procedia CIRP. pp. 619–624. https://doi.org/10.1016/j.procir.2022.02.103.

Shanmugam, V., Mensah, R.A., Försth, M., Sas, G., Restás, Á., Addy, C., Xu, Q., Jiang, L., Neisiany, R.E., Singha, S., George, G., Jose E, T., Berto, F., Hedenqvist, M.S., Das, O., Ramakrishna, S., 2021. Circular economy in biocomposite development: state-of-the-art, challenges and emerging trends. Composites Part C Open Access 5, 100138. https://doi.org/10.1016/j.jcomc.2021.100138.

Shanmugam, K., Gadhamshetty, V., Tysklind, M., Bhattacharyya, D., Upadhyayula, V.K.K., 2022. A sustainable performance assessment framework for circular management of municipal wastewater treatment plants. J. Clean. Prod. 339, 130657. https://doi.org/10.1016/j.jclepro.2022.130657.

Silvestri, F., Spigarelli, F., Tassinari, M., 2020. Regional development of circular economy in the European union: a multidimensional analysis. J. Clean. Prod. 255. https://doi.org/10.1016/j.jclepro.2020.120218.

Smart, Prague, 2019. Smart waste collection. Available online: https://smartprague.eu/projects/smart_wast_-collection. 11.22.22.
Statista, 2022. Statista Dossier about electronic waste worldwide. Available online: https://www.statista.com/study/56028/global-electronic-waste/. 11.4.22.
Steuer, B., 2021. Identifying effective institutions for China's circular economy: bottom-up evidence from waste management. Waste Manag. Res. 39, 937–946. https://doi.org/10.1177/0734242X20972796.
Tercero Espinoza, L.A., 2021. Critical appraisal of recycling indicators used in European criticality exercises and circularity monitoring. Res. Pol. 73. https://doi.org/10.1016/j.resourpol.2021.102208.
United Nations, 2015. Transforming our world: the 2030 Agenda for sustainable development. Available online: https://www.un.org/ga/search/view_doc.asp?symbol=A/RES/70/1&Lang=E. 3.30.22.
Utrilla, P.N.-C., Górecki, J., Maqueira, J.M., 2020. Simulation-based management of construction companies under the circular economy concept-Case study. Buildings 10. https://doi.org/10.3390/BUILDINGS10050094.
Varaniūtė, V., Žičkutė, I., Žandaravičiūtė, A., 2022. The changing role of management accounting in product development: directions to digitalization, sustainability, and circularity. Sustainability. https://doi.org/10.3390/su14084740.
Vardopoulos, I., Stamopoulos, C., Chatzithanasis, G., Michalakelis, C., Giannouli, P., Pastrapa, E., 2020. Considering urban development paths and processes on account of adaptive reuse projects. Buildings 10, 73. https://doi.org/10.3390/buildings10040073.
Vardopoulos, I., Konstantopoulos, I., Zorpas, A., Limousy, L., Bennici, S., Inglezakis, V., Voukkali, I., 2021. Sustainable metropolitan areas perspectives through assessment of the existing waste management strategies. Environ. Sci. Pollut. Res. https://doi.org/10.1007/s11356-020-07930-1.
Velasco-Muñoz, J.F., Mendoza, J.M.F., Aznar-Sánchez, J.A., Gallego-Schmid, A., 2021. Circular economy implementation in the agricultural sector: definition, strategies and indicators. Resour. Conserv. Recycl. 170. https://doi.org/10.1016/j.resconrec.2021.105618.
Vinci, S., Vardopoulos, I., Salvati, L., 2023. A tale of a shrinking City? Exploring the complex interplay of socio-demographic dynamics in the recent development of Attica, Greece. Cities 132, 104089. https://doi.org/10.1016/j.cities.2022.104089.
Voukkali, I., Zorpas, A.A., 2022. Evaluation of urban metabolism assessment methods through SWOT analysis and analytical hierocracy process. Sci. Total Environ. 807.
Voukkali, I., Papamichael, I., Loizia, P., Lekkas, D.F., Rodríguez-Espinosa, T., Navarro-Pedreño, J., Zorpas, A.A., 2023. Waste metrics in the framework of circular economy. Waste Manag. Res. 0734242X231190794. https://doi.org/10.1177/0734242X231190794.
Wang, N., Guo, J., Zhang, X., Zhang, J., Li, Z., Meng, F., Zhang, B., Ren, X., 2021. The circular economy transformation in industrial parks: theoretical reframing of the resource and environment matrix. Resour. Conserv. Recycl. 167. https://doi.org/10.1016/j.resconrec.2020.105251.
Wang, J.X., Burke, H., Zhang, A., 2022. Overcoming barriers to circular product design. Int. J. Prod. Econ. 243. https://doi.org/10.1016/j.ijpe.2021.108346.
Wang, D., Tang, Y.-T., Sun, Y., He, J., 2022. Assessing the transition of municipal solid waste management by combining material flow analysis and life cycle assessment. Resour. Conserv. Recycl. 177, 105966. https://doi.org/10.1016/j.resconrec.2021.105966.
Wani, N.A., Mishra, U., 2022. An integrated circular economic model with controllable carbon emission and deterioration from an apple orchard. J. Clean. Prod. 374. https://doi.org/10.1016/j.jclepro.2022.133962.
White, J.M., 2021. Standardising the city as an object of comparison: the promise, limits and perceived benefits of ISO 37120. Telematics Inf. 57. https://doi.org/10.1016/j.tele.2020.101515.
Yarahmadi, R., Moridi, H., Farshad, A.A., Taheri, F., 2020. Weighing and prioritizing the eight principles of integrated health, safety, environment and energy management in industries covered by the ministry of industry, mining and trade. Salāmat-i kār-i Īrān 17, 1–10.
Yeğin, T., Ikram, M., 2022. Developing a sustainable omnichannel strategic framework toward circular revolution: an integrated approach. Sustain. Times 14. https://doi.org/10.3390/su141811578.
Zaytsev, A., Dmitriev, N., Rodionov, D., Magradze, T., 2021. Assessment of the innovative potential of alternative energy in the context of the transition to the circular economy. Int. J. Technol. 12, 1328–1338. https://doi.org/10.14716/IJTECH.V12I7.5357.
Zorpas, A.A., 2020. Strategy development in the framework of waste management. Sci. Total Environ. 716, 137088. https://doi.org/10.1016/j.scitotenv.2020.137088.
Zorpas, A.A., Navarro-Pedreño, J., Jeguirim, M., Dimitriou, G., Almendro Candel, M.B., Argirusis, C., Vardopoulos, I., Loizia, P., Chatziparaskeva, G., Papamichael, I., 2021. Crisis in leadership vs waste management. Euro-Mediterranean J. Environ. Integr. 6, 80. https://doi.org/10.1007/s41207-021-00284-1.