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RESEARCH ARTICLE

Ranking circularity levels in industrial parks: a holistic approach incorporating environmental, economic and social indicators

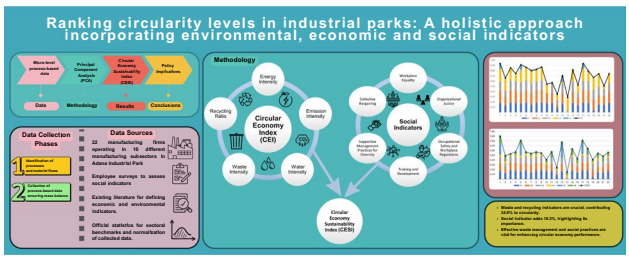
Istemi Berk[1] · Volkan Ş. Ediger[2] · Engin Bağış Öztürk[3] · Fehmi Görkem Üçtuğ[4] · Mehmet Ali Küçüker[5] · Ali İnan[6] · Gülper Basmacı Aktuna[7]

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Abstract

This study introduces a circularity ranking system at the meso-level, specifically targeting industrial parks, through the development of the Circular Economy Sustainability Index (CESI). The index comprises five economic-environmental indicators: energy intensity, emission intensity, water intensity, waste intensity, and recycling ratio, as well as a social indicator as a sixth dimension. We utilize CESI to evaluate the circular economy performance of 22 manufacturing firms in the Adana Hacı Sabancı Organized Industrial Zone (AOSB). AOSB, one of the most prominent industrial parks in Türkiye, serves as an excellent case study to assess companies' circularity performance and identify areas for improvement in the country's green industrial transformation endeavor. Our findings reveal that waste and recycling indicators are pivotal in determining circularity, contributing 34.6% to the overall score, while the social indicator adds another 16.3%. These results underscore the significance of effective waste management and social responsibility in enhancing circularity.

Graphical Abstract



Keywords Circularity ranking · Industrial parks · Holistic approach · Environmental · Economic · And social indicators

Responsible Editor: Philippe Garrigues

✉ Istemi Berk
istemi.berk@deu.edu.tr

[1] Department of Economics, Faculty of Business, Dokuz Eylul University, 35390 İzmir, Türkiye

[2] Center for Energy and Sustainable Development (CESD), Kadir Has University, 34083 İstanbul, Türkiye

[3] Department of Business Administration, Faculty of Business, Dokuz Eylul University, 35390 İzmir, Türkiye

[4] Department of Mechanical Engineering, İzmir University of Economics, 35330 İzmir, Türkiye

[5] Department of Environmental Engineering, İzmir Institute of Technology, 35430 İzmir, Türkiye

[6] Computer Engineering Department, Adana Alparslan Türkeş Science and Technology University, 01790 Adana, Türkiye

[7] Department of Business Administration, Faculty of Economics and Administrative Sciences, Dokuz Eylul University, 35390 İzmir, Türkiye

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Introduction

Sustainability has often been shaped with a focus mainly on the environment before Elkington (1997, p. 2) introduced the concept of the "triple bottom line," built upon three pillars: economic prosperity, environmental quality, and "an element which business has tended to overlook," namely, social justice. These pillars were later highlighted by the 2030 Agenda for Sustainable Development (UN 2015), and sustainability was defined as "the balanced integration of economic performance, social inclusiveness, and environmental resilience, to the benefit of current and future generations" (Geissdoerfer et al. 2017, p. 766).

The transition from a linear to a circular economy (CE) is considered a necessary step to achieve sustainability (e.g., Brennan et al. 2015; Geissdoerfer et al. 2017; Mestdagh 2021) since its adoption generates positive externalities in economic growth, human development, and the optimization of natural resource consumption (Saidani et al. 2019). However, CE mainly focuses on environmental and economic benefits, neglecting the social dimension. Walker et al. (2021), conducting surveys with 155 industrial establishments, identified that most respondents are less confident that CE would promote social benefits.

Governments play an essential role in promoting CE by creating necessary regulatory and policy frameworks, while companies seek to maximize their profits by considering this framework (Azevedo et al. 2017; Rabte 2020). Different CE frameworks are used in countries such as China, Japan, Germany, the United Kingdom, and the European Union (EU) (Azevedo et al. 2017). The EU, among them, most decisively applies the principles of CE. The European Commission (EC) officially announced CE as a new economic model for the EU in 2014 (Smol 2023) and launched the first Circular Economy Action Plan (EC 2015). In 2020, the EC adopted the New Circular Economy Action Plan as one of the main building blocks of the European Green Deal (EGD) (EC 2020). Other governments are designing policies to support the transition towards a circular economy, considering the competition, growth, and circular economy interactions (OECD 2023).

Competition helps accelerate companies' transition to the circular economy, ultimately increasing economic efficiency. Economic efficiency is composed of static efficiency, which includes productive efficiency (minimizing resource waste), allocative efficiency (matching production to consumers' demand), and dynamic efficiency, which includes improvements in production processes and quality of products via technical progress (Motta 2004). Extended Producer Responsibility, in which the responsibility for the end-of-life management of a product is given to the producer, is also central to developing a competitive market by putting pressure on companies to provide innovative, sustainable solutions (Ahlers et al. 2021).

Measuring the CE performance at the micro-, meso-, and macro-level promotes adopting an economic model focused on transformative production chain systems and consumption standards, paving the way from a linear economy to a CE (Sauvé et al. 2016; Kirchherr et al. 2017; Saidani et al. 2019; Martinho 2021). It supports managers in assessing their level of circularity and implementing some practices that could improve their companies' performances (Azevedo et al. 2017; de Oliveira Frascareli et al. 2023). Accelerating the transition to a CE will allow companies to transform their processes by creating new and more sustainable competitive advantages (Azevedo et al. 2017). Furthermore, the customers can select products by examining their circularity indexes (Thomas and Mishra 2022). As Lanaras-Mamounis et al. (2022) proposed, existing eco-labels of consumer products mainly focus on environmental impacts, primarily on CO_2 emissions, without exploiting all circularity aspects. Therefore, there is a demand for continual evaluation of system's performance focused on circularity (Santagata et al. 2020), which will significantly contribute to achieving the 2050 net-zero emission target.

This study proposes a modified ranking system for manufacturing companies based on their circularity levels, called the Circular Economy Sustainability Index (CESI). It is developed by employing Principal Component Analysis (PCA) on environmental, economic, and social factors, such as production, energy consumption, emissions, water usage, waste and recycling, and social indicators. This study is carried out at a meso-level based on Yuan et al. (2006) classification by utilizing data on 22 manufacturing companies from the Adana Organized Industrial Zone (AOSB), one of the largest industrial parks (IPs) in Türkiye. The meso-level studies are carried out to encourage the development of eco-industrial parks, networks, and clusters that will improve their economic, environmental, and social benefits (Geng et al. 2008). As discussed in the literature review section, a study of this scope and content is being carried out for the first time. Our index will accelerate the transition to a circular economy among the companies in industrial parks.

The rationale for selecting AOSB as a case study is twofold. Firstly, the Carbon Border Adjustment Mechanism (CBAM), proposed within the EGD, requires European trading partners to foster a green industrial transition. Successful CE practices in all manufacturing sectors would contribute to this transition by promoting resource efficiency and waste reduction while improving the social dimension. Various studies show that Türkiye, whose export dependency on European Markets is above 40%, would be one of the most affected countries by the CBAM (e.g., UNCTAD 2021; Acar et al. 2022; World Bank 2023b). IPs, accounting for 45% of all industrial output in Türkiye, are essential

for the country's compliance with CBAM requirements not only because of their share in total exports but also because most companies in them are small and medium enterprises (SMEs).[1] SMEs, contributing to the various phases of the value chain of exported goods, are the most vulnerable actors in the transition to a circular economy due to their low capability in financing the transition and lack of technical competence (Centobelli et al. 2021). Considering that 99.7% of all industrial establishments in Türkiye are SMEs[2], ranking the CE performance of industrial parks would give valuable insights into the country's potential for green industrial transition. Secondly, AOSB provides a critical case study for assessing circularity among the Turkish IPs due to three reasons: (1) AOSB is one of the largest industrial parks with more than 40,000 employment in 428 industrial establishments, 16 of which are in the largest 500 companies in Türkiye, (2) According to OSBUK, an umbrella parent organization of IPs, AOSB ranks third in electricity consumption among 382 IPs as of 2023,[3] and (3) AOSB has been selected as one of the four pilot IPs within the context of a World Bank project entitled "Green Industrial Parks" during 2016–2017 (Esenlikci 2023).

Literature review

Since the seminal studies of Azzone and Manzini (1994), Porter and van der Linde (1995), and Thorensen (1999), a vast amount of literature assessing the environmental performance of industrial companies has been developed. In these studies, the CE principles began to be integrated by Yuan et al. (2006), who proposed a three-layer approach that relies heavily on concepts of cleaner production, industrial ecology, and ecological modernization. These layers are studied at the micro (individual firms and companies or processes), at the meso (eco-industrial parks, networks, and clusters), and at the macro-level (eco-city, eco-municipality, or eco-province). The macro-level was initially defined for eco-city, eco-municipality, or eco-province by Yuan et al. (2006) and later extended to include "nations" by Geng et al. (2012), "countries and governments" by Ghisellini et al. (2016), and "region, nation, and beyond" by Kirchherr et al. (2017). Of this three-layer approach, the CE mainly focuses on cleaner production at the micro-level, emphasizes structuring a substance recycling eco-industrial park at the meso-level, and represents a new pattern of economic operation, aiming to create a recycling-oriented society at the macro-level (Li et al. 2010).

Several metrics have been developed to measure the level of CE since the adoption of the Closed Substance Cycle and Waste Management Act of 1994 in Germany (Ren 2007). China was the first country to set its CE indicators in 2007 (Yuan et al. 2006; Geng et al. 2012). The EU Made considerable efforts to establish a monitoring framework for progress in CE by considering more than 364 indicators (Pacurariu et al. 2021). In 2018, the EC proposed a set of 10 key CE indicators, grouped into four areas: (1) production and consumption, (2) secondary raw materials, (3) waste management, and (4) competitiveness and innovation (EC 2018).

The literature review process in this study was systematically structured. The inclusion criteria for studies to be included in the literature review were "studies with empirical applications or developing CE indices to measure circular economy performance; studies addressing index proposals that include environmental, economic, and/or social dimensions." Publications that "lacked empirical applications, presented only a normative framework, and did not develop measurable indicators" were excluded from the literature review. The literature review was conducted using Google Scholar searches. Searches were conducted using the filters "sort by relevance" and "studies conducted between 2012 and 2024." Among the search results, studies with high relevance to the query and those searched in reputable databases such as Scopus and Web of Science were examined. The search process used combinations of the following queries: ("circular economy" OR "CE" OR "circular" OR "sustainability" OR "sustainable circular" OR "socioeconomic" OR "environmental" OR "social and circular") AND ("index" OR "indexes" OR "indicator" OR "indicators" OR "measurements" OR "measurement" OR "assessment" OR "evaluation" OR "monitoring" OR "key performance indicators" OR "KPIs"). Over 250 studies were initially reviewed, and subsequently, the number of studies was reduced to 34 for detailed review for adequacy of content and compliance with the inclusion criteria. Summaries of the reviewed studies are presented in Table 8, along with the index name, purpose, indicators used, and methodology titles.

Table 8 in Appendix summarizes the literature ranking the circular economy performance at different levels using various methodologies and metrics (see also Parchomenko et al. 2019 and Mesa et al. 2020 for more details). Although the studies on CE ranking have intensified over the last decade, little attention has been paid to how to effectively measure the circularity level at various levels (Elia et al. 2017; Saidani et al. 2019; Mestdagh 2021; de Oliveira Frascareli

[1] Available at: https://tcmbblog.org/wps/wcm/connect/blog/tr/main+menu/analizler/organize+sanayi+bolgeleri+ve+ekonomik+performans. Last accessed on: 29.03.2024.

[2] Available at: https://data.tuik.gov.tr/Bulten/Index?p=Kucuk-ve-Orta-Buyuk lukteki-Girisim-Istatistikleri-2022-49438&dil=1. Last accessed on: 29.03.2024.

[3] Available at: https://www.osbuk.org/lib/dokuman/ac7afcaa-aeb8-11ee-a463-0050568cba34.pdf. Last accessed on: 29.03.2024.

et al. 2023; Galdeano-Gómez and García-Fernández, 2024; Hackenhaar et al. 2024). The existing indicators do not evaluate CE comprehensively, since they do not address all the CE goals (Parchomenko et al. 2019). In addition, the existing literature is mainly designed for macro- and meso-levels and is not suitable for the micro level, which is much more crucial (e.g., Geng et al. 2012; Ghisellini et al. 2016; Elia et al. 2017; Linder et al. 2017; Kristensen and Mosgaard 2020; Zhu et al. 2022; de Oliveira Frascareli et al. 2023; Bagheri and Abdelaziz 2024; Miatto et al. 2024; Shabanpour et al. 2024). There is also a lack of a universal indicator that measures the level of CE transformation at the national level (Smol 2023).

Finally, the social dimension of CE is missed in many studies (Geng et al. 2012; Mestdagh 2021), although the social goals of the CE include a shared economy, increased employment, and participative democratic decision-making through collaborative culture (Rossi et al. 2020). Some exemplary social indicators are given as (1) degree of public awareness and participation, (2) employment rate through CE efforts, (3) environmental justice issues by Geng et al. (2012), and (1) job creation, (2) income generated by jobs, (3) employee participation in the circular business model, (4) market characterization, (5) involvement of stakeholders in decision-making processes, and (6) mindset/cultural change by Rossi et al. (2020).

Well-defined indicators will help to evaluate the developments and the progress made in CE (Mestdagh 2021) to analyze innovations brought by CE (Rossi et al. 2020), to simplify the understanding and the information change (Verberne, 2016), to identify the varying weaknesses and search for applicable solutions (Linder et al. 2017), to show the opportunities of a circular economy and its applications (Mestdagh 2021), to create awareness about new patterns of consumption and production that support sustainability (Azevedo et al. 2017), and to influence the mindset of businesses and regulators about CE (Parchomenko et al. 2019). OECD (2020) collected 474 indicators used between 2018 and 2020 in 29 CE studies, of which eight are applied at the national level, eight at the regional level, and 11 at the local level. These indicators are related to the environment (39%), governance (34%), economic and business (14%), infrastructure and technology (8%), and jobs (5%). Among them, governance (related to education, capacity building, and regulation) and jobs (related to employment and human resources) are social indicators. EMF (n.d.) suggests including skills required to transition to a circular business model as a social indicator.

The most comprehensive study on measuring CE level, including social indicators, was carried out by Azevedo et al. (2017), inspired by the framework proposed by Salvado et al. (2015). They developed the Sustainable Circular Index (SCI) by using seven social indicators (number of accidents per year, loss of productivity, percentage of contracted women, percentage of temporary workers, absenteeism rate, rotation of workers, and percentage of people with special needs by the organization) together with three economic indicators (direct economic value generated and distributed, research and development expenditures, and number of persons employed) and four environmental indicators (rate of non-hazardous waste, rate of hazardous waste, amount of water consumed per year in industrial processes, and amount of energy used per year).

Our study differs from the existing literature by (1) constructing a meso-level index by utilizing micro-level process-based data and (2) employing a quantitative and qualitative research design to determine a social indicator and incorporating a Holistic approach to this indicator into an index together with economic and environmental indicators. In addition, this study, which was carried out on 22 manufacturing companies operating in AOSB, one of the prominent industrial parks in Türkiye, is the first effort to conduct a CE index for a Turkish IP. For these reasons, it can be considered novel and significantly contribute to the existing literature.

The index we propose in this study differs significantly from established circularity metrics such as the Material Circularity Index (MCI), proposed by the Ellen MacArthur Foundation,[4] and the Circular Transition Indicators (CTI), proposed by the World Business Council for Sustainable Development.[5] While MCI provides a product-level circularity metric that primarily emphasizes the material/resource efficiency, CTI focuses on the corporate-level circularity based on input–output flows. In contrast, our methodology proposes a meso-scale circularity benchmarking for industrial establishments, relying on standardized indicators. Moreover, existing circularity metrics such as the MCI and the CTI remain limited in incorporating the social dimension.

Data and methodology

There is no standardized method for measuring or ranking circularity levels (Linder et al. 2017; Muñoz et al. 2024). Most existing indices used for this purpose are monodimensional, using simple indicators such as accumulated energy, water usage, waste generated, etc. However, they do not sufficiently address the diverse principles of CE in an integrated way (de Oliveira Frascareli et al. 2023). For this, composite indices formed by compiling individual

[4] Available at: https://www.ellenmacarthurfoundation.org/material-circularity-indicator. Last accessed on: 01.09.2025.

[5] Available at: https://www.wbcsd.org/actions/circular-transition-indicators/. Last accessed on: 01.09.2025.

indicators into a single index by an underlying model of the multi-dimensional concepts have recently been recognized as a valuable and widespread tool for performance comparisons (Azevedo et al. 2017; Becker et al. 2017; Abberger et al. 2017).

This study proposes a composite index, namely the Circular Economy Sustainability Index (CESI), using a holistic approach integrating six economic, environmental, and social indicators that were aggregated into an index following Salvado et al. (2015) and Azevedo et al. (2017). The Circular Economy Index (CEI) is also constructed by using only economic and environmental indicators to evaluate the significance and contribution of social indicators to CE indexing.

Selection of companies and data collection

This study is conducted at a meso-level utilizing process-based micro-level data from 22 Manufacturing companies operating in 10 different manufacturing subsectors within AOSB.[6] The sectoral distribution of the companies studied represents the overall manufacturing companies in AOSB well. The textile (NACE 13) and rubber and plastic products (NACE 22) have the largest sample size with 6 and 4 companies, respectively. They are followed by food products (NACE 10), chemicals and chemical products (NACE 20), primary metals (NACE 24), and machine yard equipment (NACE 28), each with 2 companies. The remaining four subsectors, namely wood and wood products (NACE 16), paper and paper products (NACE 17), machine yard equipment (NACE 28), and motor vehicles, trailers, and semi-trailers (NACE 29), have one firm each. Companies were voluntarily included in this study after a series of meetings conducted in July 2021 to explain the implications of the EGD and the potential benefits of CE approaches to manufacturing establishments.

The data collection was conducted in two phases. Initially, processes and material flows were identified through facility visits. In the second phase, process-based datasets, including raw material inputs, energy, water consumption, waste generated, and recycling practices, are compiled ensuring mass balances. All collected data relates to the companies' activities in 2022.

CE Indicators

The economic, environmental, and social indicators are used in this study. For the first two, the existing literature is used to determine the indicators, and the data collected from the companies are used to calculate them. For the third one, a survey was conducted.

Economic and environmental indicators

Based on existing literature and data availability, we selected five economic and environmental indicators, which are calculated based on the methodology given below:

(1) Energy Intensity (EI): calculated as total energy consumption (megajoules-MJ) per unit value of production (Turkish lira-TL)

$$EI = \frac{Energy\ Consumption\ (MJ)}{Value\ of\ Production\ (TL)}$$

(2) Emission Intensity (CO_2I): calculated as total GHG emissions (tons of CO_2eq.) per unit value of production (TL)

$$CO_2I = \frac{GHG\ Emissions\ (tons\ of\ CO2eq)}{Value\ of\ Production\ (TL)}$$

(3) Water Intensity ($WaterI$): calculated as total water consumption ($m.^3$) per unit value of production (TL)

$$WaterI = \frac{Water\ consumption\ (m^3)}{Value\ of\ Production\ (TL)}$$

(4) Waste Intensity ($WasteI$): calculated as the total amount of waste generated (tons) per unit value of production (TL)

$$WasteI = \frac{Waste\ Generated\ (tons)}{Value\ of\ Production\ (TL)}$$

(5) Recycling Ratio (RR): calculated as total recycled waste (tons) per unit of waste generated (tons)

$$RR = \frac{Waste\ Recycled\ (tons)}{Waste\ Generated\ (tons)}$$

The calculated values of indicators, which mostly consisted of the stylized facts of Türkiye, have been normalized via deviation from the mean using respective subsector averages calculated based on the country's statistics such as Basic Indicators by Economic Activity 2022 (TUIK 2023a), Waste Statistics of Manufacturing Industry Subsectors 2022 (TUIK 2023b), Water and Waste Water Statistics of Manufacturing Industry Subsectors 2022 (TUIK 2023c), Greenhouse Gas Emissions by Sectors (TUIK 2023d) and Ministry

[6] Descriptions of these subsectors are available at: https://ec.europa.eu/eurostat/documents/3859598/5902521/KS-RA-07-015-EN.PDF. Last accessed on: 29.03.2024.

of Energy and Natural Resources' (MENR) Türkiye Energy Balance Sheets of 2022 (MENR 2023).

Social indicator

The social indicator used in the composite index is determined by an online survey. Thirty-six questions related to the working conditions of employees, including occupational health and safety, diversity and inclusion, positive organizational practices, mandatory practices, including forced labor and collective bargaining, and several human resource practices, are prepared based on EWCS (2023) and World Bank (2023a). The guidelines of the green management practices in Turkish IPs, such as safety, equality, and diversity, developed by TUIK (2024a), are also used.

We asked participants to grade the questions based on a 5-level Likert scale ranging from 1 (*completely disagree*) to 5 (*completely agree*). 626 employees participated in the survey, representing 8078 employees working in 22 companies. Following the inclusion criteria of employees proposed by Wright and Bonett (2002), we excluded employees with less than 3 months of organizational tenure. After removing data errors/typos and missing values, the final sample consisted of 565 workers. The average age of respondents is 35.45 (with a standard deviation of 8.03), the average tenure time is 6.25 (with a standard deviation of 5.93), and the average experience is 13.08 (with a standard deviation of 8.25). Among the respondents, 23% are female employees, 23% are university graduates, 98% are full-time employees, 41% are white collars, and 27% have managerial duties.

The exploratory factor analysis (EFA), a dimension reduction technique, is used to group 36 questions under overarching factors following Fabrigar et al. (1999). Since EFA is a large sample procedure (Kyriazos 2018), the whole sample is used to avoid factor extraction and type-one errors. For the EFA, we first examine the factor adequacy (Kaiser–Meyer–Olkin (KMO) test statistics is 0.95) and sphericity of the data ($\chi 2(595) = 19{,}030$, $p < 0.001$), which reveals satisfactory results to continue with the analyses. Then, the parallel analysis is carried out as the factor retention criterion to determine the number of factors following Harn (1965) and Hayton et al. (2004). This analysis minimizes sampling errors using resampled and random normal data. After determining the number of factors, oblique rotation is used to account for possible correlations between factors and principal axis factoring as a factor extraction method (Fabrigar et al. 1999), which is suitable for non-normal distributed sample (Mardia's multivariate skewness is 526, and kurtosis is 2402, both are statistically significant at 1%).

Since the parallel analysis suggested a six-factor solution, one of the 36 questions[7] is excluded because it Does not load onto any of the six factors. The remaining 35 items were loaded onto one of the factors, which had high internal consistency scores ranging from 0.83 to 0.97, and most of the loadings of factors are higher than 0.40, which can be accepted as a threshold (Costello and Osborne 2005). The final six-factor solution explained 65% of the total variance in the data (Table 9 in Appendix).

Six factors that we identified, namely Workplace equity (F1), Organizational justice (F2) Occupational Safety and Workplace Regulations (F3), Training and Development (F4), Workplace Diversity (F5), and Collective Bargaining (F6), align with the recognized social sustainability frameworks such as SDGs (UN 2015), UN's Corporate Sustainability principles (UN Global Compact 2015) and International Labour Office's standarts (ILO 2019). For instance, F1 focuses on equal treatment and organizational justice, F2 focuses on equity in pay and career opportunities, tapping several UN principles and ILO standards such as equality of opportunity and treatment, wages, and employment promotion. F3 is mainly in line with labour administration, occupational safety and health standards issued by ILO. F4 is also related to vocational guidance and training standards. F5 specifically focuses on the active inclusion of managerial policies, which contributes to the elimination of discrimination, which is integral to the both UN's and ILO's frameworks. F6 allowing employees the right to form or join any union is one of the core aspects of freedom of association and right to organize. All these factors also jointly tap SDGs 5, 8, and 10.

Identified six factors, and the items within these factors can be interpreted as follows: (1) 9 items grouped under the first factor are mainly related to workplace equality, (2) the second factor, in which also 9 items are grouped is related with the organizational justice covering mainly distributive and procedural aspects, (3) third factor consists of 7 items which together focus on occupational safety and workplace regulations, (4)in the fourth factor, we observe three factors related with training and development needs of the employees, (5)five items are grouped under fifth factor, which emphasizes supportive management practices towards diversity, and (6) sixth factor with two items is about collective bargaining. These six identified social factors are vital for ensuring the circular economy and sustainability (e.g., Longoni et al. 2014; Paillé et al. 2018).

The social indicator was created as a composite indicator according to Eq. (1) by calculating the weights of these 6 factors (F) using the PCA methodology explained in Section 3.3. Then, aggregating the weighted scores at the company level, we end up with the social indicator score of each company in the sample.

[7] "My job description has changed at my workplace, but this has not yet been reflected in my job description." All other 35 items in the questionnaire are provided in Appendix Table 9.

$$Social\ Indicator\ (SI) = 0.597 \cdot F_1 + 0.893 \cdot F_2 + 0.834 \cdot F_3 + 0.840 \cdot F_4 + 0.832 \cdot F_5 + 0.610 \cdot F_6 \quad (1)$$

Constructing a composite index

Two indexes are constructed by integrating five economic and environmental indicators for the Circular Economy Index (CEI) and six economic, environmental, and social indicators for the Circular Economy Sustainability Index (CESI). First, the principal component analysis (PCA) is used to determine the weight of each indicator following Ho (2006), Ediger and Berk (2011), and Berk and Ediger (2018). The partial correlation matrix is formed after the min–max normalization of indicators[8] as follows:

$$\rho_{(x_j x_k . x_l)} = \frac{\rho_{x_j x_k} - \rho_{x_j x_l}\rho_{x_l x_l}}{\sqrt{1-\rho^2_{x_j x_l}}\sqrt{1-\rho^2_{x_k x_l}}} \quad (2)$$

where each x represents identified indicators, x_l is the controlling variable, and $\rho_{(x_j x_k . x_l)}$ is the partial correlation between x_j and x_k.

The eigenvalue λ_j of indicator, j, is then computed using the correlation matrix by solving the determinantal $|R - \lambda I| = 0$ for λ, where I is the identity matrix. Ultimately, the rotated component matrix is constructed using the computed eigenvalues. Next, the following formula is used to determine each factor's coefficient:

$$\beta_j = \frac{C_{ij}\lambda_j}{\sum_{j=1}^{6}\lambda_j} \quad (3)$$

where, C_{ij} is the corresponding value of the component for the firm i and indicator j. Finally, the CEI and CESI indexes are calculated for each firm as follows:

$$CEI_i / CESI_i = \sum_{j=1}^{n}\beta_j \cdot x_{ji} \quad (4)$$

where, n represents the number of indicators in the index, namely 5 in CEI and 6 in CESI.

Results and discussions

The summary statistics of 6 indicators used to construct CEI and CESI are provided on Table 1 (per indicator) and Table 2 (per subsector).

As seen in Table 1, Water Intensity and Energy Intensity show the highest variability, with standard deviations of 1.03 and 0.81, respectively. The recycling ratio (RR) also varies widely, with several firms having zero values. In contrast, the Social Indicator shows a more uniform pattern across firms, featuring the lowest standard deviation at 0.06.

The summary statistics by manufacturing subsectors (by NACE) provided in Table 2 reveal notable differences in the sample's mean values of 6 indicators. NACE 22 (Rubber and Plastic products) stands out with low energy, emissions, and water intensity, and the highest average recycling ratio. In contrast, NACE 13 (Textiles) shows the highest intensities and minimal recycling.

Below, we provide the results of CEI and CESI and their comparison to show the importance of social indicators in ranking the circularity level of manufacturing companies operating in IPs.

Circular economy index (CEI)

CEI is calculated based on five economic-environmental indicators, namely x_1: energy intensity, x_2: emission intensity, x_3: water intensity, x_4: waste intensity, and x_5: recycling ratio. Table 3 presents the eigenvalues calculated from the correlation Matrix of the five normalized indicators. The first four highest eigenvalues explaining 97.44% of the cumulative variance are above the threshold level of 95%, which we defined based on Valle et al. (1999) and Kuncheva and Faithfull (2013). The calculated rotated component loadings are presented in Table 4.

CEI is calculated by using eigenvalues and the rotated component loadings as follows:

$$CEI_i = 0.295 \cdot x_{1,i} + 0.373 \cdot x_{2,i} + 0.299 \cdot x_{3,i} + 0.393 \cdot x_{4,i} + 0.198 \cdot x_{5,i} \quad (5)$$

Equation 5 indicates that the highest contribution is made by the waste intensity (0.393) with a weight of 25.24% and emission intensity (0.373) with a weight of 23.91%, followed by water intensity (0.299), energy intensity (0.295),

Table 1 Summary Statistics of 6 indicators

Variable	Obs	Mean	Std. dev	Min	Max
EI	22	0.63	0.81	0.04	3.08
CO_2I	22	0.02	0.03	0.00	0.12
WaterI	22	0.72	1.03	0.00	3.64
WasteI	22	0.43	0.52	0.00	1.70
RR	22	0.16	0.31	0.00	0.97
SI	22	0.67	0.06	0.55	0.82

[8] Normalization is conducted as deviation from the maximum for energy, emission, water, and waste intensity indicators and from the minimum for recycling ratio and social indicator score. With this formulation, we ensure that higher index scoring suggests a better level of circularity for a firm.

Table 2 Summary Statistics of 6 indicators per subsector

NACE	# of Firms	*EI*		CO_2I		*WaterI*		*WasteI*		*RR*		*SI*	
		Mean	Std. dev	Mean	Std. dev	Mean	Std. dev	Mean	Std. dev	Mean	Std. dev	Mean	Std. dev
10	2	0.50	0.65	0.02	0.02	0.81	1.08	0.07	0.04	0.00	0.00	0.64	0.13
13	6	1.15	1.10	0.05	0.04	1.44	1.00	0.86	0.60	0.03	0.05	0.68	0.04
16	1	0.43	-	0.02	-	0.34	-	1.49	-	0.97	-	0.61	-
17	1	0.32	-	0.02	-	3.64	-	0.54	-	0.00	-	0.66	-
20	2	0.36	0.45	0.02	0.02	0.24	0.27	0.01	0.01	0.00	0.00	0.67	0.08
22	4	0.21	0.13	0.01	0.00	0.03	0.04	0.12	0.07	0.55	0.37	0.73	0.08
24	2	0.43	0.50	0.01	0.01	0.01	0.01	0.04	0.02	0.00	0.00	0.61	0.05
27	1	2.43	-	0.02	-	0.09	-	0.11	-	0.00	-	0.62	-
28	2	0.15	0.09	0.00	0.00	0.30	0.06	0.34	0.22	0.07	0.10	0.67	0.05
29	1	0.12	-	0.00	-	0.35	-	0.67	-	0.00	-	0.66	-

and recycling ratio (0.198), with weights of 19.23%, 18.93%, and 12.69%, respectively. Consistent with the literature, the cumulative weight of waste-related indicators (37.93%), including waste intensity and recycling ratio, is the highest.

Figure 1 presents the CEI scores of each company in the sample. The highest-ranked five companies (companies 17, 1, 5, 9, and 6), which are the best cases in circular economy ranking, are operating in subsectors such as rubber and plastic products (NACE 22), basic metals (NACE 24), and chemical products (NACE 20). Moreover, four out of five worst-performing companies (companies 16, 21, 12, 14) operate in the textile (NACE 13) subsector, and one company (company 10) operates in the paper and paper products (NACE 17) subsector. In the three best-performing companies operating in NACE 22, waste intensity (average weight of 23.8%) and emission intensity (average weight of 22.4%) are the most significant contributors to CEI scores. Three companies also conduct in-house recycling practices, contributing to their ranking, whereas the worst-performing companies operating in the textile industry do not have any recycling.

Circular economy sustainability index (CESI)

In constructing CESI, the social indicator, calculated in Section 3.3 (×6), is also used in addition to five CEI economic and environmental indicators. As shown in Table 5, the cumulative variance of the first five eigenvalues calculated from the correlation Matrix exceeds the threshold level of 95%. The calculated rotated component loadings are given in Table 6.

CESI is calculated by using eigenvalues and the rotated component loadings as follows:

$$CESI_i = 0.246 \cdot x_{1,i} + 0.230 \cdot x_{2,i} + 0.189 \cdot x_{3,i} + 0.063 \cdot x_{4,i} + 0.407 \cdot x_{5,i} + 0.221 \cdot x_{6,i} \quad (6)$$

Similar to CEI, the waste-related indicators, namely waste intensity (0.063) and recycling ratio (0.407), jointly account for the largest contribution to the CESI, with a combined normalized weight of approximately 34.65%. These weights were derived by dividing each indicator's coefficient in Eq. (6) by the sum of all six coefficients, thereby ensuring comparability across indicators. Energy intensity (0.246) and emission intensity (0.230) follow waste-related indicators, contributing 18.16% and 16.96% to CESI, respectively. However, the social indicator also significantly affects the index, with a coefficient of 0.221 and a weight of 16.33%. This finding is consistent with the studies of Azevedo et al. (2017) and Temerbulatova et al. (2021).[9]

Consistent with CEI, the best-performing three companies in CESI are also in the rubber and plastic products

Table 3 Eigenvalues for the correlation matrix of normalized indicators

	λ_1	λ_2	λ_3	λ_4
Eigenvalues	2.44	1.14	0.81	0.48
Variability (%)	48.83	22.88	16.21	9.51
Cumulative Variance Explained (%)	48.83	71.72	87.93	97.44

[9] We also conducted bivariate Pearson correlation analysis with each of the social sustainability factors with five economic and environmental factors (Table 10). The robustness of correlational analysis is increased with 2000 bootstrap samples, and lower/upper bias-corrected accelerated confidence intervals are used to detect significance of correlations, i.e., whether lower and upper-level intervals include 0.

Table 4 Rotated component loadings matrix (C)

	Component 1	Component 2	Component 3	Component 4
x_1	0.5474	-0.0635	-0.3787	0.4697
x_2	0.5957	0.1384	-0.2044	0.091
x_3	0.5188	0.119	0.2012	-0.7724
x_4	0.0445	0.8222	0.4632	0.3129
x_5	0.2727	-0.5353	0.7482	0.2766

Table 5 Eigenvalues for the correlation matrix of normalized indicators

	λ_1	λ_2	λ_3	λ_4	λ_5
Eigenvalues	2.44	1.20	0.99	0.79	0.46
Variability (%)	40.70	19.92	16.47	13.19	7.59
Cumulative Variance Explained (%)	40.70	60.63	77.10	90.29	97.89

subsector (NACE 22), and the highest contribution to the index score of these companies is from waste-related indicators, including waste intensity and recycling ratio (Fig. 2). Moreover, the two worst-performing companies are the same in both indexes operating in the textile sector (NACE 13). The strong circularity performance of the rubber and plastic sector can be attributed to greater investment capacity in recycling infrastructure and established recycling processes with relatively standardized inputs and outputs. In contrast, textile firms generally face challenges due to higher waste generation and limited in-house recycling practices. Although there are some large textile firms in Türkiye showing best practices of waste management, the sector in the country is generally characterized by smaller-scale operations, highly diverse production processes and material flows, e.g., mixed fiber types, which hinder recycling potential. In addition, plastic waste recycling, particularly in the form of post-consumer recycling (PCR), has long been a regulatory focus in Türkiye, and textile waste management has recently gained higher attention through the country's Zero Waste policies and the EU's Circular Economy Action Plan.

The social indicator significantly affects the indices. Of the five companies with the highest social indicator score, three have a higher ranking in CESI when compared with CEI, and the ranking of the remaining two does not change. On the other hand, the three companies with the lowest social indicator scores declined significantly in ranking from CEI to CESI. In addition, one of the companies with the lowest social indicator score significantly increased in the CESI ranking due to its high score in the recycling ratio, whose weight increased significantly after incorporating the the social indicator into the index. These changes show the importance of the companies' social indicators in ranking manufacturing companies' circular economy performance.[10]

To enhance the interpretability and practical applicability of CESI scores, firms were classified into three circularity categories: Low, Medium, and High Circularity. This categorization was based on the percentile distribution of the CESI scores. Firms with CESI scores in the bottom 25th percentile ($CESI \leq 0.479$) were assigned to the Low Circularity, those in the top 25th percentile ($CESI \geq 0.633$) to the High Circularity, and the remaining firms to the Medium Circularity. Table 7 presents categories assigned to the firms in the sample along with their CESI scores and their subsectors (NACE).

Conclusions and policy implications

This study aims to rank the circularity levels of manufacturing companies in industrial parks. To this end, we propose a circular economy index called the **Circular Economy Sustainability Index** (**CESI**), formed with a Holistic approach by incorporating environmental, economic, and social indicators via qualitative and quantitative research design. We utilize a micro-level data set obtained from 22 Manufacturing firms operating in 10 different manufacturing subsectors in AOSB, one of the prominent industrial parks in Türkiye. CESI is compared with the Circular Economy Index (CEI), which was constructed using only economic and environmental indicators to evaluate the contribution of social indicators to CE indexing.

Our findings suggest that waste and waste management-related indicators, namely waste intensity and recycling ratio, contribute most to CEI. In contrast, CESI is driven significantly by social scores that measure employee perception within the companies. Rubber and plastic products manufacturing subsector companies are ranked the highest in both indexes. In contrast, those operating in the textile products manufacturing subsector are the lowest.

Our study and proposed indexing methodology have significant firm-level and policy-level implications.

Firm-level Implications:

- The most important finding of this study is that a more comprehensive framework for assessing the circular

[10] To evaluate the robustness of the CEI and CESI indices and to assess sensitivity, an alternative weighting scheme based on equal weights was applied. Results show consistent rankings at the top and bottom of the distribution, with notable deviations limited to a few specific firms. Please refer to the Tables 11-12 in the Appendix for detailed comparisons.

Table 6 Rotated component loadings matrix (C)

	Component 1	Component 2	Component 3	Component 4	Component 5
x_1	0.5477	0.0593	-0.0574	-0.4038	0.4396
x_2	0.5951	-0.1481	-0.0105	-0.1999	0.0944
x_3	0.518	-0.1413	-0.0067	0.2515	-0.7574
x_4	0.0441	-0.6571	0.5865	0.3499	0.2998
x_5	0.2742	0.5417	-0.0012	0.7291	0.3128
x_6	0.0193	0.4790	0.8078	-0.2822	-0.1910

economy rankings of manufacturing companies is produced when social indicators are included along with the economic and environmental indicators. Even though CEI provides valuable insights into the circularity levels of companies by evaluating the physical functioning of production facilities, CESI offers a perspective by considering the human factor when evaluating the effectiveness of sustainable circular economy practices. In this regard, we propose that composite indices created with a holistic approach by including all possible indicators related to sustainable development goals (SDGs) are superior to mono-dimensional approaches.

- Since both CEI and CESI are mainly driven by indicators related to waste management, adopting basic material/waste flow tracking systems, improving waste segregation at source to enable more efficient in-house recycling, and exploring industrial symbiosis opportunities via waste-resource matching facilitated by the industrial park management would enhance the circularity performance of the firms with low circularity scores.
- Out of different qualitative research designs to generate a composite social indicator, the one followed in this study, namely employee surveys, provides valuable insights into the circular economy and sustainability practices in the workplace. Measuring the perception of the employees on the overall functioning of the workplace, rather than relying merely on the data gathered from the company management, allows for a more objective and inclusive assessment.
- Ranking circularity levels in manufacturing companies in industrial parks is of significant importance for policymakers to prepare a green transition roadmap customized for different manufacturing subsectors. Secondly, it will help companies improve their CE levels to sustainably increase economic efficiency. Since CE principles are better employed at the company level by the active participation of all employees, incorporating employee

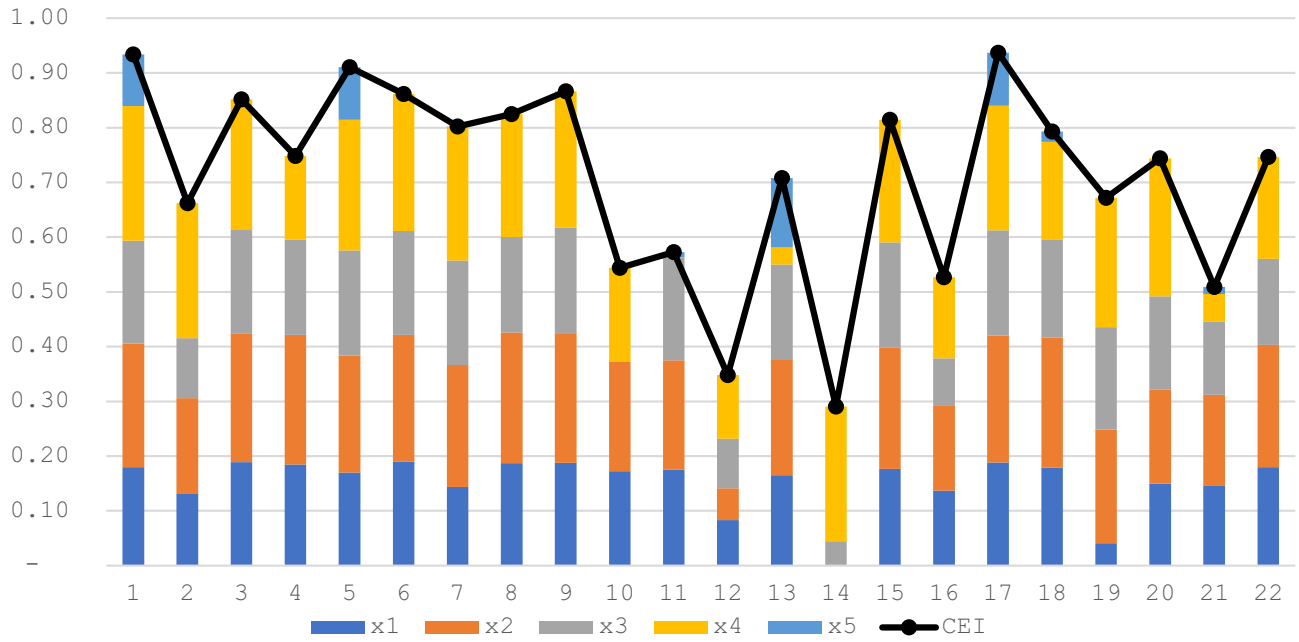


Fig. 1 Circular Economy Index (CEI) of 22 AOSB companies

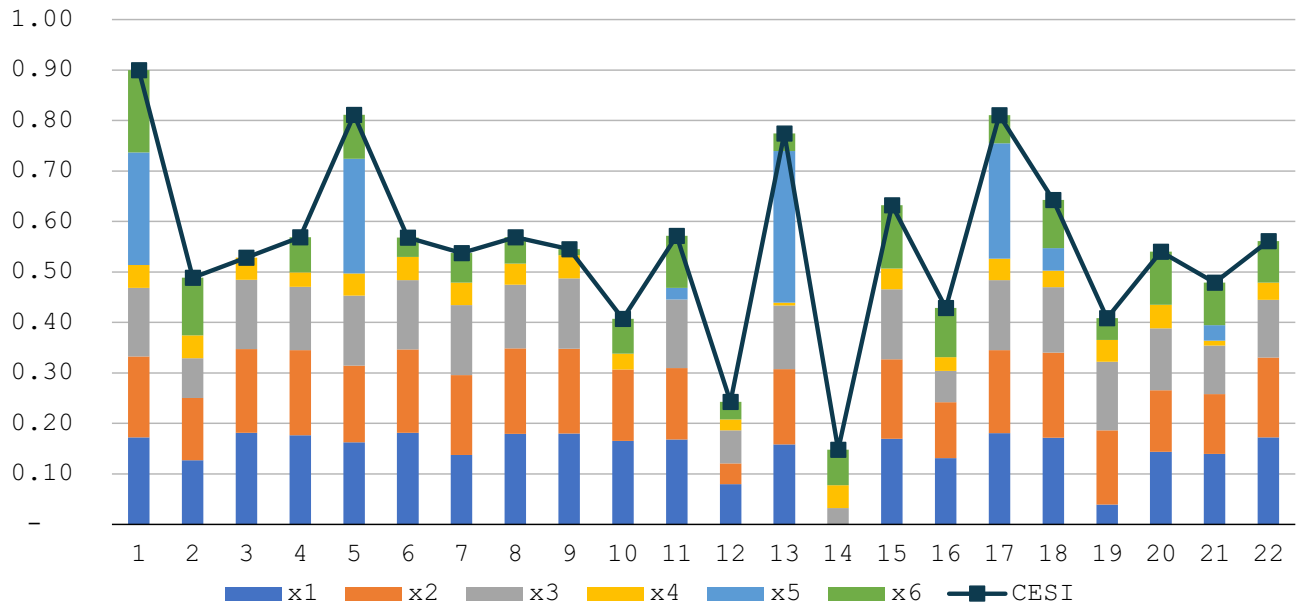


Fig. 2 Circular Economy Sustainability Index (CESI) of 22 AOSB companies

perception via social indicator scores provides essential insights for company management.

Table 7 Firm-Level CESI Scores and Circularity Classification Based on Percentile Thresholds

Firm ID	Subsector (NACE code)	CESI Score	Circularity Class
1	22	0.900	High Circularity
5	22	0.811	High Circularity
17	22	0.810	High Circularity
13	16	0.774	High Circularity
18	28	0.643	High Circularity
15	22	0.633	Medium Circularity
11	13	0.572	Medium Circularity
8	28	0.569	Medium Circularity
4	29	0.569	Medium Circularity
6	20	0.568	Medium Circularity
22	13	0.561	Medium Circularity
9	24	0.545	Medium Circularity
20	20	0.541	Medium Circularity
7	24	0.537	Medium Circularity
3	10	0.529	Medium Circularity
2	10	0.489	Medium Circularity
21	13	0.479	Low Circularity
16	13	0.429	Low Circularity
19	27	0.408	Low Circularity
10	17	0.407	Low Circularity
12	13	0.243	Low Circularity
14	13	0.148	Low Circularity

Policy-level Implications:

- The study showed that recycling activities significantly affect CE ranking, as evidenced by the high ranking of the rubber and plastic manufacturing companies. According to TUIK (2024b), Türkiye spent 12.04 billion US$ on imports of raw plastic Materials, while the total export value of these Materials was only 2.8 billion US$ in 2023. Hence, increasing the recycling ratio in this subsector would contribute not only to the green transition of the sector but also to the country's current account balance.
- The worst-performing companies in CESI are found to be in the textile subsector, whose products correspond to 12.5% of the country's total exports. Although the textile subsector has not yet been in the context of CBAM of the EGD, this would create an essential drawback to Türkiye's economic growth in the upcoming decade, as the EU has chosen the textile sector to be focused upon within its Circular Economy Action Plan (EC 2020).

This study's results are based on data from 22 AOSB companies from 10 different manufacturing subsectors. Rubber and plastic manufacturers in our sample showed high circular economy (CE) rankings due to strong recycling practices, but this doesn't imply all Turkish plastic companies perform equally. In contrast, textile companies ranked poorly, mainly due to waste management issues, although there are recognized good practices in the Turkish textile sector. More research with additional companies and

industrial parks is needed for a comprehensive understanding of the manufacturing industry's circularity in Türkiye.

Findings achieved in this study are replicable and would be extended to other industrial parks and countries for two reasons. (1) The diversity of manufacturing sub-sectors in our sample enhances CESI's representativeness, particularly for meso-level circularity assessments in a broad range of industrial settings. (2) While each industrial park operates within its unique regulatory, economic and institutional context, and our findings are grounded by Türkiye's context shaped by national circular economy roadmaps and zero waste regulations, CESI framework is adaptable to industrial parks in other countries and regions shaped with similar local, national or international policies, such as EU's Circular Economy Action Plan.

One limitation of CESI is that it mainly focuses on the economic, environmental, and social dimensions of sustainability, leaving the 'Governance' aspect of the ESG framework relatively untapped. Although, some of the factors that are used to construct company level social indicator scores, namely Organizational justice (F2) and Workplace Diversity (F5) are related to the 'Governance', future research should also address the integration of governance-related metrics to further align the CESI with ESG frameworks and strengthen its capacity to assess all institutional factors that facilitate circular economy transitions.

Moreover, in this study, we aggregate social factors into one single social indicator to incorporate into the CESI. While this approach allows us to overcome sample size to factor ratio concerns for PCA, as discussed by Osborne & Costello (2004), and take into account additive effects of social factors, future studies could investigate unique effects of individual social factors on the firm-level circular economy performance.

Appendix

Table 8 Summary of Literature on Circular Economy Indices

Study	Name of Index and Abbreviation	Purpose	Indicators	Methodology
Li and Su (2012)	CE Evaluation Index System (CEEIS)	Evaluation of the circular economy development level of Chinese chemical enterprises	18 indicators grouped in 5 criteria levels, including (1) economic development, (2) resource exploiting, (3) pollution reducing, (4) ecological efficiency, (5) developmental potential	A weighted sum based on relative criteria importance through score aggregation
Zaman and Lehmann (2013)	Zero Waste Index (ZWI)	Performance measurement of waste management systems in a "zero waste city"	(1) Potential amount of waste managed by the city, (2) substitution for the systems, (3) total amount of waste generated in the city	The ratio of total amount of waste managed and substituted to total waste generated
Zhou et al. (2013)	Circular Economy in Iron and Steel Enterprises	Providing a scientific tool for iron and steel enterprises to assess and improve their circular economy status	13 micro-level indicators covering material flow in processes from resource input, to recycling and output	Support Vector Machines (SVM)
Ma et al. (2014)	Circular Economy Efficiency Composite Index (CEECI)	Mode of circular economy in China's iron and steel Industry in Wu'an city	(1) Equipment efficiency, (2) material utilization rate, (3) pollutant emissions, (4) freshwater consumption	Weighting indicators based on expert opinion
Di Maio and Rem (2015)	Circular Economy Index (CEI)	Decision-making instruments include strategic, economic, social, and environmental aspects of recycling	(1) Material value produced by the recycler (market value), (2) material value entering the recycling facility	The ratio of the material value produced by the recycler (market value) by the material value entering the recycling facility
Yi and Liu (2016)	Evaluation index system for the circular economy of construction enterprises	Constructing a comprehensive evaluation index system of circular economy development level	(1) Capital resource investment and benefits indicators, (2) resource recycling indicators, (3) and resource output indicators	Analytic hierarchy process (AHP)
van Schaik and Reuter (2016)	Material Recycling Index (MATERIAL-RI)	Performance of the Circular Economy	(1) recovery rates in recycling processes, (2) material-RI visualization, (3) life cycle assessment	Recycling optimization via Product-centric and life-cycle approach
Azevedo et al. (2017)	Sustainable Circular Index (SCI)	Assessing the sustainability and circularity of manufacturing companies	Total 21 indicators, including social, economic, and environmental indicators	The Delphi method and Simple Additive Weighting (SAW)
Cullen (2017)	Circularity Index (CI)	Assessing the level of circularity in resource use and comparing it with the theoretical ideal of a fully circular economy	Materials and energy inputs considering recycling and raw material extraction	The ratio between materials and energy inputs considering recycling and raw material extraction
Kayal et al. (2019)	Circonomics Index	Assessing the circularity within the wastewater industry	(1) Wastewater production efficiency, (2) Composite wastewater reuse, (3) Wastewater Recycling	Aggregation by multiplication

Table 8 (continued)

Study	Name of Index and Abbreviation	Purpose	Indicators	Methodology
García-Bernabeu et al. (2020)	Circular Economy Composite Index (CEI)	Developing an index to benchmark EU countries performance	17 performance indicators across four dimensions: (1) Production and Consumption, (2) Waste Management, (3) Secondary Raw Materials, (4) Competitiveness and Innovation	Multi-criteria TOPSIS methodology
Rabta (2020)	Circularity Index (CI)	As a tool to measure the circularity level of the item	(1) order quantity, (2) circularity level of the product, (3) demand rate, (4) unit gross profit	Economic order quantity (EOQ) inventory model
O'Grady et al. (2021)	Disassembly, Deconstruction and Resilience Index (3DR Index)	A circular economy-based index applied to the construction environment	(1) Disassembly (D) (ease of building components), (2) Deconstruction (D) (ease of deconstructability), (3) Resilience (R) (reusability and durability)	Sum of weighted performance
García-Sánchez et al. (2021)	Circular Economy Business Index (CEBI)	Measuring the progress made by businesses around the world towards achieving a circular economy	based on 17 environmental practices that companies have implemented to reduce the generation of waste and emissions and to increase the reuse and efficiency of materials and energy	CUR matrix decomposition
Luomi et al. (2021)	Circular Carbon Economy Index (CCE Index)	Measuring countries' progress towards and potential for achieving circular carbon economies	It is a composite indicator comprised of 43 quantitative variables or indicators	Simple average of equally weighted normalized scores
Milanović et al. (2021)	Waste Management Composite Index (WMCI)	Analyzing the Circular Economy performance of the 26 European Union (EU) countries	Recycling Rates Indicator (RRI), Recycling for Specific Waste Streams Indicator (RSWSI)	Data Envelopment Analysis
Temerbulatova et al. (2021)	Circular Economy Development Index	Assessing the current and future state of the circular economy's development in 27 countries of the European Union	(1) Generation of municipal waste per capita, (2) Water exploitation index, (3) Final energy consumption, and (4) Social Progress Index	Data Envelopment Analysis
Thomas and Mishra (2022)	The circularity Index (CI)	Developing a sustainable circular supply chain model within a carbon cap policy, utilizing 3D printing to reduce waste, implementing greener techniques to cut emissions, and lowering ordering costs via capital investment	Variables included in the model are; ordering quantity, circularity index (ci) (as a measure to determine the percentage of the original product that can be reused), ordering cost, investment in waste minimization and emission reduction, carbon cap policy, customer demand, unit profit, carbon taxes, opportunity costs	Static optimization model

Table 8 (continued)

Study	Name of Index and Abbreviation	Purpose	Indicators	Methodology
Zhu et al. (2022)	China Circular Economy Index based on Technology-Organization-Environment (TOE) framework	Analyzing the technological, organizational, and environmental conditions that influence circular economy performance	(1) Big data development, (2) Economic development, (3) Technological innovation, (4) Environmental regulation, (5) Factor endowments, (6) Industrial structure upgrading	Fuzzy set qualitative comparative analysis method
de Oliveira Frascareli et al. (2023)	Macro-level Circular Economy Index (MaCEI)	Evaluation of the circularity level of the European Union (EU) countries	A total of 56 potential macro-level circular economy indicators across 10 dimensions were identified from the literature. After a selection process based on data availability, a final set of 10 indicators across 5 dimensions were chosen to construct the MaCEI	Data envelopment analysis (DEA), principal component analysis (PCA) and social network analysis (SNA)
Do et al. (2023)	Integrated Circular Economy Index (ICEI)	Measuring the circular economy performance of a wood production chain	(1) Carbon emission reduction rate, (2) internal renewable fuel substitution rate, (3) internal renewable electricity substitution rate, (4) thermal energy recovery rate, (5) and economic efficiency rate	Best–Worst Method (BWM) and Linear Goal Programming (LGP)
Khan et al. (2023)	CE Index	CE index considers carbon emissions and different operations related to the life cycle of products	Production quantity, circularity index (the level of circularity achieved by the manufacturer's produced items. It is a decision variable that ranges between 0 and 1) demand, per unit gross profit, carbon emissions, setup costs, holding costs, carbon tax payments	Economic production quantity (EPQ) model based on optimization via Lagrange multiplier
Anselmi et al. (2024)	Sustainable Development Goal Index (SDG)	Assessing the economic, environmental, and social performance of 27 European countries	Multicriteria decision analysis (MCDA) with 58 indicators covering 2018–2020	Multiple Criteria Decision Analysis (MCDA)
Galdeano-Gómez and García-Fernández (2024)	Transition towards circular economy in EU countries	Analyzing the transition to circularity in EU countries	Multidimensional indicators for CE performance, interrelationship between macroeconomic indicators and CE implementation levels	Multivariant analysis
Hackenhaar et al. (2024)	Life Cycle Sustainability Assessment, resource circularity and criticality (LC3SA)	Framework covering LCSA, resource circularity and criticality	Critical Raw Materials (CRM), circular economy, sustainability framework	Integrated comprehensive LCSA framework
Miatto et al. (2024)	Australia's circular economy metrics and indicators	Comprehensive economy-wide material flow analysis of the Australian economy	Analysis of domestic extraction, trade, end-of-life flows, recycling rate, overall circularity rate	Material flow analysis

Table 8 (continued)

Study	Name of Index and Abbreviation	Purpose	Indicators	Methodology
Shabanpour et al. (2024)	Macro-scale circularity and eco-efficiency assessment	Assessing circularity performance and CO2 emissions of OECD countries	Methodological development of a macro-level framework and benchmarks for national sustainable circularity assessments	Dynamic network data envelopment analysis (DN-DEA)
Aljamal et al. (2024)	Circular Economy Key Performance Indicators in Manufacturing	Analyzing CE KPIs in the manufacturing industry for sustainable development	Sustainability's triple bottom lines—environmental, economic, and social dimensions	Social Network Analysis (SNA)
Lee et al. (2024)	Circular Supply Chain Indicators	Enhancing sustainability in purchasing and supply management via circular economy indicators	Monetary, energy and environment, material, temporal, efficiency dimensions	Fuzzy analytical hierarchy process (FAHP)
Arias et al. (2024)	Safety and Sustainability by Design and Circularity Index (CI-SSbDC)	Evaluating safety, sustainability, and circularity in emerging technologies via a composite indicator based on European Commission guidelines, applied to bio-based and fossil-based products	Safety, sustainability, and circularity	Multiple Criteria Decision Analysis (MCDA)
Bagheri and Abdelaziz (2024)	Efficiency Rankings of Economic Sectors	Assessing environmental and energy efficiency of UAE's economic sectors	Sustainability and circularity objectives	Data envelopment analysis input–output model
Ghinoi et al. (2024)	Municipality Indicator of Circular Economy (MICE)	Developing a composite indicator for circular economy applicable to 329 municipalities in Emilia-Romagna, Italy	Environmental variables grouped into five areas: green enterprise, sustainable mobility, sustainable energy, biodiversity, emissions and pollution	Principal Component Analysis (PCA)
Muñoz et al. (2024)	The 9R circularity index	A bottom-up circularity index from a material flow analysis perspective	Rethink, Reduce, Reused, Repaired, Refurbished, Remanufactured, Repurposed, Recycled, Recovered	Analytic hierarchy process (AHP)
https://www.msci.com/our-solutions/indexes/thematic-investing/circular-economy-indexes	MSCI ACWI IMI Circular Economy Indexes	Composite index covering 5 different indices such as Renewables and Energy Efficiency Index, Sharing Economy Index, Sustainable Water Transition Index, Natural Resources Stewardship Index, Plastics Transition Index	5 different indices such as Renewables and Energy Efficiency Index, Sharing Economy Index, Sustainable Water Transition Index, Natural Resources Stewardship Index, Plastics Transition Index	MSCI IMI Parent indexing methodology

Table 9 Exploratory Factor Analysis Results—Six-Factor Solution

Items	Exploratory Factor Analysis – Factor Loadings					
	F1	F2	F3	F4	F5	F6
F1: Workplace Equality						
1. At work, everyone is treated equally and fairly in terms of race	**1.01**	-.08	-.05	.10	-.04	-.03
2. At work, everyone is treated equally and fairly in terms of language	**.98**	-.10	-.03	.10	-.03	-.01
3. At work, everyone is treated equally and fairly in terms of religion	**.96**	-.07	-.07	.08	.00	-.01
4. At work, everyone is treated equally and fairly in terms of physical disabilities	**.92**	-.07	-.04	.04	.02	.01
5. At work, everyone is treated equally and fairly in terms of mental disabilities	**.92**	-.10	-.03	.00	.03	.02
6. At work, everyone is treated equally and fairly in terms nationality	**.91**	.01	-.06	-.01	.07	-.04
7. At work, everyone is treated equally and fairly in terms of age	**.89**	.11	.09	-.12	-.06	.01
8. At work, everyone is treated equally and fairly in terms of sexual orientation	**.86**	.06	-.03	-.08	.02	.03
9. At work, everyone is treated equally and fairly in terms of gender	**.86**	.17	.01	-.07	-.12	.01
F2: Organizational Justice						
10. I am paid according to the quantity and quality of my work compared to other employees in the company at my workplace	-.02	**.95**	-.05	-.02	-.07	.01
11. I am paid according to the quantity and quality of my work compared to other companies in the sector at my workplace	-.06	**.93**	-.08	.07	-.08	.03
12. An equal pay for equal work policy is applied at my workplace	.05	**.85**	.00	-.23	.13	-.03
13. All employees are offered equal career opportunities at my workplace	.01	**.72**	.13	-.17	.14	.04
14. There are opportunities for advancement in my field of work at my workplace	.05	**.61**	-.05	.28	.03	-.11
15. The problems of work and working conditions expressed by the employees are taken into account at my workplace	.01	**.49**	.15	.33	-.02	.04
16. Employees are provided with accessible means to express their problems with work and working conditions at my workplace	.01	**.48**	.20	.23	.07	-.03
17. There are mechanisms at my workplace that ensure that the problems of work and working conditions expressed by the employees are resolved	.01	**.47**	.15	.29	.03	.00
18. Employees are encouraged to express the problems they experience with work and working conditions at my workplace	.04	**.45**	.09	.32	.07	-.03
F3: Occupational Safety and Workplace Regulations						
19. Necessary occupational safety measures are taken for my work at my workplace	-.04	.00	**.96**	-.08	-.05	-.04
20. Information is provided at my workplace that increases work safety, such as how to use each tool and what safety precautions to take at what time	-.08	-.08	**.83**	.07	.03	-.08
21. I have access to a healthcare professional at my workplace that I can reach at any time	-.05	-.01	**.65**	-.06	-.14	.21
22. It is not difficult to get permission, when I need to take sick leave at my workplace	.17	.11	**.64**	-.26	-.05	.06
23. Necessary checks and controls are carried out at my workplace to prevent child labor	.00	-.39	**.52**	.15	.19	.05
24. There is a system at my workplace that can track overtime	.04	-.03	**.40**	.15	.06	.03
25. The rules and policies applied at my workplace are in compliance with the legal legislation	.12	.00	**.39**	.26	.17	-.07
F4: Training and Development						
26. I received the necessary in-service training regarding my work at my workplace	-.04	-.11	-.03	**.95**	-.05	.04
27. I received the necessary orientation regarding my work at my workplace	.08	.02	-.03	**.85**	-.03	-.01
28. Feedback is provided on the personal development of employees during performance evaluations at my workplace	-.03	.25	-.03	**.60**	.02	.06
F5: Workplace Diversity						
29. We are in open communication with vulnerable groups at my workplace, such as women, people with disabilities, immigrants, temporary workers	.06	-.15	-.03	.03	**.87**	-.02
30. Immigrant workers are provided with the support they need to overcome the language barrier at my workplace	-.08	.09	-.15	-.07	**.79**	.06
31. Individuals belonging to vulnerable groups are protected at my workplace	.01	.06	.03	-.10	**.76**	.00
32. There are applications at my workplace that will improve the working conditions for people with disabilities	-.12	.04	.14	.12	**.60**	.01
33. There are applications specific to women only at my workplace, such as maternity leave and the opportunity for mothers to work part-time or flexibly	.19	-.19	.21	.09	**.32**	.13

Table 9 (continued)

Items	Exploratory Factor Analysis – Factor Loadings					
	F1	**F2**	**F3**	**F4**	**F5**	**F6**
F6: Collective Bargaining						
34. The right to form a trade union or join existing trade unions is recognized at my workplace in accordance with the laws	.03	.00	-.04	.06	.10	**.84**
35. The right to conclude a collective bargaining agreement is granted at my workplace	-.02	.06	.02	.11	-.05	**.81**
SS Loadings	7.83	4.68	3.26	2.79	2.62	1.49
Proportion of Variance	.224	.134	.093	.080	.075	.042

N = *565*. Bold font depicts the highest factor loadings for the EFA solution

Table 10 Bivariate Pearson correlation analysis

Social Sustainability Factors	Economic and Environmental Factors	Original Value	Bias Corrected (acc.) Confidence Interval Lower	Bias Corrected (acc.) Confidence Interval Upper
Workplace_Equality	Emission Intensity	0.05	-0.37	0.60
Workplace_Equality	Waste Intensity	0.43	0.10	0.72
Workplace_Equality	Recycling Ratio	0.51	0.09	0.79
Workplace_Equality	Energy Intensity	0.65	0.24	0.81
Workplace_Equality	Water Intensity	0.66	0.32	0.83
Organizational_Justice	Water Intensity	-0.12	-0.58	0.27
Organizational_Justice	Recycling Ratio	-0.07	-0.49	0.30
Organizational_Justice	Waste Intensity	0.07	-0.38	0.36
Organizational_Justice	Emission Intensity	0.25	0.07	0.45
Organizational_Justice	Energy Intensity	0.44	-0.07	0.72
Occ_Safety_Regulations	Waste Intensity	-0.13	-0.59	0.30
Occ_Safety_Regulations	Recycling Ratio	-0.06	-0.50	0.43
Occ_Safety_Regulations	Water Intensity	-0.02	-0.46	0.27
Occ_Safety_Regulations	Energy Intensity	-0.01	-0.41	0.32
Occ_Safety_Regulations	Emission Intensity	0.08	-0.38	0.36
Train_Development	Waste Intensity	-0.39	-0.77	0.20
Train_Development	Water Intensity	-0.3	-0.77	0.19
Train_Development	Recycling Ratio	-0.24	-0.64	0.24
Train_Development	Energy Intensity	-0.23	-0.76	0.32
Train_Development	Emission Intensity	-0.07	-0.73	0.32
Workplace_Diversity	Recycling Ratio	-0.04	-0.38	0.38
Workplace_Diversity	Emission Intensity	0.00	-0.64	0.37
Workplace_Diversity	Water Intensity	0.23	-0.07	0.49
Workplace_Diversity	Waste Intensity	0.28	0.00	0.50
Workplace_Diversity	Energy Intensity	0.68	0.36	0.94
Collective_Bargaining	Water Intensity	-0.07	-0.35	0.32
Collective_Bargaining	Waste Intensity	0.12	-0.28	0.49
Collective_Bargaining	Recycling Ratio	0.13	-0.24	0.50
Collective_Bargaining	Emission Intensity	0.2	-0.14	0.52
Collective_Bargaining	Energy Intensity	0.3	-0.16	0.66

Table 11 Sensitivity Analysis CEI with PCA vs. CEI with equal weighting

Firm ID	CEI—PCA	Rank	CEI-Equal Weighting	Rank
17	0.937	1	0.937	1
1	0.934	2	0.934	2
5	0.911	3	0.911	3
9	0.866	4	0.866	4
6	0.862	5	0.862	5
3	0.852	6	0.852	6
8	0.825	7	0.825	7
15	0.814	8	0.814	9
7	0.802	9	0.802	11
18	0.793	10	0.793	10
4	0.748	11	0.748	12
22	0.746	12	0.746	13
20	0.744	13	0.744	14
13	0.708	14	0.708	8
19	0.672	15	0.672	15
2	0.662	16	0.662	16
11	0.572	17	0.572	17
10	0.544	18	0.544	19
16	0.527	19	0.527	20
21	0.509	20	0.509	18
12	0.348	21	0.348	21
14	0.291	22	0.291	22

Table 12 Sensitivity Analysis CESI with PCA vs. CESI with equal weighting

Firm ID	CESI—PCA	Rank	CESI—Equal Weighting	Rank
1	0.900	1	0.932	1
5	0.811	2	0.838	2
17	0.810	3	0.828	3
13	0.774	4	0.666	11
18	0.643	5	0.718	5
15	0.633	6	0.753	4
11	0.572	7	0.574	16
8	0.569	8	0.685	7
4	0.569	9	0.651	14
6	0.568	10	0.698	6
22	0.561	11	0.657	12
9	0.545	12	0.674	8
20	0.541	13	0.673	9
7	0.537	14	0.668	10
3	0.529	15	0.652	13
2	0.489	16	0.612	15
21	0.479	17	0.497	19
16	0.429	18	0.501	18
19	0.408	19	0.543	17
10	0.407	20	0.475	20
12	0.243	21	0.305	21
14	0.148	22	0.273	22

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Data availability The data generated or analyzed during this study are available upon reasonable request. Researchers interested in accessing the data for academic or verification purposes may contact the corresponding author at istemi.berk@deu.edu.tr to request the dataset.

Declarations

Ethical approval This is not applicable.

Consent to participate This is not applicable.

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