Technology in Society 86 (2026) 103322

Contents lists available at ScienceDirect

Technology in Society

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

Digital platforms and composite measurement of an urban circular economy: Developing the digital circularity index

Luca Giraldi [a,*], Luca Rossi [b], Mirko Olivieri [c]

[a] Department of Law, University of Turin, Turin, Italy
[b] "Niccolò Cusano" University, Rome, Italy
[c] Università Cattolica del Sacro Cuore, Rome, Italy

ARTICLE INFO

Keywords:
Urban circular economy
Digital transformation
Smart cities
Composite sustainability indicators
Digital platforms for circularity
Urban governance and policy

ABSTRACT

Digital platforms are increasingly central to advancing the circular economy in urban contexts. However, current measurement tools rarely capture the complexities linking digital adoption, environmental performance, and socio-economic factors, leaving a significant gap between theory and practice. To address this gap, this study develops the Digital Circularity Index (DCI), a novel composite indicator that analyses and compares urban circularity by integrating digital platform adoption, waste-management outcomes, and contextual socio-economic variables. Using data from Italy's 14 metropolitan cities, we construct the DCI using partial least squares path modelling (PLS-PM), which accommodates theoretical relationships across dimensions and yields interpretable, reliable weights for each indicator. The results reveal significant disparities across cities, demonstrating how balanced integration of digital engagement, environmental practices, and socio-economic capacities increases circularity. The DCI advances research by offering a multi-dimensional measure of urban circularity that explicitly integrates digitalisation and provides valuable insights for policymakers. The DCI is a replicable decision-support tool for monitoring urban circularity and guiding investment strategies.

1. Introduction

Digital platforms are widely used to support the transition towards a circular economy (CE), particularly in urban areas, where apps and online marketplaces facilitate the reuse, sharing, and recycling of goods and materials, enabling waste reduction and extending product life-cycles (Gupta et al., 2025). For example, Lisbon, in Portugal, uses a digital platform for sustainable procurement planning and a 'Pay-As-You-Throw' system to boost waste sorting, Riga, in Latvia, connects construction material suppliers and users through a digital platform, and Oulu, in Finland, optimises daily waste collection via Internet of Things (IoT) smart bins (Feleki et al., 2025).

Recent studies suggest that such digital platforms reduce the barriers between the supply and demand of scrap materials and second-hand goods, establishing more efficient urban ecosystems (Tian et al., 2024). In this vein, Fosso Wamba et al. (2024) highlight the key influence of artificial intelligence on environmental performance. Despite these advancements, existing CE metrics generally neglect the digital dimension. However, a growing body of research indicates that digital platforms are associated with circular behaviours by lowering transaction costs, improving matching efficiency, and enabling real-time coordination among users (e.g., Rossi & Srai, 2025). These mechanisms are important because they directly affect whether secondary materials, reusable items, and surplus resources can circulate effectively within urban ecosystems. Digital infrastructure can facilitate trust-building and faster exchanges. Accordingly, digital adoption is increasingly being examined as an enabling condition that co-occurs with higher observed levels of urban circularity (Carlos et al., 2024).

According to previous research, digital platforms are key tools for advancing CE practices by facilitating stakeholder collaboration (Ferreira & Dabic, 2022). Furthermore, these platforms improve resource use (Kovacic et al., 2020) and support the development of sustainable business approaches (Blackburn et al., 2023). Although researchers have developed circularity and sustainability indicators, these indicators typically focus on environmental or material flows and do not integrate digital platforms, despite their growing relevance in shaping urban CE practices. This represents an underexplored area at the intersection between CE measurement, urban studies, and digitalisation. Indeed, although scholars have widely analysed the influence of digital platforms on supporting CE models (e.g., Al Halbusi et al., 2025; Langley

* Corresponding author.
E-mail addresses: luca.giraldi@unito.it (L. Giraldi), luca.rossi@unicusano.it (L. Rossi), mirko.olivieri@unicatt.it (M. Olivieri).

https://doi.org/10.1016/j.techsoc.2026.103322
Received 11 September 2025; Received in revised form 21 March 2026; Accepted 23 March 2026
Available online 24 March 2026

et al., 2023), the research remains limited in terms of empirical frameworks that capture the contribution of digital platforms to urban CE practices systematically and comparably (Feleki et al., 2025; Vanderhorst et al., 2024). Specifically, to the best of our knowledge, no existing composite indicator explicitly incorporates digital platform adoption as a core dimension of urban circularity, leaving a gap in the CE literature regarding how digitalisation translates into measurable CE outcomes. In this regard, CE scholars highlight the need to adopt a holistic and integrated approach in a framework that quantifies the effectiveness of CE strategies (e.g., Lozano et al., 2021), particularly in complex urban contexts characterised by intertwined technological, environmental, and socio-economic dynamics. To fill this research gap, we have developed the Digital Circularity Index (DCI), which analyses and compares urban circularity by integrating digital platform adoption, waste-management outcomes, and contextual socio-economic variables through partial least squares path modelling (PLS-PM). Italy provides an appropriate empirical context for this analysis, because its metropolitan cities exhibit strong heterogeneity in terms of digital maturity and CE performance, ranging from the highly industrialised and digitally advanced Northern regions to Southern areas facing structural and infrastructural constraints. This diversity provides a useful setting for assessing whether the DCI is sensitive to variations in territorial, socio-economic, and digital conditions, strengthening the DCI's external validity. Moreover, recent national programmes, such as Italia Digitale 2026, have accelerated digital services and platform adoption in urban contexts, establishing an appropriate setting for investigating how digital advancement interacts with urban circularity.

This study focuses in particular on consumer-oriented platforms such as Too Good To Go, Vinted, and Subito.it, as they have national coverage, high user penetration, and consistent data availability. These characteristics make these platforms suitable for analysing behavioural patterns of reuse, redistribution, and waste prevention on an urban scale.

Our results reveal clear inter-urban differences, with higher DCI values occurring where digital, environmental, and socio-economic dimensions are mutually reinforcing. This study makes two main contributions: it introduces the first urban-scale composite indicator that explicitly integrates digitalisation and circularity, and it provides empirical evidence that digital adoption is associated with circular performance across heterogeneous metropolitan contexts. From a methodological perspective, the PLS-PM approach anchors component weights to theory, strengthening the robustness and interpretability of the DCI. The findings provide novel insights into the evolution of digital, environmental, and socio-economic factors in the context of urban circularity.

From a managerial and policy perspective, the DCI offers a practical decision-support tool for guiding investments in digital infrastructure, training programmes, and high-impact CE projects. The index facilitates governance by providing a common framework for comparing cities and regions, supporting coordination among public institutions and private stakeholders.

This paper is structured as follows. Section 2 presents the state of the art on the topic of urban circularity in the academic debate, focusing on the role of indicators. The methodology is illustrated in Section 3, and the results are provided in Section 4. Section 5 discusses the results, and Section 6 concludes the paper.

2. State of the art

The transition towards circular urban systems is a critical component of sustainable development, rooted in the broader CE framework, which integrates environmental governance with economic and social dimensions and emphasises resource efficiency, reuse, and recycling (Kennedy & Linnenluecke, 2022). This section details the conceptual background of the paper by presenting the theoretical foundations and defining key constructs and indicators. By providing this framework, this section ensures that subsequent analyses are grounded in a coherent theoretical and empirical context.

CE is being widely investigated as a systemic model for sustainable production and consumption. Recent studies highlight the influence of CE on consumers' decision-making (Lu et al., 2026; Olivieri et al., 2026). However, CE application in urban contexts requires additional consideration of infrastructural and societal factors (Bourdin & Jacquet, 2025). Researchers emphasise digitalisation as a significant enabling condition for CE transitions (Perotti et al., 2024; Ranjbari et al., 2024). Digital platform adoption is frequently described as relevant to addressing the operational challenges associated with the CE transition and supporting innovation pathways that are often observed alongside more advanced CE practices in empirical settings (Pan et al., 2023; Yu et al., 2025). For example, Nham and Ha (2022) find that digitalisation advances circular business models by reducing costs and resource use, supporting reliable data, fostering modular and repairable product design and requiring collaboration across the entire ecosystem to close resource loops. However, although digital transformation enhances efficiency and sustainability, it can also introduce unforeseen outcomes, particularly by reconfiguring inter-organisational power dynamics and weakening traditional boundaries between organisations (Chung et al., 2025).

Urban circularity can be understood as the application of CE principles within cities with specific characteristics such as high population density, complex material flow and interactions between citizens, firms and public administrations (Singhvi et al., 2025). In this regard, Bozeman III et al. (2023) highlight two interconnected research priorities for sustainable urban systems—circular approaches and the use of digital twins. Accordingly, future circularity research should prioritise developing integrated measurement systems capable of capturing material flow, reuse dynamics and resource efficiency coherently. Advancing this field requires more comprehensive assessment frameworks. In parallel, research on digital twins should focus on enhancing their applicability to complex sustainability challenges by improving interoperability between data sources and system components and facilitating access to timely, high-quality data. Strengthening the connection between digital twins and circular analyses will support effective evaluations of CE strategies and their impacts across different urban systems (Bozeman III et al., 2023).

Accurately assessing urban circularity necessitates effective measurement frameworks that capture its complex and multi-dimensional nature (Oliveira et al., 2024; Pekdemir et al., 2025). While numerous approaches are proposed to evaluate cities' CE performance (Formisano et al., 2022; Wu et al., 2022), adding digital transformation and socio-economic factors, which are critical for urban CE, is underexplored.

The academic literature highlights the need for conceptual and analytical frameworks that consider urban circularity as a systemic and multi-dimensional phenomenon that includes material flows, digital transformation and socio-economic dynamics. This integrated perspective is crucial for advancing measurement approaches and understanding how digital platforms can effectively support circular transitions in complex urban systems.

2.1. Using composite indicators to assess urban circularity

Measuring an urban system's circularity in an integrated way is a complex challenge, as urban circular initiatives are often disjointed, with limited metrics, policy alignment and evaluation of social outcomes (Mubarik et al., 2024; Muñoz & Navia, 2021). In this vein, Cui (2022) proposes a Circular Urban Metabolism framework designed to evaluate urban resource consumption patterns and identify opportunities for circular policy interventions. This model conceptualises material flows across urban sectors as a cyclical system, integrating resource use assessments and circularity potential. This framework is applied to the case of Shanghai and reveals a significant increase in material inputs and outputs, highlighting strong dependencies on external regions with high resource consumption and pollution generation.

Several studies have developed composite indicators to assess cities' environmental, economic, and social performance (Miatto et al., 2024). For example, Ahmadi et al. (2025) propose the Circularity-based Embodied Carbon index, providing a comparative tool for evaluating how circular practices influence the embodied carbon of construction projects. Expanding on standard CE assessments, this index considers material inputs and outputs, adjusts for usage patterns, and considers modifications in building lifespan strategies. Švarc et al. (2022) provide a comprehensive assessment of European monitoring frameworks for CE, emphasising the challenges in interpreting indicator-based assessments due to contextual socio-economic differences and the need for careful, deliberate methodological choices when designing composite indices. Composite indicators combine multiple metrics into a single synthetic measure, enabling comparisons across cities and over time. In the CE context, these indices aggregate metrics such as recycling rates, energy and material-use efficiency, the share of renewable energy, product lifetimes and socio-economic variables such as CE-related employment and citizen awareness. Some recent studies propose multi-dimensional urban CE indices that also include digital infrastructure quality and civic participation in CE models (Garrido et al., 2023, pp. 1–21). This trend reflects the growing awareness that CE transitions are interconnected with digitalisation and participatory governance (Fernandes et al., 2022). For example, Di Maio and Rem (2015) argue that effective CE measurement requires multi-dimensional frameworks that integrate physical flow with systemic enablers, such as innovation capacity and institutional support.

From the same perspective, Khadim et al. (2023) present the Whole-Building Circularity Indicator (WBCI), proposing a comprehensive metric that integrates the most effective elements of previous indicators and evaluates circularity across all material flows throughout a building's life cycle. The WBCI is compatible with established sustainability assessment tools, such as Life Cycle Assessment, and was tested using an Italian residential building to reveal the effects of material-intensive construction and extended building lifespan.

The main advantages of composite indicators are that they provide a holistic view of urban sustainability, integrate multiple perspectives, and translate complex data into insights for policymakers. These systems enable the identification of specific gaps, such as high waste-management performance but low water reuse, to inform targeted interventions. Recent studies show that such tools make it possible to rank cities and measure the impact of CE policies (Toboso-Chavero et al., 2025).

The frameworks and composite indicators reviewed focus on the potential and the limitations of current approaches for measuring urban CE, highlighting the need for integrated and multi-dimensional methodologies. These tools highlight the importance of connecting material flow assessments with socio-economic, institutional, and governance dimensions to support more effective, context-sensitive circular transition policies.

2.2. Constructing the Digital Circularity Index: limitations of current metrics and integration of the digital dimension

Despite recent progress, our review reveals that many urban CE indicators focus primarily on environmental variables and physical flow, neglecting the influence of digital transformations and socio-economic factors (Gupta et al., 2025; Miatto et al., 2024). Some indices assess the volume of recycled waste or the proportion of recovered materials, but do not include the contribution of digital platforms or information and communication technology (ICT) infrastructure to these outcomes (Ranjbari et al., 2024). Conversely, many 'smart city' metrics track urban digital innovation (sensors, open data and online services) without verifying whether such innovations foster circularity.

This lack of integration is a significant methodological and conceptual gap that necessitates the development of a DCI. This composite indicator integrates digital variables (e.g. online circular platform adoption), environmental variables (e.g. recycling rates) and socio-economic variables (e.g., CE employment, equitable service access) (Garrido et al., 2023, pp. 1–21). The DCI addresses the need to understand the correlations and interdependencies between digital adoption and circular transitions in urban systems, providing decision makers with a comprehensive tool for monitoring progress and guiding policies.

Other studies highlight the importance of multi-dimensional measurement systems. For example, the Urban Circularity Assessment Framework proposes a planning, monitoring, evaluation, and learning architecture that blends environmental, social, and governance elements into a coherent framework based on extensive stakeholder engagement (Vanhuyse, 2024).

From a broader conceptual perspective, researchers argue that composite circularity indices are underdeveloped and that including digital or systemic performance indicators remains rare (De Pascale et al., 2021). While some theoretical frameworks explore circularity to support digital traceability and agile resource reuse from the perspectives of modularity, commonality, and loop dynamics, they rarely extend into urban metrics (Munonye, 2025).

The academic literature increasingly emphasises that frameworks excluding digital and socio-economic dimensions risk producing an incomplete picture of urban circularity. Without these perspectives, evaluations may not capture the full potential and challenges of the ongoing urban CE transformations.

Previous literature reveals a persistent gap in urban circularity measurement, where digitalisation and socio-economic dynamics are insufficiently integrated into existing indicators. Addressing this gap through multi-dimensional tools such as the DCI is essential to accurately investigating the systemic nature of urban CE transitions and supporting more effective policymaking.

3. Methodology

This study develops a composite DCI to analyse and compare urban circularity by integrating digital platform adoption, waste-management outcomes and contextual socio-economic variables. The multi-dimensional nature of the phenomenon requires an in-depth methodological approach to select an appropriate aggregation technique that is scientifically robust, theoretically grounded, and interpretively useful for public decision makers. To do so, we considered several well-known approaches in the literature (Oliveira et al., 2024).

- Principal component analysis (PCA). PCA is a dimensionality-reduction technique that condenses a set of variables into a smaller number of uncorrelated components. Although it is widely used in the sustainability and urban innovation literature, it does not account for theoretical relationships between variables, relying solely on statistical correlations. The weights of principal components are not theoretically interpretable, which makes it difficult to use the results to guide local policies.
- Data envelopment analysis (DEA). DEA is a non-parametric method that measures the relative efficiency of decision-making units. This technique is employed to assess cities' environmental or digital performance. However, DEA assigns variable weights to each city, rendering results non-comparable across datasets. Moreover, it can reward "efficient units" even when they perform well in only one area, thereby overlooking imbalances across other dimensions.
- Machine-learning techniques (e.g., Random Forest feature importance). Although more recent approaches propose using supervised algorithms to assign weights to variables based on their predictive power, these models require an external target (which does not exist in this case) and yield weights that are not easily interpretable from a regulatory or social standpoint.

In light of these limitations, we employ a PLS-PM approach that belongs to the family of structural equation models (SEMs) and enables us to model latent (not directly observable) constructs as combinations of observed variables, while respecting explicit theoretical relationships. This choice is motivated by the nature of the construct and the analytical requirements of the study. PLS-PM is suitable for examining multi-dimensional latent variables, reflective measurement structures, heterogeneous indicators (binary, proportional, or continuous), and relatively small samples, and imposes minimal distributional assumptions. Previous research on sustainability, urban resilience, and CE modelling applies PLS-PM in similar contexts, supporting its suitability for latent index construction and policy-oriented diagnostics (Acquah et al., 2024; Sarstedt et al., 2014). This study conceptualises the three dimensions as manifestations of the underlying level of urban digital circularity, and their integration through a reflective PLS-PM structure ensures the DCI's theoretical coherence and empirical stability.

We specify the DCI as a higher-order reflective construct derived from digital adoption, environmental performance, and socio-economic dimensions. The reflective approach (Mode A) assumes that the latent construct drives its observable manifestations. In other words, if a city has a high digital circularity level, we posit that it will simultaneously exhibit a strong interest in circular platforms, favourable environmental outcomes, and a supportive socio-economic configuration. This interpretation is consistent with the urban sustainability literature, where complex multi-dimensional phenomena are conceived as latent causes of their indicators. Accordingly, we model the three dimensions as manifestations of the same underlying condition of urban digital circularity, aligning with established guidelines on higher-order SEM specification (Becker et al., 2012; Jarvis et al., 2003).

3.1. Dimensions and indicator selection

Our model comprises three first-order reflective blocks, each of which is linked to the second-order DCI construct. We have selected quantitative indicators for each dimension that are easily accessible from reliable secondary sources (Table 1).

3.1.1. Adoption of digital circular platforms

The first dimension considered in constructing the DCI is local adoption of digital platforms that support circularity, based on technological tools that facilitate reuse, waste reduction, and the valorisation of used goods. In Italy, notable applications include Too Good To Go, which enables surplus food to be recovered; Vinted, which facilitates the exchange and sale of second-hand clothing; and Wallapop and Subito.it, which support peer-to-peer reuse and trading. The spread and use of these platforms represent a leading indicator of the extent to which digitalisation supports CE development, particularly in urban settings. We use Google Trends data to measure this dimension, which enables comparative analysis of online search volumes for specific keywords, filtered by geographic area and time interval. The Google Trends index, expressed on a 0–100 scale, serves as a proxy for quantifying interest and territorial penetration of the digital platforms under investigation. This approach builds on recent studies that validate the use of online search analysis as an indicator of localised digital behaviours and sustainability-related intentions to use (Afolabi, 2025, pp. 1–21).

Specifically, Afolabi (2025) further emphasise digital practices as a leading indicator of sustainable technology adoption, highlighting how web-based data complements traditional structural data when assessing a territory's circular maturity. Considering these contributions, employing Google Trends is a methodologically sound solution for quantifying the territorial diffusion of digital circular platforms in the absence of direct disaggregated data.

Table 1
Indicators used in the digital circularity index (DCI).

Latent Block	Observed Indicator	Data Source	Type
Adoption of Digital Circular Platforms	Google Trends search volume: *TooGoodToGo*	Google Trends	Normalised (0–1)
	Google Trends search volume: *Vinted*	Google Trends	Normalised (0–1)
	Google Trends search volume: *Wallapop*	Google Trends	Normalised (0–1)
	Estimated active users per 1000 inhabitants	Company reports, Statista	Continuous
Urban Environmental Performance	Waste sorting rate (% of total waste)	ISPRA, Municipalities	Proportion (%)
	Urban waste generation per capita (kg/inhabitant)	ISPRA, ISTAT	Continuous
	Urban carbon dioxide (CO_2) emissions per capita (t/inhabitant)	ISPRA, ARPA, EEA	Continuous
Socio-Economic Contextual Factors	Disposable income per capita (€)	ISTAT	Continuous
	University graduates (aged 25–64)	ISTAT	Proportion (%)
	Urban Digital Maturity Index (e.g. DESI local proxy if available)	AgID (Italian Digital Agency)	Composite Index

3.1.2. Urban environmental performance

The second fundamental dimension of the DCI is urban environmental performance, which we assess using key waste-management indicators. In particular, we employ the separate collection rate and the annual amount of municipal solid waste per capita (expressed in kg per inhabitant/year). These indicators are consolidated and widely recognised metrics for evaluating the efficiency and sustainability of environmental management systems on an urban scale.

This choice is supported by recent international literature, which identifies waste management as an operational pillar of the urban CE transition. For example, in a systematic review of major CE indicators, Munonye (2025) ranks per capita waste generation as one of the most relevant territorial metrics, highlighting its ability to reflect consumption levels, the degree of waste prevention and the effectiveness of public policies.

Methodologically, including these two indicators captures the total quantity of waste produced, which expresses the city's gross environmental impact, and treatment quality, expressed by the proportion actually sent to recycling or reuse. This approach enables a more balanced and comprehensive assessment of urban environmental performance, aligning with the methods promoted by recent benchmarking practices in European cities.

Our data are drawn from official and up-to-date sources, in particular the 2024 Urban Waste Report published by the Italian Institute for Environmental Protection and Research (ISPRA)[1] and environmental datasets provided by the Italian National Institute of Statistics (ISTAT).[2] The data are available at the city level and ensure high quality standards, coverage and temporal comparability.

The DCI's environmental dimension enables us to measure the efficiency and sustainability of the urban system in managing resources and waste, establishing a foundation for reliable comparisons across cities and for integrated analysis with the digital and socio-economic dimensions.

Notably, material-specific recycling rates (e.g. plastics, paper and construction waste recovery) are not included, because these indicators are not uniformly available at the city level across all areas of Italy. For comparability, we only use two nationally standardised and consistently reported metrics (waste sorting rate and per capita waste generation) to capture the quantity and quality of urban waste management. Future

[1] https://www.isprambiente.gov.it/it/pubblicazioni/rapporti/rapporto-rifiuti-urbani-edizione-2024.

[2] https://www.istat.it/statistiche-per-temi/ambiente-e-territorio/.

research may extend the environmental dimension of the DCI when more granular and harmonised data, such as construction waste reuse or material-specific recovery rates, become available.

3.1.3. Socio-economic contextual factors

The third dimension of the DCI is the socio-economic context, captured through a set of structural characteristics that may directly or indirectly influence circular digital platform adoption and cities' environmental performance. The literature widely recognises that economic means, level of education and the population's digital maturity are decisive elements in enabling virtuous practices and sustainable technologies at the urban level.

We employ three key indicators to measure this dimension.

- Disposable income per capita at the provincial/metropolitan level (in €),
- Share of the population aged 25–64 with a university degree, and
- A synthetic Urban Digital Maturity Index derived from official sources such as the European Digital Economy and Society Index (DESI) and Italy's Equitable and Sustainable Well-being (ISTAT-BES) datasets.

The Urban Digital Maturity Index uses the harmonised indicators provided by the DESI and ISTAT-BES datasets, combining (i) basic digital skills; (ii) intermediate and advanced competencies, including digital problem solving and content creation; and (iii) intensity in the use of online services such as e-government, e-commerce and digital public services. Following the methodological guidelines of the sources, we normalised each indicator using a min–max procedure and aggregated them through equal weighting for each sub-dimension. The three subdimensions also contribute equally to the overall score, consistent with the balanced composite indicator approach adopted by the DESI and ISTAT-BES. Maintaining this weighting scheme ensures methodological transparency, territorial comparability and index reproducibility.

These indicators provide a robust measure of a city's capacity to absorb and leverage digital solutions that support the CE, and they are widely used in recent comparative studies across Europe. For example, Georgescu et al. (2025) analyse the impact of human capital and technology investment on reuse rates and circular materials use in the European Union, demonstrating that cities with higher education levels and greater wealth tend to adopt circular practices more rapidly. Methodologically, widespread digital skills are a fundamental prerequisite for adopting the platforms analysed. Furthermore, education and income affect the types of goods exchanged, the propensity for reuse and overall environmental awareness. ISTAT[3] and DESI[4] sources enable a disaggregated and up-to-date territorial analysis, allowing us to assess these structural conditions on an urban scale. Including the socio-economic dimension in the DCI follows a systemic logic whereby digital circularity does not develop in a social vacuum and urban communities' cultural, economic and technological structure strongly condition CE development. These measures make it possible to understand both current performance and the different inherent transitional potential of the territories.

We selected these dimensions and indicators following widely adopted analytical criteria in circularity and urban sustainability studies. Environmental and socio-economic dimensions reflect the core pillars of the EU Circular Economy Action Plan and frameworks from recent empirical literature (Carayannis et al., 2022; Iacovidou & Lovat, 2020; Moraga et al., 2019). The digital adoption dimension draws on studies highlighting platform-mediated circularity as a relevant driver of urban reuse, repair and resource optimisation (Guldmann & Huulgaard, 2020; Mont et al., 2021). The indicators represent established measures for benchmarking urban circularity, adjusted to ensure systematic comparability across Italian cities. This configuration is also consistent with recent proposals for circular city indicator systems and assessment frameworks that emphasise the joint consideration of environmental, socio-economic and governance-related dimensions on an urban scale (Vanhuyse, 2024). Furthermore, the focus on platform-enabled circular practices aligns with emerging evidence on digital CE platforms as enablers of new urban reuse, repair and sharing services (Ritala & Keränen, 2023).

3.2. Construction of the composite index

The relationship between the blocks and the composite index can be expressed formally as follows:

$$DCI = \beta_1 D + \beta_2 E + \beta_3 S + \epsilon,$$

where D is the latent score of the Digital block, E is the score of the Environmental block, S is the score of the Socio-economic block, β_i denotes the weights estimated by the model, and ε is the residual error.

Each latent construct is estimated as a weighted average of its observed indicators, normalised to the 0–1 range as follows:

$$Bj = \sum_{i=1}^{nj} w_{ij} x_{ij},$$

where x_{ij} is the i-th indicator of block j, w_{ij} is the estimated weight for that indicator and n_j is the number of indicators in the block.

Before modelling, we normalised all observed indicators to the 0–1 scale using the following min–max formula:

$$x_{ij}^{norm} = \frac{x_{ij-(x_j)}}{(x_j) - (x_j)}$$

where x_{ij} is the raw value of the indicator j for the city, i, x_{ij}^{norm} is the normalised value and (x_j) are the respective minimum and maximum observed for the variable j in the dataset. x_{ij}^{norm} is the normalised value, and k is a dummy index iterating over all cities when computing the minimum and maximum for the indicator j that is distinct from the focal city index i. For cost-type indicators (e.g. waste, CO_2), we applied the following reverse coding:

$$x_{ij}^{norm} \leftarrow 1 - x_{ij}^{norm}.$$

The model is estimated using SmartPLS 4 and validated via bootstrapping with 5000 samples to calculate the statistical significance of the path coefficients (Méndez-Suárez, 2021). In addition, we assessed the following quality indicators (Shela et al., 2023).

- Composite reliability (CR > 0.7)
- Average variance extracted (AVE >0.5)
- Collinearity (VIF <3.3)
- R-squared (R^2) of the DCI (>0.6)

We tested the robustness of the index by evaluating the stability of the weights and comparing them with alternatives such as weighted arithmetic means and PCA, confirming the consistency and interpretability of our results (Kurniawan et al., 2025).

We employed a cross-sectional analysis ($N = 14$) and did not identify causal effects. All statements are descriptive/associational, and coefficients are interpreted as correlational patterns.

4. Results

Our analysis covers 14 Italian metropolitan cities: Milan, Bologna,

[3] https://www.istat.it/statistiche-per-temi/focus/benessere-e-sostenibilita/obiettivi-di-sviluppo-sostenibile/gli-indicatori-istat/.

[4] https://digital-strategy.ec.europa.eu/en/policies/desi.

Turin, Florence, Rome, Naples, Genoa, Venice, Bari, Palermo, Catania, Cagliari, Messina and Reggio Calabria. The model is estimated using PLS-PM in SmartPLS 4, adopting a reflective configuration (Mode A) for each of the three conceptual blocks (digital circular platform adoption, urban environmental performance and socio-economic contextual factors), linked to a second-order latent construct representing the DCI. This approach enables us to quantify the shared variance between the indicators within each block, ensuring theoretical consistency and empirical robustness.

A brief correlation analysis across the DCI dimensions reveals that the digital adoption component is moderately and positively associated with the socio-economic dimension ($r \approx 0.45$), reflecting the expected correlation with income levels, education, and overall digital maturity. Conversely, correlations with the environmental dimension are weaker ($r \approx 0.18$), indicating that waste-management performance does not necessarily co-evolve with digital or socio-economic conditions. These results confirm that the three DCI components capture conceptually distinct but complementary facets of urban circularity. The full correlation matrix is presented in Appendix Table A.2.

Model validity and reliability are confirmed using CR values consistently above 0.70, AVE greater than 0.50, and a maximum VIF below 3.3. The coefficient of determination (R^2) for the DCI is 0.67, indicating good explanatory power (Table 2).

We conducted several complementary tests to verify the robustness and reliability of our index. Model stability is supported by CR values consistently above 0.80 and AVE higher than 0.50 across all dimensions, and the maximum VIF remains below 3.3, confirming internal consistency and the absence of multi-collinearity concerns. The significance of all indicator weights is validated through a bootstrap procedure with 5000 resamples (***$p < 0.001$), yielding t-values that range between ~7.0 and ~9.5. As an external robustness test, we compared the DCI with two alternative aggregation approaches, weighted arithmetic mean and PCA, revealing highly convergent patterns (the differences between methods generally remain within 0.01–0.02 points and never exceed ~0.11, while ranking positions remain substantially unchanged across cities). These combined results provide triangulated evidence of the DCI's construct validity, reliability, and robustness as a synthetic measure of urban digital circularity.

Considering the reflective nature of the model and the need to verify the statistical stability of the relationships between indicators and latent constructs, we estimated the standardised weights (Table 3) using a bootstrapping procedure with 5000 resamples. The results reveal that all indicators are statistically significant ($p < 0.001$), confirming the robustness and reliability of our estimates.

Based on the standardised weights in Table 3, we calculated a synthetic value of the DCI for each city as a weighted linear combination of the normalised indicators across the model's three dimensions (Table 4).

To support the interpretation of the results and provide a clearer understanding of how the index is constructed, we produced a heatmap (Fig. 1) using Python 3.11 with the pandas, seaborn, and matplotlib libraries. The heatmap illustrates the normalised (0–1) values of the DCI's three dimensions for each city, using a YlGnBu colour gradient. The figure highlights each urban context's strengths and weaknesses and enables our subsequent assessment of the relative contribution of each dimension to the DCI's overall score. For example, the figure reveals that Milan and Bologna stand out for high performance across all dimensions. In contrast, Reggio Calabria and Messina have room for improvement, particularly in digital adoption and environmental performance. When applying alternative aggregation approaches (such as the weighted mean and PCA), Rome also emerges among the highest-scoring cities, reflecting different weighting logics while preserving top-performing cities' overall clustering.

The DCI's robustness is assessed by comparing the DCI scores estimated through PLS-PM with those obtained using a weighted arithmetic mean and PCA (Table 5 and Fig. 2). The weighted arithmetic mean is included as a baseline benchmark to verify whether adopting a more complex model produces substantially different results (OECD, 2008); however, it is not selected as the primary method because it assigns fixed weights that are not derived from the data and does not account for correlations between indicators, limiting its ability to capture the multi-dimensional nature of the phenomenon accurately. As noted in Section 3, PCA is considered for comparison with a widely used statistical approach in the literature; however, this approach also fails to integrate theoretical relationships and produces weights that are difficult to interpret from a normative perspective. Although numerical differences are larger in some cases (up to ~0.10 points), the three aggregation methods yield highly similar ranking patterns, indicating the DCI's robustness and the relative positioning of the cities. These results validate the choice of PLS-PM as the most theoretically grounded and operationally interpretable approach, while confirming that the overall

Table 2
Model validity and reliability indicators.

Construct	CR	AVE	VIF (max)	R^2 (for DCI)
Digital Adoption	0.87	0.62	2.15	–
Urban Environmental Performance	0.84	0.57	2.22	–
Socio-Economic Context	0.91	0.68	2.05	–
Digital Circularity Index (DCI)	–	–	–	0.67

Table 3
Standardised Weights of the Indicators (***$p < 0.001$).

Dimension	Indicator	Standardised Weight	t-value	Sig.
Adoption of Digital Circular Platforms	Google Trends search volume: TooGoodToGo	0.32	7.85	***
	Google Trends search volume: Vinted	0.30	7.41	***
	Google Trends search volume: Wallapop	0.28	7.02	***
	Estimated active users per 1000 inhabitants	0.36	8.91	***
Urban Environmental Performance	Waste sorting rate (% of total waste)	0.42	9.10	***
	Urban waste generation per capita (kg/inhabitant-year) (inverted)	0.38	8.04	***
	Urban CO_2 emissions per capita (t/inhabitant) (inverted)	0.33	7.62	***
Socio-Economic Contextual Factors	Disposable income per capita (€)	0.36	8.21	***
	Share of the population aged 25–64 with a university degree (%)	0.34	7.92	***
	Urban Digital Maturity Index	0.39	9.00	***

Table 4
DCI values for Italian Metropolitan Cities.

City	DCI Value
Rome	0.685
Milan	0.740
Naples	0.613
Turin	0.713
Palermo	0.576
Genoa	0.683
Bologna	0.743
Florence	0.713
Bari	0.600
Venice	0.697
Catania	0.573
Cagliari	0.653
Messina	0.560
Reggio Calabria	0.547

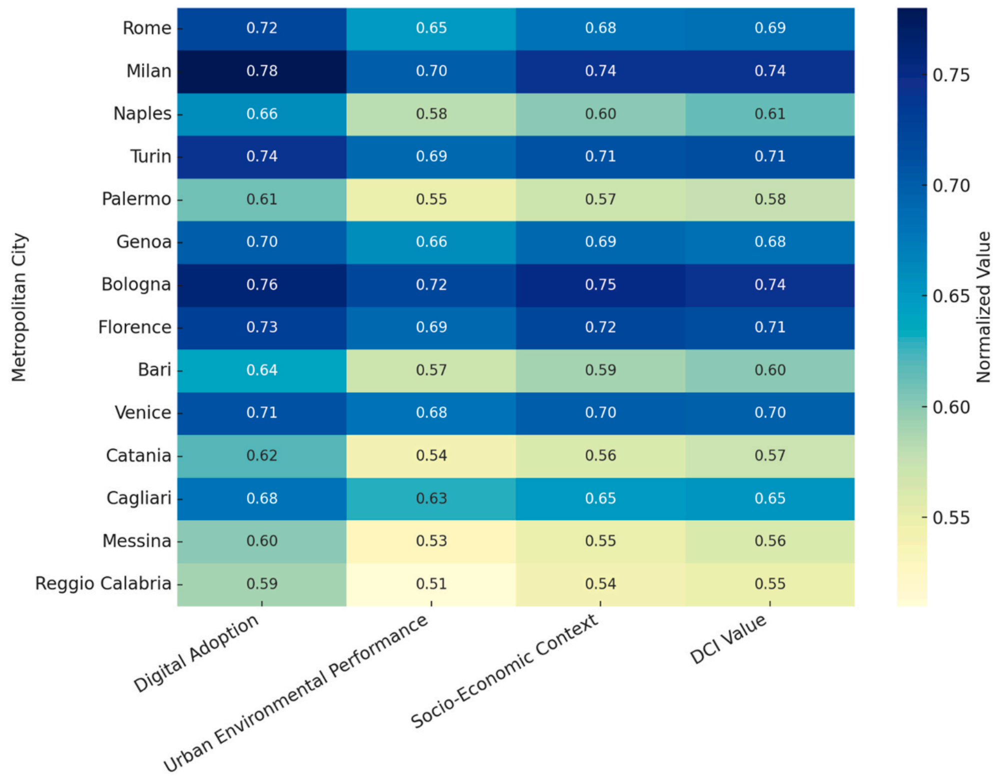

Fig. 1. Heatmap of digital circularity index (DCI) components and values - Italian cities.

Table 5
Comparing DCI scores using PLS-PM, Weighted Arithmetic Mean and PCA.

City	DCI (PLS-PM)	DCI (Weighted Mean)	DCI (PCA)
Milan	0.740	0.751	0.839
Rome	0.685	0.798	0.793
Turin	0.713	0.704	0.698
Bologna	0.743	0.757	0.734
Florence	0.713	0.731	0.695
Naples	0.613	0.626	0.598
Bari	0.600	0.618	0.591
Genoa	0.683	0.700	0.672
Palermo	0.576	0.581	0.559
Catania	0.573	0.583	0.561
Venice	0.697	0.702	0.682
Cagliari	0.653	0.665	0.631
Messina	0.560	0.554	0.551
Reggio Calabria	0.547	0.556	0.529

conclusions remain robust across alternative index formulations.

This convergence is attributable to the high correlation between indicators across the three dimensions, which makes even simpler aggregation techniques (weighted mean or PCA) yield results that are consistent with the theoretically grounded PLS-PM technique. The similarity confirms that the DCI captures a stable underlying structure of urban circularity.

This evidence validates the DCI as a robust and practical tool for comparing urban contexts, identifying priority areas for intervention and informing local policies and business strategies to support the CE transition. The patterns in Fig. 1 further demonstrate that Italian cities can be grouped into distinct archetypes based on DCI configurations. Balanced leaders such as Milan and Bologna have high and relatively homogeneous performance across digital adoption, environmental conditions and socio-economic factors. In these contexts, governance priorities should emphasise consolidating circular ecosystems, strengthening data-sharing agreements between municipalities and platforms, promoting circular procurement in public agencies and testing regulatory sandboxes to scale innovative solutions.

Digitally strong but environmentally weaker cities (e.g. Turin and Florence) show high levels of platform engagement and socio-economic potential, but comparatively weaker environmental indicators. These cities could leverage existing user activation to accelerate environmental transition through investments in waste-sorting infrastructure, community repair hubs, incentives for green logistics and urban policies that expand reuse networks or reduce CO_2-intensive patterns.

Conversely, cities with socio-economic potential but lower digital activation (e.g. Bari, Palermo and Catania) may benefit from measures that stimulate entry into circular marketplaces through campaigns targeted towards small and medium-sized enterprises and artisans, onboarding programmes in collaboration with chambers of commerce, training on digital circular business models and alignment with regional innovation strategies. In such cities, improving the integration of local businesses within circular platforms should be consistent with broader improvements in observed environmental and inclusion indicators.

This archetype-based reading renders the DCI more operational for governance purposes, demonstrating that circular transition trajectories are not uniform and policy effectiveness may increase when interventions target the specific configuration of strengths and weaknesses revealed by the DCI. In this sense, the DCI supports differentiated policy portfolios rather than homogeneous or ‘one-size-fits-all’ strategies.

Notably, the sample comprises all major Italian cities ($N = 14$). Although this ensures full national coverage, the limited number of statistical units naturally constrains the inferential power of our structural estimates and requires caution in extending the conclusions beyond the contexts analysed. Furthermore, as the analysis is based on cross-sectional evidence, the findings should not be interpreted in causal terms. The DCI should be considered a descriptive and diagnostic tool for identifying current territorial gaps and supporting informed decision-making. The numerical differences between the main DCI table (PLS-PM results) and the comparative table reflect their different purposes. The former presents index values obtained using our theoretically grounded model, whereas the latter provides robustness tests using

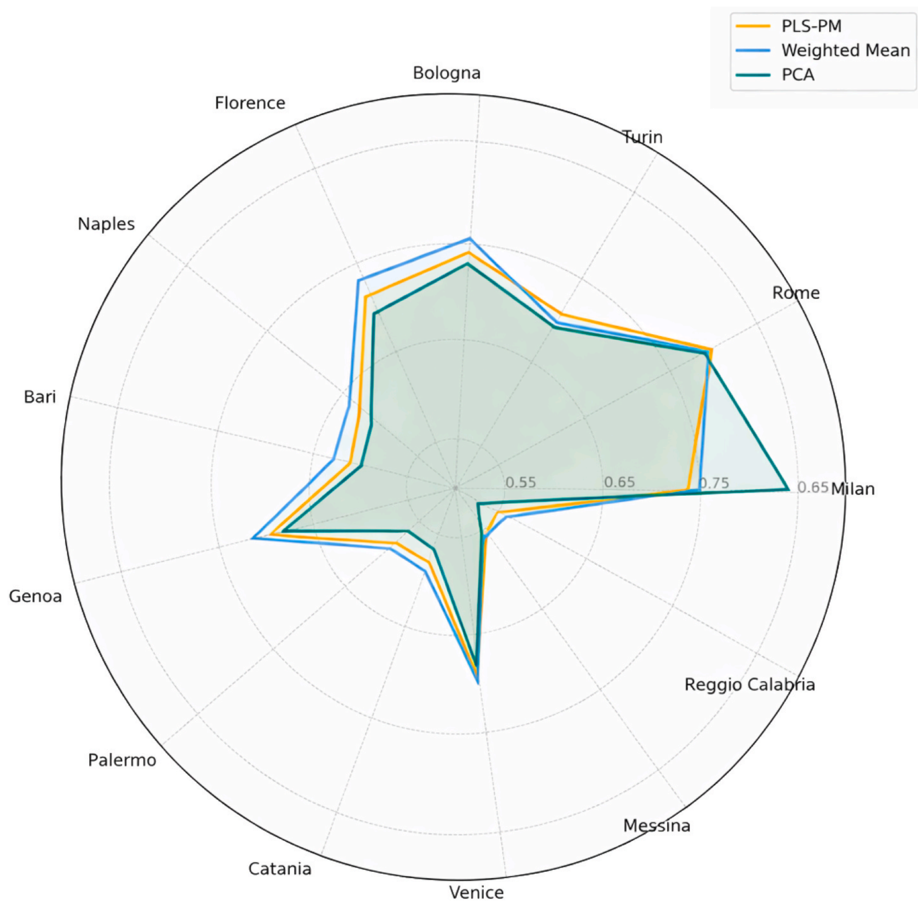

Fig. 2. Radar chart of DCI scores across metropolitan cities.

alternative aggregation techniques (weighted mean and PCA).

5. Discussion

Digital platforms are being widely explored as potential enablers for CE practices in cities, specifically for supporting reuse, sharing and recycling through apps, IoT and data analytics (Feleki et al., 2025; Gupta et al., 2025). While academic research highlights the influence of digital platforms on collaboration, governance and sustainable business models (Fernandes et al., 2022), no studies have yet examined these associations in urban contexts using composite latent constructs (Ferreira & Dabic, 2022). This study addresses the lack of integrated measurement tools by developing the DCI, a composite indicator built using PLS-PM that combines platform use, waste-management outcomes, and socio-economic factors. The findings reveal substantial heterogeneity across cities, with higher scores observed where digital, environmental, and socio-economic conditions are more closely aligned. A more contextualised interpretation of the DCI can be obtained by considering the observed differences between cities alongside documented urban policies and territorial dynamics. For example, Bologna's high score aligns with an institutional ecosystem that has long promoted CE initiatives, including actions implemented following the Bologna Circular City programme (City of Bologna, 2022), sustained investments in waste prevention and consolidated recycling performance. Similarly, Milan benefits from advanced digital infrastructures, high uptake of online public services and one of the most efficient waste-management systems in Italy, as reported in national assessments (City of Milan, 2020; ISPRA–Italian Institute for Environmental Protection and Research, 2024). Florence exhibits a comparable balance, supported by municipal strategies oriented towards material valorisation, prevention programmes and growing diffusion of reuse and sharing practices. In contrast, the lower scores in cities such as Reggio Calabria, Messina, or Catania indicate weaker digital maturity, less stable environmental performance, and more heterogeneous socio-economic conditions. This interpretative approach connects the measurement framework with urban governance theory, meaning that circularity configurations reflect technological adoption, policy coherence, and institutional capacity. While this contextualisation does not involve causal relationships, it helps interpret the urban CE configurations reflected in the DCI and illustrates how the index captures heterogeneous development trajectories across Italian cities. Additional contextual details for individual cities are presented in Appendix Table A.1.

These results align with the literature that identifies platform-mediated reuse, repair, and sharing systems as salient correlates of the circularity of urban ecosystems, confirming the importance of integrating digital dimensions with environmental and socio-economic factors (Guldmann & Huulgaard, 2020; Mont et al., 2021). In line with previous studies on territorial CE assessment (Carayannis et al., 2022; Iacovidou & Lovat, 2020; Moraga et al., 2019), waste efficiency, CO_2 intensity, education and disposable income are confirmed as core correlates of observed differences in urban circular performance. By integrating these variables into a single theoretical construct, the DCI addresses the research gap identified in the literature concerning fragmented circularity metrics in relation to our research objective of empirically examining whether digitalisation varies with environmental and socio-economic performance at the urban level. This study extends existing research by demonstrating that combining these factors into a single latent construct yields stable results even when we estimate the index using alternative aggregation techniques (weighted mean and PCA). The relative positioning of the cities and the structural configuration of the index remain largely unchanged, indicating that digital circularity patterns have internal coherence and can be represented by a multi-dimensional latent structure. The DCI therefore enriches current empirical research by offering (i) a unified, multi-domain structure, (ii) empirical evidence on the statistical convergence of measurement approaches, and (iii) an operational index that can be replicated across cities.

The DCI is a viable measurement and governance tool that integrates three essential dimensions for understanding the transition towards sustainable urban models: digital circular platform adoption, environmental performance and the socio-economic context. These dimensions are theoretically correlated as digital platforms act as coordination mechanisms, environmental outcomes represent material performance, and socio-economic variables include the necessary human and institutional capital for the CE transition. This structure closes the gaps highlighted by recent studies demonstrating that most urban CE indicators focus solely on environmental or material variables, overlooking the influence of ICT infrastructure and human capital in creating resilient and innovative ecosystems (Georgescu et al., 2025). In contrast, the DCI provides a holistic and comparable technique that supports performance monitoring and the development of more effective public policies and investment strategies.

From a methodological perspective, the use of a PLS-PM model enabled us to estimate weights consistent with the theoretical relationships between variables, avoiding distortions arising from purely statistical approaches such as PCA or DEA. This methodological approach reflects the study's theoretical positioning, according to which measurement should be driven by theory rather than data to ensure coherence between the conceptual framework, research objectives and empirical implementation. This is particularly relevant because it supports the DCI's interpretability and operational solidity, enabling decision makers to use the results not only descriptively but also to guide actual interventions. The robustness demonstrated in comparison with alternative methods strengthens the index's validity as a stable tool that is replicable across different territorial contexts.

From an economic perspective, our composite DCI makes it possible to optimise public and private resource allocation. By identifying the most deficient geographic areas or thematic dimensions, investments can be directed towards digital infrastructure, education and training programmes and high-impact CE projects. This approach is consistent with Garrido et al. (2023), who show that such tools can support evidence-based strategic planning and improve the effectiveness of transition policies. The DCI provides a common language that facilitates comparison across cities and regions, enables institutional coordination and aligns with major international frameworks, including the European Green Deal (EGD) and the 2030 Agenda. For example, the environmental dimension of the index, which includes waste-management outcomes, directly relates to EGD targets such as the 50% reduction of municipal waste sent to landfills and the 65% recycling target for municipal waste by 2030. The digital adoption component contributes indirectly to these goals by facilitating platform-mediated reuse, sharing and redistribution, reducing material consumption and waste generation. In addition, the socio-economic dimension supports EGD ambitions for inclusive growth and equitable access to sustainable services, reducing the risk that the sustainable transition only benefits areas that are already more developed and exacerbates existing inequalities (Calisto Friant et al., 2023).

Another key aspect is the DCI's ability to identify different territorial configurations; some cities may show strong environmental performance but low levels of digital adoption, while others may excel in the technological dimension yet require significant waste-management or air quality improvements. This diagnostic function makes the DCI a valuable measurement tool, as well as a guide for designing targeted action plans to maximise resource efficiency and the impact of public policies. By explicitly linking theory, measurement and policy relevance, the DCI responds directly to our research objective and contributes to advancing the conceptual and empirical understanding of digital CE transitions in urban systems. The DCI provides a solid, replicable and strategic indicator that translates complex data into operational intelligence for developing integrated urban policies. Its systematic use can steer the transition towards more sustainable, digital and inclusive cities while supporting economic innovation and social cohesion processes.

6. Conclusions

This study proposes and tests the DCI, a composite indicator that integrates digital circular platform adoption, urban environmental performance and socio-economic factors. The PLS-PM framework anchors the weights to theoretically grounded relationships between the dimensions, yielding an interpretable index that can be used operationally by public decision makers.

Our analysis of Italian cities demonstrates that the highest scores occur in areas where the three dimensions are balanced, while lower scores reflect marked imbalances between digital capacity, waste management, and socio-economic conditions. Although some numerical differences emerge across aggregation methods (up to around 0.10 points in selected cases), the overall ranking patterns remain similar, supporting the structural robustness of the proposed DCI and the validity of the baseline conclusions.

6.1. Theoretical and practical implications

From a theoretical perspective, this study advances the literature on CE and urban sustainability by conceptualising digital circularity as a multi-dimensional construct. Recent studies highlight the need to analyse the influence of digital platforms as enablers of CE practices in the territorial context; for example, Li et al. (2025) focus on the impact of digital adoption on CE strategies in Chinese provinces. Specifically, by integrating digital platform adoption, environmental performance and socio-economic conditions into a single PLS-PM framework in the proposed DCI, we contribute to the academic debate that traditionally considers digitalisation, economic and environmental factors separately. According to Lozano et al. (2021), theory and practice must take a holistic approach, integrating different CE dimensions such as economic and environmental factors. Specifically, the recent research agenda provided by Neri et al. (2025) highlights that scholars should conduct holistic investigations of how digital technologies contribute to the CE transition.

The DCI combines different dimensions and integrates them in an approach that responds to recent calls for more holistic and system-oriented measurement frameworks. Indeed, Muñoz et al. (2024) argue that existing approaches lack a comprehensive framework to assess the efficacy of CE strategies. Our study integrates the evolution of technological, environmental and social dynamics in urban transitions.

Furthermore, the use of a theoretically anchored structural model demonstrates that composite indicators can serve as theory-based representations of complex socio-technical systems, and not merely descriptive tools. Beyond its descriptive value, the DCI has a diagnostic function that enables each city to identify improvement margins within specific components and plan targeted interventions.

As for the practical implications, the DCI can be used to set investment priorities for digital infrastructure and circular services, calibrate prevention and recycling policies, design digital literacy initiatives and build public–private partnerships focused on reuse and waste reduction. The DCI provides public authorities and urban decision makers with a practical tool to support circular transition planning and governance. By assessing digital platform adoption, environmental outcomes, and socio-economic conditions jointly, the index enables cities to identify specific structural imbalances and priority areas for intervention. The DCI can inform the allocation of digital infrastructure, circular services and human capital development investments, support waste prevention and calibration of recycling policies, and guide the design of digital literacy and inclusion initiatives to reduce territorial and social disparities. Moreover, the comparability of results across cities enables benchmarking to spread best practices, facilitating coordination across departments and levels of government. If embedded in periodic monitoring frameworks or public dashboards, the DCI can also enhance transparency, accountability and stakeholder engagement, strengthening the effectiveness of urban CE strategies and supporting more inclusive and resilient strategic directions.

6.2. Limitations and future research directions

This study has several limitations that suggest directions for future research. Firstly, the proxy for digital adoption based on online search volumes does not fully capture actual CE platform transactional intensity, and it may be affected by intrinsic platform-specific biases such as uneven brand penetration, marketing visibility, or differing user trust. In addition, variations in broadband access, digital literacy and socio-demographic characteristics may influence online activity, introducing a potential 'digital divide' effect that could partially skew city rankings. Environmental and socio-economic indicators may also be subject to reporting lags and regional data collection heterogeneity. Furthermore, our analysis is limited to the urban scale and to the total population of Italian metropolitan areas ($N = 14$). While this ensures full national coverage, the relatively small number of statistical units naturally constrains the inferential power of the structural estimates and necessitates caution in generalising the findings to other urban contexts. In addition, the single-country scope reflects a singular regulatory, infrastructural and socio-cultural setting, which may limit external comparability with cities operating under different institutional conditions.

Secondly, a key limitation of this study is that the DCI relies on consumer-oriented platforms (e.g. Too Good To Go, Vinted and Subito.it) that provide broad coverage and accessible data but underrepresent industrial or municipal CE processes. Future research could integrate data from industrial and consortia-based platforms to provide a more comprehensive picture of urban digital circularity.

Lastly, while the DCI captures structural conditions related to digital adoption, environmental performance and socio-economic factors at the metropolitan scale, it does not reflect intra-urban inequalities. This limitation derives from the fact that harmonised neighbourhood-level data on income, digital platform usage and environmental performance are not consistently available across Italian metropolitan areas. As a result, the index does not assess socio-spatial disparities within cities, such as whether lower-income neighbourhoods exhibit reduced digital circular platform access. Future research could address this important dimension of urban sustainability when granular and comparable sub-municipal datasets become available.

These limitations emphasise that the empirical results should be interpreted with caution when assessing causal mechanisms or performing cross-country benchmarking. Future index development is expected to mitigate these biases by integrating direct platform usage data via API access (e.g., active user flow, transaction volume or embedded circularity metrics) and updating the model with time-series observations to account for temporal dynamics, learning effects and policy responses. Longitudinal designs and incremental cross-country applications will enable researchers to test the DCI's stability under diverse institutional arrangements to enhance external validity and support more robust assessments of how urban digital circularity trajectories evolve in response to governance interventions and market conditions. The DCI can also be further refined and operationalised through model variants adapted to differing data availability or embedded within annual municipal planning cycles supported by public dashboards, measurable targets and periodic outcome review.

CRediT authorship contribution statement

Luca Giraldi: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Formal analysis, Data curation, Conceptualization. **Luca Rossi:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Formal analysis, Data curation, Conceptualization. **Mirko Olivieri:** Writing – review & editing, Writing – original draft, Conceptualization.

Funding

No funding was received.

Declaration of 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.

Appendix

Table A1
Contextual interpretation of DCI patterns across the metropolitan cities

Metropolitan City	DCI Profile	Positive contextual factors	Structural limitations	Interpretation
Turin	Medium–High	Strong innovation ecosystem; improving digital infrastructure; increasing platform use	Environmental performance less stable than northern peers	Digital strengths help offset environmental variability
Milan	High	Advanced digital services; strong human capital; highly efficient waste-management system	High waste generation due to economic density	High DCI reflects synergy of innovation and governance
Venice	Medium	Strong tourism economy with circular initiatives; improving recycling rates	Tourist pressure increases per capita waste	Balanced but challenged by seasonal dynamics
Genoa	Medium	Solid waste-sorting performance; gradual digitalisation	Lower socio-economic indicators compared to other northern cities	Stable but moderate DCI aligned with gradual transition
Bologna	High	Circular City programme; strong waste prevention; high digital maturity	Minor improvement margins in emissions	DCI consistent with advanced institutional commitment
Florence	High	Material valorisation policies; prevention programmes; active reuse/sharing culture	Tourist-generated waste pressure	Balanced and consistent with proactive environmental policy
Rome	Medium–High	Strong e-government services; large population enabling platform diffusion	Fragmented waste management; administrative complexity	High potential moderated by operational challenges

(*continued on next page*)

Table A1 (*continued*)

Metropolitan City	DCI Profile	Positive contextual factors	Structural limitations	Interpretation
Naples	Medium	Growing digital initiatives; emerging circularity practices	Lower recycling levels; socio-economic disparities	Reflects heterogeneous territorial conditions
Bari	Medium–Low	Expansion of digital initiatives; improving recycling trends	Lower digital-skill levels; variable environmental indicators	Transitional profile with digital growth potential
Reggio Calabria	Very Low	Emerging local initiatives	Weak digital infrastructure; low socio-economic indicators; poor waste performance	Structural fragility consistent with lowest DCI
Palermo	Medium–Low	Community-led circular initiatives	High waste generation; limited digital maturity	Challenges across all dimensions reflected in DCI
Messina	Low	Early-stage reuse initiatives	Limited digital adoption; uneven waste performance	Profile aligned with weak digital circularity patterns
Catania	Low	Interest in reuse and local initiatives	Low recycling rates; modest income levels; limited digital skills	DCI reflects systemic weaknesses
Cagliari	Medium	Improving digitalisation; positive recycling trends	Socio-economic variability	Transitional configuration with emerging strengths

This table provides an interpretative overview of the Digital Circularity Index (DCI) for all Italian metropolitan cities. It contextualises differences in scores based on documented digital, environmental, and socio-economic characteristics. The analysis is descriptive and does not imply causal relationships.

Table A2
Pairwise correlations among the three DCI dimensions

Dimension	Digital Adoption	Environmental Performance	Socio-economic Factors
Digital Adoption	1.00	0.18	0.45
Environmental Performance	0.18	1.00	0.22
Socio-economic Factors	0.45	0.22	1.00

References

Acquah, I. S. K., Quaicoe, J., & Gatsi, J. G. (2024). Modelling circular economy capabilities and sustainable manufacturing practices for environmental performance: Assessing linear (PLS-SEM) and non-linear (fsQCA) effects. *Technological Forecasting and Social Change, 205*, Article 123501. https://doi.org/10.1016/j.techfore.2024.123501

Afolabi, J. A. (2025). Advancing the circular economy in Europe: The role of eco-innovation, economic complexity, and digitalization. *Technology in Society, 83*, Article 103027. https://doi.org/10.1016/j.techsoc.2025.103027

Ahmadi, M., Pournaghshband, A., Piadeh, F., & Hosseini, M. R. (2025). Circularity-based embodied carbon performance in building design: Index development and circular initiatives. *Journal of Cleaner Production, 518*, Article 145909. https://doi.org/10.1016/j.jclepro.2025.145909

Al Halbusi, H., Popa, S., Soto-Acosta, P., & Alshallaqi, M. (2025). The nexus of managerial and technical AI knowledge, disruptive innovation and the circular economy: The role of organizational change capability and financial resilience. *Technology in Society*. , Article 102937. https://doi.org/10.1016/j.techsoc.2025.102937

Becker, J.-M., Klein, K., & Wetzels, M. (2012). Hierarchical latent variable models in PLS-SEM: Guidelines for using reflective–formative type models. *Long Range Planning, 45* (5–6), 359–394. https://doi.org/10.1016/j.lrp.2012.10.001

Blackburn, O., Ritala, P., & Keränen, J. (2023). Digital platforms for the circular economy: exploring meta-organizational orchestration mechanisms. *Organ. Environ., 36*, 253–281. https://doi.org/10.1177/10860266221130717.

Bourdin, S., & Jacquet, N. (2025). Closing the loop at the local scale: Investigating the drivers of and barriers to the implementation of the circular economy in cities and regions. *Ecological Economics, 231*, Article 108542. https://doi.org/10.1016/j.ecolecon.2025.108542

Bozeman III, J. F., Chopra, S. S., James, P., Muhammad, S., Cai, H., Tong, K., … Bilec, M. (2023). Three research priorities for just and sustainable urban systems: Now is the time to refocus. *Journal of Industrial Ecology, 27*(2), 382–394. https://doi.org/10.1111/jiec.13360

Calisto Friant, M., Reid, K., Boesler, P., Vermeulen, W. J. V., & Salomone, R. (2023). Sustainable circular cities? Analysing urban circular economy policies in Amsterdam, Glasgow, and Copenhagen. *Local Environment, 28*(10), 1331–1369. https://doi.org/10.1080/13549839.2023.2206643

Carlos, R. L., de Souza, E. B., & Mattos, C. A. (2024). Enhancing circular economy practices through the adoption of digital technologies. *Business Strategy & Development, 7*(1), Article e330. https://doi.org/10.1002/bsd2.330

Chung, L., Tan, K. H., & Yoshie, O. (2025). Sustainable circular economy: Unpacking the unintended consequences of digital transformation in Japanese SMEs. *Technological Forecasting and Social Change, 221*, Article 124335. https://doi.org/10.1016/j.techfore.2025.124335

City of Bologna. (2022). Bologna circular city: Strategies and initiatives for the urban circular transition. https://www.comune.bologna.it.

City of Milan. (2020). Milan digital agenda 2020–2030: Strategies for urban innovation and digital public services. https://www.comune.milano.it.

Cui, X. (2022). A circular urban metabolism (CUM) framework to explore resource use patterns and circularity potential in an urban system. *Journal of Cleaner Production, 359*, Article 132067. https://doi.org/10.1016/j.jclepro.2022.132067

De Pascale, A., Arbolino, R., Szopik-Depczyńska, K., Limosani, M., & Ioppolo, G. (2021). A systematic review for measuring circular economy: The 61 indicators. *Journal of Cleaner Production, 281*, Article 124942. https://doi.org/10.1016/j.jclepro.2020.124942

Di Maio, F., & Rem, P. C. (2015). A robust indicator for promoting circular economy through recycling. *Journal of Environmental Protection, 6*(10), 1095–1104. https://doi.org/10.4236/jep.2015.610096

Feleki, E., Tschapke, V., Borngesser, W., & Kiesel, L. (2025). Transforming urban landscapes: Circular economy practices in European cities. *Circular Economy and Sustainability, 5*, 4945–4956. https://doi.org/10.1007/s43615-025-00674-5

Fernandes, C., Ferreira, J. J., Veiga, P. M., Kraus, S., & Dabić, M. (2022). Digital entrepreneurship platforms: Mapping the field and looking towards a holistic approach. *Technology in Society, 70*, Article 101979. https://doi.org/10.1016/j.techsoc.2022.101979

Ferreira, J. J., & Dabic, M. (2022). Guest editorial. Circular economy and entrepreneurial ecosystems: A missing link? *Management of Environmental Quality: An International Journal, 33*(1), 1–8. https://doi.org/10.1108/MEQ-01-2022-303

Formisano, V., Iannucci, E., Fedele, M., & Bonab, A. B. (2022). City in the loop: Assessing the relationship between circular economy and smart sustainable cities. *Sinergie Italian Journal of Management, 40*(2), 147–168. https://doi.org/10.7433/s118.2022.07

Fosso Wamba, S., Queiroz, M. M., & Trinchera, L. (2024). The role of artificial intelligence-enabled dynamic capability on environmental performance: The mediation effect of a data-driven culture in France and the USA. *International Journal of Production Economics, 268*, Article 109131. https://doi.org/10.1016/j.ijpe.2023.109131

Garrido, S., Rodríguez-Antón, J., Amado, C., Santos, S., & Dias, L. (2023). Development and application of a composite circularity index. *Journal of Environmental Management, 337*, Article 117752. https://doi.org/10.1016/j.jenvman.2023.117752

Georgescu, L. P., Fortea, C., & Antohi, V. (2025). Economic, technological and environmental drivers of the circular economy in the European Union: A panel data analysis. *Environmental Sciences Europe, 37*(76), 1–30. https://doi.org/10.1186/s12302-025-01119-4

Guldmann, E., & Huulgaard, R. D. (2020). Barriers to circular business model innovation: A multiple-case study. *J. Clean. Prod., 243*, 118160. https://doi.org/10.1016/j.jclepro.2019.118160.

Gupta, S., Dwivedi, A., & Kumar, H. (2025). Digital platforms as catalysts of circular economy in pursuit of SDG 11: A rigorous exegesis of smart cities. In *Innovating sustainability through digital circular economy* (pp. 373–390). IGI Global Scientific Publishing. https://doi.org/10.4018/979-8-3373-0578-3.ch017.

Iacovidou, E., & Lovat, E. (2020). Approaches to monitoring and evaluation of resource recovery from waste towards a circular economy. In *The Routledge Handbook of Waste, Resources and the Circular Economy* (pp. 132–141). Routledge.

ISPRA – Italian Institute for Environmental Protection and Research. (2024). *Urban waste report 2024*. Rome: ISPRA. Retrieved from https://www.isprambiente.gov.it.

Jarvis, C. B., MacKenzie, S. B., & Podsakoff, P. M. (2003). A critical review of construct indicators and measurement model misspecification in marketing and consumer research. *Journal of Consumer Research, 30*(2), 199–218. https://doi.org/10.1086/376806

Kennedy, S., & Linnenluecke, M. K. (2022). Circular economy and resilience: A research agenda. *Business Strategy and the Environment, 31*(6), 2754–2765. https://doi.org/10.1002/bse.3004

Khadim, N., Agliata, R., Thaheem, M. J., & Mollo, L. (2023). Whole building circularity indicator: A circular economy assessment framework for promoting circularity and sustainability in buildings and construction. *Building and Environment, 241*, Article 110498. https://doi.org/10.1016/j.buildenv.2023.110498

Kovacic, I., Honic, M., & Sreckovic, M. (2020). Digital platform for circular economy in AEC industry. *Eng. Proj. Organ. J., 9*, 1–16. https://doi.org/10.25219/epoj.2020.00107.

Kurniawan, R. D., Riza, H., Wardhani, S. S. W., Ba'Abdullah, F., & Kusumaningrum, D. (2025). Advancing country-level research benchmarking: A bibliometric multistage principal component analysis based composite index approach. *Journal of Scientometric Research, 14*(1), 16–31. https://doi.org/10.5530/jscires.20251297

Langley, D. J., Rosca, E., Angelopoulos, M., Kamminga, O., & Hooijer, C. (2023). Orchestrating a smart circular economy: Guiding principles for digital product passports. *Journal of Business Research, 169*, Article 114259. https://doi.org/10.1016/j.jbusres.2023.114259

Li, H., Li, Z., & Zhu, P. (2025). Digital platforms as enablers of circular economy practices: Insights from a Chinese province? *Technology in Society*. , Article 103075. https://doi.org/10.1016/j.techsoc.2025.103075

Lozano, R., Bautista-Puig, N., & Barreiro-Gen, M. (2021). Elucidating a holistic and panoptic framework for analysing circular economy. *Business Strategy and the Environment, 30*(4), 1644–1654. https://doi.org/10.1002/bse.2699

Lu, J., Song, Z., Troise, C., & Bresciani, S. (2026). Is circular economy a success factor for electronic waste-management projects? Investigating consumer behavior in the context of crowdfunding. *Business Strategy and the Environment, 35*(1), 415–423. https://doi.org/10.1002/bse.70204

Méndez-Suárez, M. (2021). Marketing mix modeling using PLS-SEM, bootstrapping the model coefficients. *Mathematics, 9*, 1832. https://doi.org/10.3390/math9151832.

Miatto, A., Emami, N., Goodwin, K., West, J., Taskhiri, M. S., Wiedmann, T., & Schandl, H. (2024). Australia's circular economy metrics and indicators. *Journal of Industrial Ecology, 28*(2), 216–231. https://doi.org/10.1111/jiec.13458

Mont, O., Curtis, S. K., & Palgan, Y. V. (2021). Organisational response strategies to COVID-19 in the sharing economy. *Sustain. Prod. Consum., 28*, 52–70. https://doi.org/10.1016/j.spc.2021.03.025.

Moraga, G., Huysveld, S., Mathieux, F., Blengini, G. A., Alaerts, L., Van Acker, K., et al. (2019). Circular economy indicators: What do they measure? *Resour. Conserv. Recycl, 146*, 452–461. https://doi.org/10.1016/j.resconrec.2019.03.045.

Mubarik, M. S., Kontoleon, A., & Shahbaz, M. (2024). Beyond the hurdles: Exploring policy obstacles in the path to circular economy adoption. *Journal of Environmental Management, 370*, Article 122667. https://doi.org/10.1016/j.jenvman.2024.122667

Munonye, W. C. (2025). Towards circular economy metrics: A systematic review. *Circular Economy and Sustainability, 5*, 4093–4135. https://doi.org/10.1007/s43615-025-00604-5

Muñoz, S., Hosseini, M. R., & Crawford, R. H. (2024). Towards a holistic assessment of circular economy strategies: The 9R circularity index. *Sustainable Production and Consumption, 47*, 400–412. https://doi.org/10.1016/j.spc.2024.04.015

Muñoz, E., & Navia, R. (2021). Circular economy in urban systems: How to measure the impact? *Waste-management & Research, 39*(2), 197–198. https://doi.org/10.1177/0734242X21989173

Neri, A., Cagno, E., Susur, E., Urueña, A., Nuur, C., Kumar, V., … Sorrentino, C. (2025). The relationship between digital technologies and the circular economy: A systematic literature review and a research agenda. *R & D Management, 55*(3), 617–713. https://doi.org/10.1111/radm.12715

Nham, N. T. H., & Ha, L. T. (2022). Making the circular economy digital or the digital economy circular? Empirical evidence from the European region. *Technology in Society, 70*, Article 102023. https://doi.org/10.1016/j.techsoc.2022.102023

OECD. (2008). *Handbook on constructing composite indicators: Methodology and user guide*. OECD Publishing.

Oliveira, P. S. P. C., Ferreira, F. A. F., Dabić, M., Ferreira, J. J. M., & Ferreira, N. C. M. Q. F. (2024). Analyzing the causal dynamics of circular-economy drivers in SMES using interpretive structural modeling. *Energy Economics, 138*, 1–12. https://doi.org/10.1016/j.eneco.2024.107842

Olivieri, M., Testa, G., & Giraldi, L. (2026). Communication strategies in hospitality: A study on Michelin green star sustainable restaurants. *Business Strategy and the Environment, 35*(1), 237–250. https://doi.org/10.1002/bse.70184

Pan, X., Yuan, J., Mangla, S. K., Song, M., Siranova, L., & Ferraris, A. (2023). How does circular economy affect firms' innovation performance? The interaction effect of open innovation. *IEEE Transactions on Engineering Management, 71*, 11872–11883. https://doi.org/10.1109/TEM.2023.3321887

Pekdemir, S., Guaralda, M., & Limb, M. (2025). The missing link: Circularity in urban design-a systematic review of circular paradigms for resilient and self-sustaining cities. *Cities, 162*, Article 106007. https://doi.org/10.1016/j.cities.2025.106007

Perotti, F. A., Dhir, A., Ferraris, A., & Kliestik, T. (2024). Investigating digital technologies' implementation in circular businesses: Evidence from the going circular path. *Journal of Management and Organization, 30*(3), 421–451. https://doi.org/10.1017/jmo.2023.60

Ranjbari, M., Shams Esfandabadi, Z., Siebers, P.-O., Pisano, P., & Quatraro, F. (2024). Digitally enabled food sharing platforms towards effective waste-management in a circular economy: A system dynamics simulation model. *Technovation, 130*, Article 102939. https://doi.org/10.1016/j.technovation.2023.102939

Ritala, P., & Keränen, J. (2023). Digital platforms for the circular economy: Exploring meta-organizational orchestration mechanisms. *Organization & Environment, 36*, 253–281. https://doi.org/10.1177/10860266221130717

Rossi, L. A., & Srai, J. S. (2025). The role of digital technologies in configuring circular ecosystems. *International Journal of Operations & Production Management, 45*(4), 863–894. https://doi.org/10.1108/IJOPM-12-2023-0973

Sarstedt, M., Ringle, C. M., & Hair, J. F. (2014). Partial least squares structural equation modeling (PLS-SEM): A useful tool for family business researchers. *Journal of Family Business Strategy, 5*(1), 105–115. https://doi.org/10.1016/j.jfbs.2014.01.002

Shela, V., Ramayah, T., Aravindan, K. L., Ahmad, N. H., & Alzahrani, A. I. (2023). Run! this road has no ending! A systematic review of PLS-SEM application in strategic management research among developing nations. *Heliyon, 9*(12), Article e22476. https://doi.org/10.1016/j.heliyon.2023.e22476

Singhvi, A., Athanassiadis, A., & Binder, C. R. (2025). *Configurations for circularity? A scoping review of urban planning approaches in the circular economy literature* (pp. 1–21). Urban Research & Practice. https://doi.org/10.1080/17535069.2025.2465961

Švarc, J., Dabić, M., & Lažnjak, J. (2022). Assessment of the European monitoring frameworks for circular economy: The case of Croatia. *Management of Environmental Quality: An International Journal, 33*(2), 371–389. https://doi.org/10.1108/MEQ-07-2021-0170

Tian, S., Sharma, A., Wu, L., & Pawar, K. S. (2024). A systematic literature review on the digital platform and its role in the circular economy: State-of-the-art and future research directions. *Journal of Digital Economy, 3*, 132–145. https://doi.org/10.1016/j.jdec.2024.12.001

Toboso-Chavero, S., de Jong, M., Schraven, D., & Zisopoulos, F. K. (2025). Urban circular economy initiatives: Development and application of a unified theoretical framework. *Cities, 167*, Article 106371. https://doi.org/10.1016/j.cities.2025.106371

Vanderhorst, H. R., Heesom, D., & Yenneti, K. (2024). Technological advancements and the vision of a meta smart twin city. *Technology in Society, 79*, Article 102731. https://doi.org/10.1016/j.techsoc.2024.102731

Vanhuyse, F. (2024). The urban circularity assessment framework (UCAF): A framework for planning, monitoring, evaluation, and learning from CE transitions in cities. *Circular Economy and Sustainability, 4*(2), 1069–1092. https://doi.org/10.1007/s43615-023-00314-w

Wu, K. J., Hou, W., Wang, Q., Yu, R., & Tseng, M. L. (2022). Assessing city's performance-resource improvement in China: A sustainable circular economy framework approach. *Environmental Impact Assessment Review, 96*, Article 106833. https://doi.org/10.1016/j.eiar.2022.106833

Yu, J., Khattak, S. I., & Ahmad, M. (2025). Enhancing sustainable development through digital economy and natural resource management in one belt one road countries. *Technology in Society, 81*, Article 102812. https://doi.org/10.1016/j.techsoc.2025.102812