Journal of Cleaner Production 315 (2021) 128070

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

Unraveling how the concept of circularity relates to sustainability: An indicator-based meta-analysis applied at the urban scale

V. Superti [a,*], A. Merino-Saum [a], I. Baur [b], C.R. Binder [a]

[a] Laboratory on Human-Environment Relations in Urban Systems (HERUS), École Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland
[b] Agricultural Department, Canton of Glarus, Switzerland

ARTICLE INFO

Handling editor: Kathleen Aviso

Keywords:
Circular economy
Urban sustainability
Indicators
SDGs
Cluster analysis

ABSTRACT

Cities account for 75% of resource consumption and 80% of CO_2 emissions. With rising urbanization, achieving urban sustainability becomes crucial. The Circular Economy (CE) concept has been proposed to reduce resource consumption, although its link to sustainability remains unclear from theoretical and practical perspectives. This paper provides an in-depth comparative analysis of 57 indicator sets used in academia or practice to measure either CE in urban areas or urban sustainability. Indicators were extracted and categorized according to three conceptual frameworks, namely: the STEEP categories, the Sustainable Development Goals, and inductively-created thematic groups. The similarities among the 57 sets were analyzed to derive clusters. Results show that CE represents a subset of urban sustainability, while offering more indicators to assess specific thematic groups (e.g., waste). In the discussion, the value added by targeting a CE rather than sustainability is questioned, and insights are provided to support actors involved in an urban transition to develop well-informed city targets. The results offer theoretical, practical, and methodological contributions, and aid involved actors, especially those leading urban transition agendas, to unravel the conceptual link between CE and sustainability, specifically at the urban scale.

1. Introduction: cities and their transition to sustainability

Over the last century, urban populations have increased considerably, exacerbating the pressure on the natural environment (World Economic Forum, 2018). Between 1900 and 2018, the population living in urban areas increased from 14% to 55%, with forecasts projecting a rise to 68% by 2050 (UN, 2019). This greater urbanization has been accompanied by increased resource consumption, global CO_2 emissions, and waste generation. Forecasts predict that from 2012 to 2025, the latter will almost double from 1.3 to 2.2 billion tons (Kaza et al., 2018). If responsible and equitable resource management for the current and the future generations is considered a target worth pursuing, these unsustainable production and consumption practices require urgent change. As cities are seen as the engine of global change and the cradles for experimentation and innovation (Jacobs, 2016; Soja, 2003), implementing solutions at the local scale may represent a promising pathway for a broader transition towards a sustainable society.

In recent years, various concepts linked to cities and sustainability have emerged: green, smart, and circular cities have been planned, studied, and assessed worldwide. Notably, the notion of a circular city stems from the Circular Economy (CE) concept, which aims to reduce resource consumption, i.e., using resources more efficiently through value-retention processes and waste minimization (EMF, 2013). As CE is viewed as an alternative to a traditional take-make-dispose linear economy, it has increasingly received attention in the movement towards sustainability (Hanumante et al., 2019; Rossi et al., 2020). However, the interconnectedness between CE and sustainability, the ways in which CE contributes to achieving sustainability, and whether these two concepts might support or hinder one another have not yet been entirely clarified (Schröder et al., 2019b). Notably, while the role of cities in promoting sustainability transitions has long been of interest, the development of an understanding of the interrelationships between urban sustainability and circular urban areas has received relatively little attention (Fratini et al., 2019).

When a city is targeting a CE, several steps should be taken into account (Paiho et al., 2020): setting forth a definition of what circularity means, specifying the pathways to be followed in the transition, defining which targets to reach, choosing which indicators to use, deciding on the concrete means while taking into account regulations, enabling services of support, and interacting and engaging with stakeholders. Hence, a

* Corresponding author.
E-mail address: Valeria.superti@epfl.ch (V. Superti).

https://doi.org/10.1016/j.jclepro.2021.128070
Received 17 February 2021; Received in revised form 3 May 2021; Accepted 21 June 2021
Available online 24 June 2021

critical reflection of what a CE in a city entails is pivotal for collecting target knowledge (Wuelser et al., 2012) and defining a vision, a first step in planning a CE transition (World Economic Forum, 2018).

An assumption that cities should challenge is, for example, whether a transition towards a CE would inherently lead to sustainability and, if not, how to make this happen. In this regard, academic research can support practitioners by systematically analyzing different approaches, perspectives, and practices. To date, the majority of the studies aimed at comparing CE to sustainability have focused on practices and policies (Calisto Friant et al., 2021; Schröder et al., 2019a). Further in-depth research to generate more empirical evidence on the links between CE and related concepts such as sustainability is needed (Henry et al., 2021; Schröder et al., 2019a). Such a contribution would not only bring theoretical insights to the field, but it could also support practitioners by orientating them towards more aligned management of resources (both tangible and intangible) within the overall scope of reducing inefficiencies, avoiding conflicting targets, and enhancing concerted efforts (Kennedy et al., 2011).

A recent report from the Organisation for Economic Co-operation and Development (OECD, 2020) highlighted that cities transitioning towards a CE show gaps in five main categories of enabling factors: funding, regulatory, awareness, capacity, and policy. Concerning the latter (a lack of a holistic vision from policymakers), it is increasingly difficult for city policymakers to relate to the ambiguous relationship between the concepts of circular and sustainable cities (Prendeville et al., 2018), since the concepts are often used interchangeably in the same context. It is not rare that city policymakers embed CE plans into larger sustainability plans; this observation suggests a connection between circularity and sustainability but does not sufficiently elucidate the nature of this relation. Therefore, the concept of a circular city needs critical reflection. This inquiry should result in interpretable insights aimed at better guiding and supporting actors, offering actionable knowledge and suitable tools (Kirchherr, 2019).

Based on the considerations presented in the previous sections, two main research gaps were identified.

- First, the concept of a CE, especially applied at the urban scale, has been interpreted in several ways. Further research is needed to understand this conceptual ambiguity and to support urban agents of change in their journey through a CE/sustainability transition. To fill this gap, this paper aims to provide a comprehensive meta-analysis of CE indicator sets used at the macro (city) level, to shed light on how the concept of a CE in urban areas has been operationalized. The term "operationalization" refers to the act of turning abstract concepts into measurable observations. Indicators represent the focus of the study since they are the tools used to measure progress towards circularity and because, to be operational, their number in an indicator set can only be limited, thus mirroring what is deemed to be relevant in assessing circularity.
- Second, the conceptual links between CE and sustainability have mainly been discussed at a theoretical level, based on qualitative arguments and neglecting a quantitative, evidence-based analysis of how these two concepts are interrelated at the urban level. Therefore, the meta-analysis aims to contribute to the development of a scientific understanding of the two selected concepts, clarifying what counts for each of them, and how important this is in their respective overall representations. The goal is to unpack these two concepts and highlight differences and overlaps, in order to support practitioners in making informed decisions for establishing the transition targets of their cities. Urban agents of change might find helpful elements here to understand whether CE and sustainability should be interpreted as similar, alternative, or complementary concepts.

This paper is structured as follows. Section 2 provides the theoretical background. Section 3 presents the research design and methodology applied. Section 4 reports the results. Section 5 discusses the main findings and limitations of the study, together with suggestions for future research. Finally, Section 6 presents the conclusions.

2. Conceptual background

The concepts of sustainability, sustainable development, and, specifically, urban sustainability have established themselves within both the socio-political and academic spheres (Caprotti et al., 2017; Castán Broto, 2017). Scientific approaches specifically targeting urban sustainability have proliferated since the 1990s (Alberti, 1996; Maclaren, 1996). Despite such recognition, ambiguity is still linked to the concepts introduced above (Huang et al., 2015; Merino-Saum et al., 2020). An increasing perception that the concepts are too vague to be implemented and are beginning to lose momentum could motivate why other approaches, as the CE one, are receiving increasing consideration (Kirchherr et al., 2017). Viewed as an alternative to a traditional take-make-dispose linear economy (Reike et al., 2018), CE has received growing attention amidst attempts to operationalize and achieve sustainability (Ghisellini et al., 2016; Kirchherr et al., 2017; Rossi et al., 2020). In the following sub-sections, different related notions are introduced (i.e., the link between CE and sustainability and the assessment of CE through indicators), which represent the basis of the methodology presented in Section 3.

2.1. Introducing the link between circular economy and sustainability

In order to advance the discussion on the CE, two main steps need to be taken. First, a shared understanding and common language would be beneficial (Blomsma and Brennan, 2017; Bocken et al., 2017), challenging the complexity and trade-offs that this popular concept involves. For a general understanding, one of the most cited definitions of CE is reported, the meta-definition by Kirchherr et al. (2017, p.224): "*circular economy describes an economic system that is based on business models which replace the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes, thus operating at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond), with the aim to accomplish sustainable development, which implies creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations*". However, multiple definitions of a CE currently exist, implying many interpretations and vast room for implementing divergent interventions (Blomsma and Brennan, 2017; Kirchherr et al., 2017). Second, it would be equally important to link the CE concept to related ideas, such as sustainability (Blomsma and Brennan, 2017). Understanding if the pursuit of circular targets is moving the system closer or further away from sustainability is pivotal in untangling conflictual or synergic goals, finding common ground between policies, and aligning efforts towards a sustainable system. Knowledge linked to the relationship, similarities, and differences between these two concepts is key for "*conceptual clarity, as well as to reveal the interests and goals behind the use of these terms by policymakers and companies*" (Geissdoerfer et al., 2017, p760). Authors still debate whether current interpretations of a CE are indeed in line with creating societal and environmental benefits, and therefore if a CE is inherently

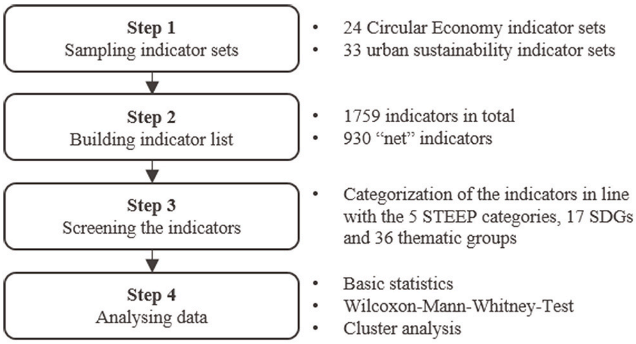

Fig. 1. Steps of the research.

sustainable, independently of the scale used for the analysis.

2.2. CE at the macro level

Research and practice on the CE focus on different levels of analysis: micro (single company or consumers), meso (symbiosis or industrial associations), and macro (city, province, region, country) (Ghisellini et al., 2016). Research at the macro-level is key to understanding system interactions and to refining a systemic approach. A systemic shift is indeed what many researchers call for, in order to enable a CE transition (Kirchherr et al., 2017). In this regard, urban settings are believed to offer the testbeds needed in order to understand how to align resource flows and actor constellations across different system domains (Frantzeskaki et al., 2017). This level of analysis can be justified by the role of cities as ideal testing grounds for CE models (World Economic Forum, 2018), as more than 80% of the global GDP is generated in cities. In the wide literature on CE, the question of how CE is applied in urban contexts is increasingly being posed (Prendeville et al., 2018). However, in spite of the numerous efforts made, barriers to the implementation of a CE still exist, and include: cultural, regulatory, financial, technological (OECD, 2020), and of course, the issue of finding an efficient and pertinent way to track progress and allow for benchmarks and comparisons.

2.3. CE indicators

The question of how to measure a CE is rapidly evolving in the literature (Di Maio et al., 2017; Jacobi et al., 2018). Several authors highlight the importance of having well-designed and effective indicators for measuring and monitoring progress towards CE (Di Maio and Rem, 2015; Genovese et al., 2017; Pauliuk, 2018). As CE operates on three systemic levels (i.e., micro, meso, macro), the tools and indicators for measuring CE differ depending on the level of application (Su et al., 2013). In the supplementary material (Table S.1) an overview of the latest research on CE indicators is presented. This is not meant to be an exhaustive literature review, but rather an introduction to the most relevant streams of current research on the topic.

Overall, previous studies on CE indicators have paid attention to the three systemic levels typically mentioned in the literature. Some of the reviewed studies have compared available tools used to measure specific aspects of CE, and some have suggested new metrics that could improve this process. To the best of the authors' knowledge, no comprehensive analysis exists on macro-level indicators for CE, which focuses on the measurement approach, its alignment with sustainability dimensions, and involves a comparison with urban sustainability indicators. In section 2.4, the specific approach applied is elaborated, notably the use of indicators for the assessment and the comparison of concepts.

2.4. Using indicators for the assessment and the comparison of concepts

Merino-Saum et al. (2020, p.2) provide an extensive discussion on the concept of an indicator and its role in sustainability assessment. As explained by the authors, "*indicators are multifaceted constructs ideally composed of the following interrelated elements: […] a label, […] a unit of measurement, […] a definition, […] accessible data, […] a reference point […] and an anchoring in the conceptual framework*". Indicators have been used for multiple goals: support for decision-making management, advocacy and communication, participation and consensus-building, and for research and analysis (Morse, 2015; Parris and Kates, 2003). The most predominant use of indicators has been as data providers of the variable taken into consideration. However, indicators can also play a role as "information" or "message carriers" (Lehtonen et al., 2016), communicating arguments, ideas and expectations of the developers of the assessment tool (Merino-Saum et al., 2018). In this paper, indicators are interpreted as pieces of a puzzle that, viewed together, mirror the conceptualization of the very concept that they are measuring.

When using indicators as conceptual elements, different frameworks or lenses can be applied to elucidate the key components and features that constitute a particular concept. In this regard, no lens can be used as a one-size-fits-all tool suitable for every context. Indeed, indicators can be categorized and systematically analyzed through diverse logics (e.g., thematic, teleological, systemic) and through either deductive or inductive approaches (see: Halla and Merino-Saum, Forthcoming). Furthermore, multiple potential frameworks exist for each logic, thereby leading to a multitude of potential combinations for the analysis. Three conceptual frameworks were selected to employ in the analysis of CE and sustainability indicators: the STEEP framework, the Sustainable Development Goals (SDGs), and inductively-created thematic groups. This choice was based on the following criteria: (i) utilizing frameworks with different descriptive levels (or granularities), therefore allowing for interpretation at multiple degrees of detail; (ii) combining deductive and inductive approaches as a way to warrant comparability with analogous studies, while remaining sample-specific; (iii) mixing frameworks that stem from both academia and policy practice, in order to reach and to resonate with a larger audience. More information about the first two frameworks is available in the supplementary material (S.2). In the paragraph below, we elaborate on the choice of using inductively -created thematic groups.

To categorize indicators, some scholars suggest that an inductive approach avoids the risk of restricting *a priori* the perspective over the data under study, which could leave some elements unrecognized (Parchomenko et al., 2019). Although self-made categories might bring subjectivity, this is a common approach used in many comparable research projects (Feleki et al., 2020; Kaur and Garg, 2019). For example, Parchomenko et al. (2019) applied the method of Multiple Correspondence Analysis to an assessment of 63 CE metrics and 24 features relevant to CE, such as recycling efficiency, longevity, and stock availability. Elia et al. (2017) proposed a taxonomy based on the parameter(s) to be measured using indicators, introducing four categories: material and energy flow, land use and consumption, and other life-cycle-based categories. Finally, the OECD (2020) *Inventory of CE Indicators* collected more than 400 indicators, classifying them into five categories (Environment, Governance, Economic and business, Infrastructure and technology, Social), 33 sub-categories, and 11 sectors. In the present paper, a list of 36 thematic groups was inductively developed, based on the indicators collected from the sample (see Section 3.3 for further details).

3. Materials and methods

The research was performed in four main steps, as depicted in Fig. 1.

3.1. Step 1: sampling indicator sets

In order to obtain indicator sets that are used to assess CE at the urban scale, the Scopus database was used. A research was performed using the Google's search engine, adapting the research keywords in English, French, Spanish and Italian. The keywords used in google.com and Scopus were ("circular*" AND ("indicator*") AND ("urban" OR "city"). The search was performed in June 2020. Moreover, a snowball approach was used, asking organizations whose reports were found online whether they were aware of other frameworks at the urban level. For inclusion of an indicator set in the final sample, the following criteria were applied: the framework clearly states that it measures the circularity of an urban area; the indicators are available (listed in the reference documents); the set of indicators cover several areas/city functions (not only transport or energy, for example); the set was last updated between 2005 and 2020. This process led to a sample of 24 indicator sets.

The indicator sets dealing with urban sustainability were imported from Merino-Saum et al. (2020). For an extensive explanation of the literature search, the interested reader is invited to refer to the original paper. Additional exclusion criteria were applied to the urban sustainability sample, to generate a sample comparable to the one obtained for CE indicator sets. Specifically, only those indicator sets with the same geographical focus as the CE indicators sets sample were retained, to allow for better-informed comparisons. In practical terms, a list was compiled of all of the countries of the cities for which the CE indicator sets were developed. This list was then used to retain indicator sets coming from the urban sustainability sample. The complete list of indicator sets is available in the supplementary material (Table S.3). In Table 1, an overview of the final sample is provided.

3.2. Step 2: compiling the indicator list

Indicators were extracted from the retrieved sets, yielding 1759 indicators. Out of these, 535 come from the CE indicator sets and 1224 from the urban sustainability indicator sets. Indicators measuring exactly the same variable, potentially with a slightly different label/ definition, were registered as only one indicator. This approach highlighted doubles in the initial catalog (see: Merino-Saum et al., 2018). Thus, from a "gross" list made of 1759 entries, a final "net" catalog including 930 indicators was obtained.

3.3. Step 3: screening the indicators

An increasing level of detail guided the screening of the indicators. First, the sets in which each of the 930 (net) indicators was present were reported. Deductive and inductive analytical grids (typologies) were purposely combined to increase comprehensiveness and methodological pluralism while keeping subjectivity at an acceptable level. As illustrated in Fig. 2, the analysis moved from a more abstract level to a more detailed one; in other words, the process started with the typology including the smallest number of categories (STEEP) and progressively moved towards those involving a higher level of details, i.e., the SDGs and thematic groups. Regarding the intermediary level of description (i.e., the SDGs framework) and its role in the overall methodological approach, its deductive application to our sample allowed us to identify potential gaps that would have otherwise remained hidden if only the list of thematic (inductively created) groups was used. The thematic list

Table 1
Description of the sample.

Set group	N	Average # of indicators (min - max)
Circular Economy	24	22 (8–39)
Urban sustainability	33	36 (8–103)

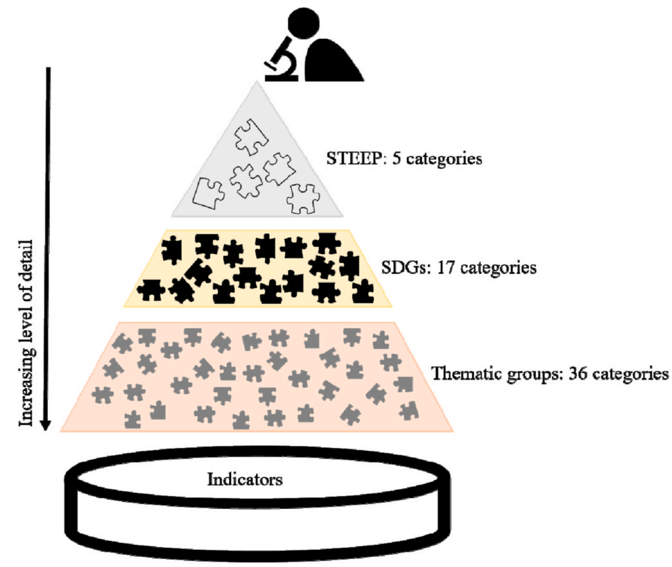

Fig. 2. The screening of indicators was performed using three different typologies as analytical grids to characterize the 930 indicators.

was developed in accordance with an iterative procedure. The research team created several preliminary lists that were tested with the indicators from the sample and subsequently revised until a consensual, consistent (i.e., avoiding overlaps) and balanced (i.e., simple but not simplistic) list was reached. The 36 thematic groups included in the final list should be understood as umbrella concepts that are distinct enough from each other to allow subsequent analysis. Indeed, within each thematic group, multiple interrelated ideas are embedded, which as a whole, convey an easily understandable and united signification. The list of all of the categories within each framework is reported in Table 2. In the assessment of the link between indicators, STEEP categories, SDGs, and thematic groups, each indicator could be linked to only one thematic group, but to multiple STEEP and SDG categories, as those categories pertaining to the latter two frameworks are not necessarily mutually exclusive.

3.4. Step 4: statistical analysis

First, the focus was set on the number of indicators that the two groups had in common. It was recorded whether the indicators were used by at least one CE or urban sustainability indicator set. It was then calculated how many indicators were only derived from the list compiled with the CE indicator sets, and what the overlap was with the list of indicators used by the urban sustainability indicator sets. The same analysis was replicated at the thematic groups' level. The thematic groups that were assessed by the majority of CE sets were identified, as well as those that were assessed by the majority of urban sustainability sets. Percentage thresholds were used to identify different groups of thematic groups (i.e., core, periferic) based on how frequently they were included in the indicator sets.

To compare the two groups (urban sustainability and CE), the coverage of each category of the three typologies was calculated by dividing the number of indicators linked to that specific category by the total number of indicators of the set analyzed. Since most of the distributions of the variables were non-normal, the non-parametric Two-sample Wilcoxon rank-sum (Mann-Whitney) test was performed. The numerical results of the tests are reported in the supplementary material (S.4, S.5, and S.6). The statistical analysis was performed with STATA 16.1.

Finally, three hierarchical cluster analyses (HCA) of the indicator sets were performed based on their coverage of the STEEP categories, the SDGs, and the thematic groups. HCA is a technique used to classify

Table 2
List of the STEEP categories, the SDGs, and the thematic groups used in this analysis. Between brackets, the number of indicators of the combined sample related to each category. Thematic groups are listed in alphabetic order.

STEEP	SDGs	Thematic groups
Social (560)	SDG1 No poverty (76)	Air pollution (32)
Technological (231)	SDG2 Zero hunger (31)	Biodiversity (12)
Economic (250)	SDG3 Good health and well-being (108)	Businesses (8)
Environmental (523)	SDG4 Quality education (70)	Communication & Connectivity (5)
Political (83)	SDG5 Gender equality (21)	Demographics (15)
	SDG6 Clean water and sanitation (70)	Disaster vulnerability (8)
	SDG7 Affordable and clean energy (62)	Education & Culture (47)
	SDG8 Decent work and economic growth (170)	Employment (25)
	SDG9 Industry, innovation and infrastructure (169)	(Conventional) Energy (31)
	SDG10 Reduced inequalities (44)	(Renewable) Energy (22)
	SDG11 Sustainable cities and communities (313)	GDP & Added value (18)
	SDG12 Responsible consumption and production (291)	Green House Gases (GHG) (13)
	SDG13 Climate action (42)	Health & Wellbeing (50)
	SDG14 Life below water (37)	Housing (40)
	SDG15 Life on land (63)	Income/poverty (29)
	SDG16 Peace, justice and strong institutions (68)	Inequalities (37)
	SDG17 Partnerships for the goals (33)	Land and soil use (17)
		Leisure & Urban infrastructure (34)
		Local products (9)
		Material resources consumption (51)
		Participation/engagement (17)
		Personal safety (9)
		Public finances (12)
		Research & Development (5)
		Role in global networks (11)
		Sustainability/circularity awareness (15)
		Sustainable/circular initiative (70)
		Sustainable/circular labels & R&D (13)
		Tourism (7)
		(Conventional) Transport (26)
		(Sustainable) Transport (42)
		Trust in authorities (12)
		Urban Green/blue areas &urban ecosystems (35)
		Urban planning (21)
		Waste production and management (82)
		Water (50)

items according to factors (cluster variates) and separate them into groups (clusters). In the present case, individual indicator sets were the items, and the values of coverage of the three typologies (STEEP, SDGs, thematic groups) were the cluster variates. Since cluster analysis is influenced by the type of cluster variates used (Pastor and Erbacher, 2019), three independent analyses were performed to produce insights from different approaches and triangulate them. The hypothesis was that two main clusters could be identified: one containing only CE indicator sets, and one containing only urban sustainability indicator sets. This finding would mirror the fact that consistency exists in how the parameters are covered by the indicator sets belonging to each of the two groups. The consistency of the assessment was elicited *a posteriori,* identifying the location of each indicator set in the resulting dendrogram. For the statistical analysis, STATA 16.1 was used, applying Ward's linkage and L2 dissimilarity measure.

4. Results

This chapter presents the research findings, following the order presented in the methodology: from the identification of shared or unique indicators, to the comparison between CE and urban sustainability indicator sets, and finally to the cluster analyses. An extended discussion of these results is provided in Section 5.

4.1. Identifying common and specific indicators in CE and urban sustainability measurement initiatives

Of the 930 indicators compiled from the sample, only 86 (~9%) were used to measure both CE and urban sustainability concepts (i.e., they are present in at least one CE indicator set and at least one urban sustainability indicator set). In contrast, 281 (~30%) indicators are unique to the CE group, and 563 (~60%) are unique to the group of urban sustainability. In Appendix A, the top 5% indicators used in CE sets (panel *a*) and urban sustainability (panel *b*) are reported. Some of the most common indicators present in both groups are CO_2eq emissions, municipal solid waste generated, and the percentage of municipal waste recycled.

4.2. Comparing the groups in terms of coverage of the STEEP categories

Fig. 3 depicts the coverage of the STEEP categories by the two groups of indicator sets. The CE indicator sets clearly cover the Environmental category extensively. The results of the Mann-Whitney test indicate that only the values for the Social and Environmental categories are

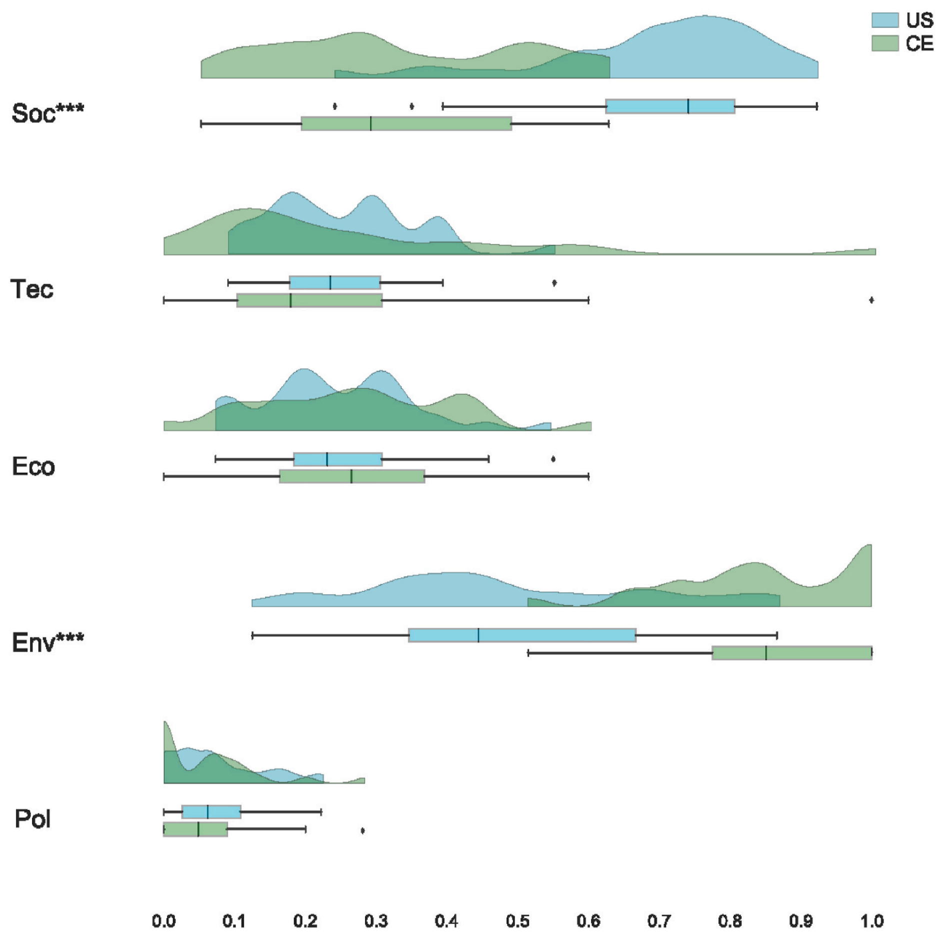

Fig. 3. Raincloud plots and boxplots showing the distribution of coverage of the 5 STEEP categories by CE indicator sets (in green) and urban sustainability indicator sets (in blue). The asterisks show the significant differences, based on the Mann Whitney test (Significance levels *: $p < 0.05$; **: $p < 0.01$; ***: $p < 0.001$). Raincloud plots after Allen et al., 2019..

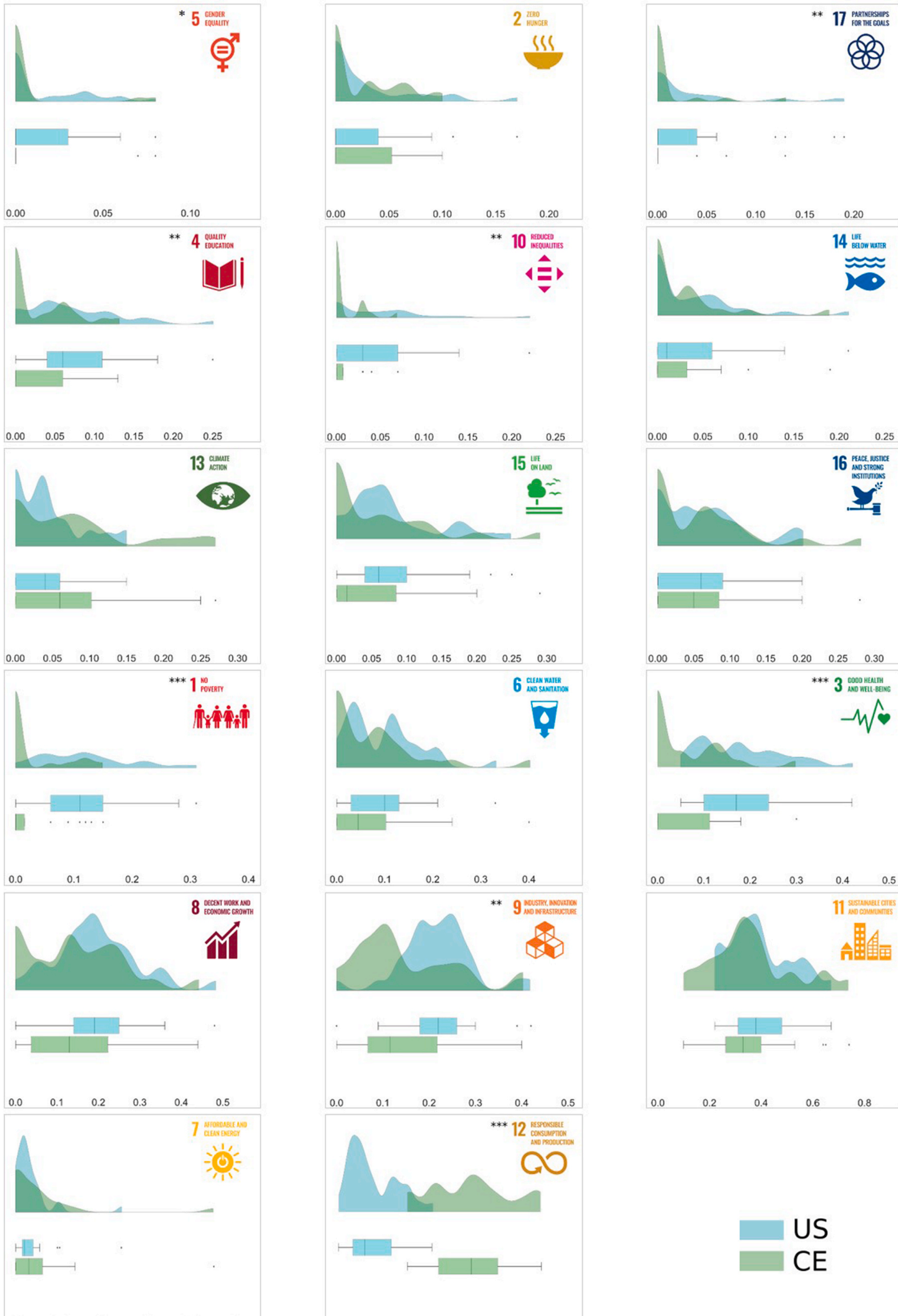

Fig. 4. Raincloud plots and boxplots of SDG coverages. X-axis: coverage of the SDGs (proportion of indicators in each set) by CE indicator sets and urban sustainability (US) indicator sets. Significant difference levels based on the Mann-Whitney test *: p < 0.05; **: p < 0.01; ***: p < 0.001). Graphs are ordered horizontally according to the overall coverage of the SDGs (smallest to biggest), which is reflected by the adjusted x-axis. This allows to see even the very narrow distributions of the coverage of some SDGs. Raincloud plots after Allen et al. (2019).

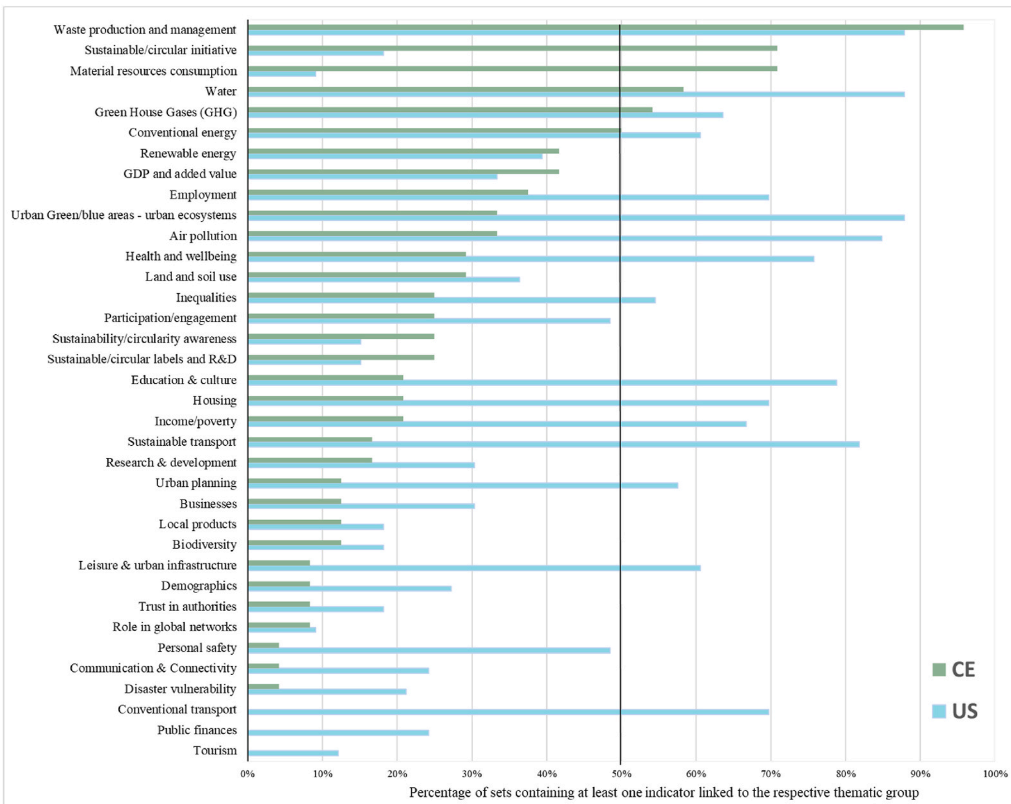

Fig. 5. Percentage of indicator sets that contains at least one indicator covering a specific thematic group. The black vertical bar represents a 50% threshold.

Table 3
Results of the Two- sample Wilcoxon rank-sum (Mann-Whitney) test. The test compares the coverage of thematic groups between the two groups of indicator sets (CE and urban sustainability (US)). For all variables, N(CE) = 24 and N(US) = 33. Values reported are means, medians, standard deviation, z value, significance level (*: $p < 0.05$; **: $p < 0.01$; ***:$p < 0.001$), and small size effect coefficient $\hat{p}_{US,CE}$. Effect size coefficient $\hat{p}_{US,CE} = U/(n_{US}n_{CE})$ (Grissom and Kim, 2012).

Thematic group	Mean CE	Mean US	Mdn CE	Mdn US	Sd CE	Sd US	z	p	$\hat{p}_{US,CE}$
Air pollution	0.03	0.07	0.00	0.05	0.05	0.06	−3.441	<.001***	0.24
Biodiversity	0.00	0.01	0.00	0.00	0.01	0.01	−0.497	.772	0.48
Businesses	0.01	0.01	0.00	0.00	0.02	0.02	−1.408	.188	0.42
Communication & Connectivity	0.00	0.01	0.00	0.00	0.01	0.02	−1.974	.074	0.40
Demographics	0.01	0.01	0.00	0.00	0.02	0.03	−1.703	.116	0.41
Disaster vulnerability	0.00	0.01	0.00	0.00	0.01	0.02	−1.806	.094	0.41
Education & culture	0.01	0.06	0.00	0.06	0.02	0.06	−4.202	<.001***	0.19
Employment	0.02	0.04	0.00	0.04	0.03	0.03	−2.001	<.05*	0.35
(Conventional) Energy	0.06	0.04	0.02	0.03	0.13	0.06	−0.330	.748	0.48
(Renewable) Energy	0.04	0.02	0.00	0.00	0.07	0.03	0.401	.691	0.47
GDP & Added value	0.02	0.02	0.00	0.00	0.03	0.04	0.552	.585	0.46
Green House Gases (GHG)	0.03	0.03	0.03	0.02	0.03	0.03	−0.176	.865	0.49
Health & Wellbeing	0.02	0.06	0.00	0.06	0.03	0.06	−3.318	<.001***	0.25
Housing	0.01	0.04	0.00	0.03	0.02	0.04	−3.511	<.001***	0.24
Income/poverty	0.02	0.05	0.00	0.04	0.04	0.05	−3.141	<.01**	0.27
Inequalities	0.01	0.04	0.00	0.03	0.02	0.05	−2.588	<.01**	0.32
Land and soil use	0.02	0.01	0.00	0.00	0.04	0.03	−0.106	.923	0.49
Leisure & Urban infrastructure	0.01	0.04	0.00	0.03	0.02	0.05	−3.836	<.001***	0.24
Local products	0.01	0.01	0.00	0.00	0.02	0.02	−0.548	.660	0.47
Material resources consumption	0.12	0.00	0.11	0.00	0.11	0.01	5.063	<.001***	0.16
Participation/engagement	0.01	0.02	0.00	0.00	0.02	0.03	−1.588	.112	0.39
Personal safety	0.00	0.03	0.00	0.00	0.01	0.03	−3.619	<.001***	0.27
Public finances	0.00	0.01	0.00	0.00	0.00	0.04	−2.570	<.05*	0.38
Research & Development	0.01	0.01	0.00	0.00	0.03	0.02	−0.910	.380	0.45
Role in global networks	0.00	0.01	0.00	0.00	0.01	0.02	−0.082	.999	0.50
Sustainability/circularity awareness	0.02	0.01	0.00	0.00	0.03	0.01	1.256	.207	0.43
Sustainable/circular initiative	0.15	0.01	0.1	0.00	0.15	0.02	4.626	<.001***	0.18
Sustainable/circular labels & R&D	0.02	0.01	0.00	0.00	0.04	0.02	1.126	.224	0.44
Tourism	0.00	0.01	0.00	0.00	0.00	0.02	−1.752	.207	0.44
(Conventional) Transport	0.00	0.04	0.00	0.04	0.00	0.03	−5.036	<.001***	0.15
(Sustainable) transport	0.02	0.06	0.00	0.06	0.07	0.05	−4.329	<.001***	0.18
Trust in authorities	0.00	0.01	0.00	0.00	0.01	0.02	−0.977	.445	0.45
Urban Green/blue areas & Urban ecosystems	0.03	0.06	0.00	0.05	0.06	0.04	−2.790	<.01**	0.29
Urban planning	0.01	0.03	0.00	0.03	0.02	0.04	−3.288	<.001***	0.28
Waste production and management	0.25	0.06	0.20	0.04	0.17	0.05	5.196	<.001***	0.10
Water	0.07	0.08	0.03	0.07	0.10	0.07	−1.551	.122	0.38

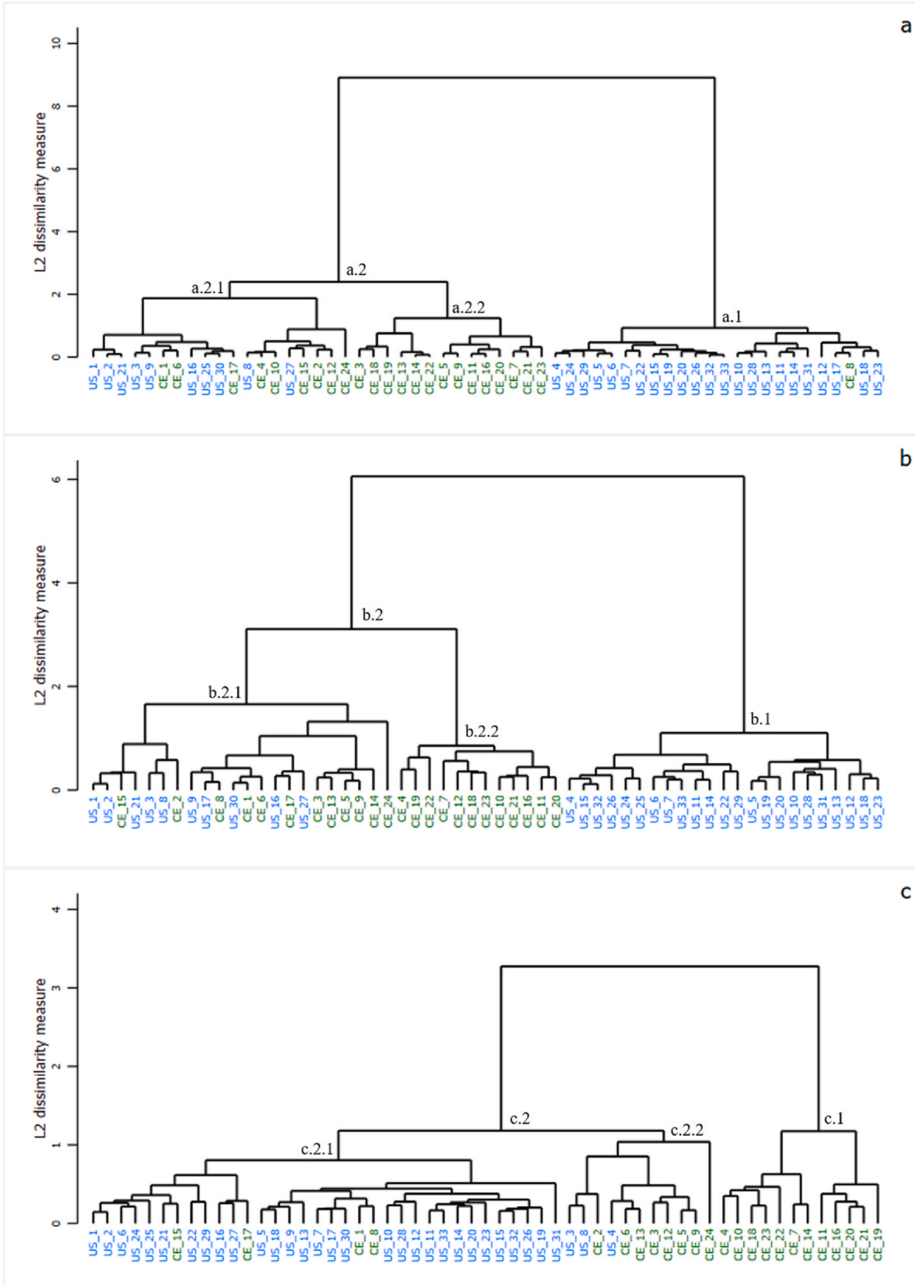

Fig. 6. Cluster analysis based on the coverage by CE and urban sustainability indicator set of the STEEP categories (a), the SDGs (b) and the thematic groups (c). The sets measuring urban sustainability are labeled "US_#" (in blue). Those measuring Circular Economy in urban areas are labeled "CE_#" (in green).

significantly different. Indeed, in comparison to the urban sustainability indicator sets, the CE indicator sets cover the Environmental dimension significantly more, while they cover the Social dimension significantly less. In terms of coverage of Technological, Economic, and Political categories, the two groups do not show significant differences.

4.3. Comparing the groups in terms of coverage of the SDGs

Fig. 4 shows the coverage of the SDGs by the CE and urban sustainability indicator sets. There is no significant difference between the coverages of CE and urban sustainability indicator sets for ten of the SDGs. The coverages of SDG1 *No poverty*, SDG3 *Good health and well-being*, SDG4 *Quality education*, SDG5 *Gender equality*, SDG9 *Industry, innovation and infrastructure*, SDG10 *Reduced inequalities*, SDG12 *Responsible consumption and production*, SDG17 P*artnerships for the goals*, appear to be significantly different between the two indicator sets groups. Among these cases, only SDG12 *Responsible production and consumption* is covered more by CE indicator sets.

4.4. Comparing the groups in terms of coverage of the 36 thematic groups

The results show that CE indicator sets do not cover three of the 36 thematic groups (Tourism, Conventional transport, and Public finances; see: Fig. 5). Only six thematic groups can be identified as core CE thematic groups (i.e., are covered by at least 50% of the CE indicator sets). In the urban sustainability sub-sample, these are 16 core thematic groups. In the CE sub-sample, 30 thematic groups are only sporadically covered (i.e., less than 50% of the indicator sets contain at least one indicator related to that thematic group). For example, Personal safety, Communication & Connectivity, and Disaster vulnerability are covered by only one CE indicator set (i.e., only one set out of 24 contains at least one indicator linked to those thematic groups).

The results shown so far in relation to the 36 thematic groups were based on a binary logic (i.e., if an indicator set contained at least one indicator covering a specific thematic group). In Table 3, the relative importance that each thematic group receives on average in the two set groups (i.e., the percentage of indicators covering a specific thematic group) are reported. Seventeen thematic groups show significant differences between CE and urban sustainability indicator sets groups.

4.5. Cluster analysis

Fig. 6 shows the three dendrograms obtained through the cluster analysis based on the coverage by the indicator sets of the STEEP categories (a), the SDGs (b), and the thematic groups (c). In the first two dendrograms ("a" and "b"), a similar pattern can be identified. On the right side of dendrogram "a", cluster a.1 is composed of urban sustainability sets, whereas on the left side the clusters a.2 can be divided into a mixed sub-cluster (a.2.1), and a CE sub-cluster a.2.2. The dendrogram in panel "c" appears to be slightly different. Two main clusters can be identified: c.1 includes only CE indicator sets, and c.2 contains all of the urban sustainability sets and twelve CE indicator sets.

5. Discussion

The concept of a CE, especially applied at the urban scale, has been interpreted in many ways. These different perspectives might hinder the success of transition (urban) agendas. This research aimed at shedding light on this conceptual ambiguity and supporting urban agents of change in their journey through a CE/sustainability transition. In the discussion, the focus is first on the comprehensive meta-analysis of CE indicator sets used at the macro (city) level, to understand how the concept of a CE in urban areas has been operationalized (sub-section 5.1). Furthermore, an elaboration on the comparison between the concepts of CE in urban areas and urban sustainability is presented to clarify the conceptual boundaries between them, and how they articulate with each other (CE as a similar, alternative, or complementary concept to urban sustainability; sub-section 5.2). Finally, the limitations of the research are acknowledged, and avenues for further investigation are suggested (sub-section 5.3).

5.1. Operationalizing the CE in urban areas

In this sub-section, the results of the analysis of CE measurement initiatives are discussed in two main points: i) the focal areas of CE measurement initiatives, and ii) consistency among initiatives.

The results show that CE is mainly focused on environmental issues. This standpoint is supported by the analysis of the most frequent indicators (see Appendix A), the STEEP categories (see: Fig. 3), the SDGs (see Fig. 4), and the thematic groups (see Fig. 5). Although marginally, CE indicators are also used to assess aspects of a CE such as health and well-being, participation, and inequalities. All the CE indicator sets contain at least a small percentage of indicators covering social aspects. In line with scholars advocating for the social dimension to be increasingly taken into account by circular perspectives (Moreau et al., 2017), the results suggest that evidence of these approaches exists, though they have not yet been mainstreamed. The incorporation of indicators other than those linked to the environmental dimension is advocated in the literature, arguing for a systemic perspective to monitor circular strategies. Recalling the definition of CE (Kirchherr et al., 2017) proposed in Section 2.1, a CE should help "*to accomplish sustainable development, which implies creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations*". Without incorporating suitable indicators, it remains unclear to which degree it could be possible to track the progress of a CE transition in those areas (an exception is made for the environmental one). The risk is that indicators are cherry-picked to fit specific goals, showing biased results, which do not necessarily contribute to broader sustainability goals (Pauliuk, 2018). Regarding technological aspects, the results show that this category is marginally covered by CE indicator sets, while from a transition perspective, a future CE requires considerable investments in technology and infrastructure (Prendeville et al., 2018). The question arises as to whether the technological aspect of a CE, offering the needed infrastructure for the transition, is actually underrepresented in practice, and only mentioned in theoretical approaches and urban visions that have not yet been translated into measurement tools.

Based on the sample analyzed in this research, a shared perspective on the core elements of a circular city (i.e., what is essential to measure) might still be far from being reached. Two insights support this statement. First, concerning the 535 indicators extracted from the CE sub-sample, repetitions were only found in 168 cases, suggesting that the measurement initiatives predominantly use several different indicators. Second, the results (see: Fig. 5) indicate that most thematic groups are targeted by only a few (between 4% and 50%) indicator sets. Only six out of 36 thematic groups are covered by at least 50% of the CE indicator sets. In practical terms, these results suggest that when assessing the circularity of urban areas, there is great variability in what is deemed to be important and informative. Peculiarities of indicator sets might be beneficial for an assessment (considering local characteristics and needs), and a specific focus on core thematic groups might not represent an issue *per se*, since it could simply mirror a very narrow yet efficient circumscription of targets. However, the extant risk is that important aspects needed by cities for a holistic transition are not adequately covered, as a holistic transition depends on the recognition of the interlinkages among barriers at different levels (Salmenperä et al., 2021).

Many scholars call for a minimal degree of consistency with other assessments, to allow benchmarking to, and synergies with, other urban realities (Merino-Saum et al., 2020). This consistency could potentially be achieved through challenging and rethinking the processes of indicator selection. Although the roles of several urban actors in a CE transition are often acknowledged (Prendeville et al., 2018), there is a possibility of broadening the consulted actors to involve agents of change that are active in other urban realities, as their expertise on common challenges and best practices could represent a valuable contribution. The stabilization around a few key thematic groups in CE indicator-based initiatives would contribute to the building of a more robust conceptual foundation on which the CE notion could rely. Regarding the development of new assessment frameworks, there is a risk of needing a substantial amount of resources, while multiple experiences around the globe can already inform the assessment methodology and provide suitable indicators. The use of core indicators in different assessment exercises has the significant potential of allowing for a comparison between the different urban realities and informing a more robust discussion on the respective results obtained. This puts the emphasis then on those core issues that our societies are facing in the transition towards sustainability. Additional insights about the issue of assessment consistency will be discussed at the end of sub-section 5.2, based on the results of the cluster analyses performed with both CE and urban sustainability indicator sets.

5.2. Insights from the comparison of CE in urban areas and urban sustainability

Looking at the thematic groups covered by at least one indicator in the two indicator lists (CE and urban sustainability), it appears that the concept of a CE in urban areas is nested into the concept of urban sustainability (see Fig. 5). No thematic group is unique to the CE sub-sample, while three thematic groups (Tourism, Conventional transport, and Public finances) are only covered by indicator sets belonging to the urban sustainability sub-sample. This represents a surprising finding, since a reasonable amount of information is available on what is necessary for a circular tourism sector (Manniche et al., 2017; Rodríguez et al., 2020), or on the need to assess trends in both conventional (oil-based) and sustainable (renewables-based) mobility for circular cities (Christis et al., 2019; Gravagnuolo et al., 2019; Lee et al., 2016). This would imply that the CE, alone, might not accompany our societies towards broad sustainability (Henry et al., 2021).

In comparison with urban sustainability sets, CE indicator sets clearly focus less on social aspects, a difference widely highlighted in the literature on sustainability and CE in general (Geissdoerfer et al., 2017; Murray et al., 2017). The use of STEEP categories as a research lens adds a layer of detail. In fact, even though previous literature has highlighted a difference of focus between urban sustainability and CE, those studies predominately considered only social and environmental issues, while the analysis performed here allows a broader range of issues to be taken into account (namely political, technological and economic). Regarding technological aspects, the results show that no significant difference can be identified in comparison with urban sustainability sets. In addition, it appears that policy/regulative aspects are neglected in CE indicator sets. However, this shortcoming is not only inherent of CE indicator sets but is a feature shared with the indicator sets focusing on urban sustainability.

Using the SDGs lens allowed us to go one step further and to offer insights to those actors currently targeting SDGs in their agendas. CE indicator sets only cover SDG12 to a higher extent than urban sustainability indicator sets. This is in line with what is shown in the literature, where SDG12 *Responsible Consumption & Production* is considered the SDG with the highest affinity to the concept of the CE (Dantas et al., 2021; Fatimah et al., 2020; Schröder et al., 2019a). Schröder et al. (2020) identified gaps and issues relating CE to SDG1 *No poverty*, SDG3 *Good health and well-being*, SDG4 *Quality education*, SDG5 *Gender equality*, SDG10 *Reduced inequality*, SDG17 *Partnerships for the goals*. In the sample, significantly different coverages between CE and urban sustainability indicator sets were found for all of these SDGs. Regarding the SDGs mostly linked with the use of natural resources (SDG6, SDG13, SDG14, SDG15), no significant difference can be highlighted between the two set groups. Hence, the higher focus of CE indicator sets on environmental issues might be highly driven by those covered by SDG12 *Responsible consumption and production* (for which a significant different coverage was found), which is often linked to both economic and environmental aspects (Mccormick and Leire, 2020)

A noteworthy aspect of the results is that indicator sets used to assess a CE offer additional indicators for covering specific thematic groups. For all the thematic groups covered by the CE sub-sample (with the exception of Disaster vulnerability, Personal safety, and Research & Development), the list of indicators used by CE indicator sets contains at least one indicator (281 in total) that was not used in the urban sustainability sub-sample. This primarily applies to Sustainable/circular initiatives (61 additional indicators), Waste production and management (57), and Material resources consumption (47). This implies that CE sets could provide indicators to deepen the level of assessment of certain thematic groups that might only be measured superficially when using urban sustainability indicator sets. Examples of these indicators are, respectively: Green products purchasing rate of the government, Waste from Electrical and Electronic Equipment (WEEE) generated, Total raw material productivity.

The results of the cluster analyses offer additional insights on the issue of consistency among indicator sets that are (supposedly) used to assess the same concept, either a CE in urban areas or urban sustainability. Integrating urban sustainability indicator sets into the cluster analysis offered us an external point of reference to better elicit differences among CE indicator sets. As the three chosen typologies are linked to each other, but not redundant, the insights derived from the cluster analyses offer a slightly different but generally consistent picture. First, there is an overall consistency in how CE in urban areas and urban sustainability are assessed (i.e., two separate clusters arise, with reasonable segregation of CE and urban sustainability sets). However, in all three dendrograms, it is possible to identify indicator sets belonging to one group as closer (and therefore more similar) to indicator sets of the other group. The question arises as to whether some indicator sets are simply labeling similar concepts under different names, creating a conceptual fuzziness. For instance, in the case of the clustering based on the STEEP framework (Fig. 6, panel a) the indicator set “CE6”, which is positioned among the urban sustainability indicator sets, covers aspects related to the social dimension in a way that is more similar to the average of the urban sustainability indicator sets, rather than the average of the CE indicator sets. Details on the provided examples can be seen in the supplementary material (S.7, S.8, and S.9). As another example, the location of set “US1” in Fig. 6 panel b, far from the other urban sustainability indicators, might be determined by its divergent coverage of SDG1 *No poverty*, SDG3 *Good health and well-being*, and SDG12 *Responsible consumption and production*. Additionally, the vicinity of some indicator sets might mirror the specific visions or approaches of the indicator sets’ developers. For example, the indicator sets “CE3”, “CE5”, “CE6”, “CE9”, “CE13” are found in clear proximity in the sub-cluster c.2 (Fig. 6, panel c). Regarding their origin, they all come from instances in which one actor (a Dutch consultancy focused on circularity) was involved. These sets are also found in separate clusters dissimilar to the core CE indicator set group c.1. This distance might be due to their coverages of thematic groups like Participation/engagement, Inequalities, Health & Well-being, Employment, Urban green/blue areas, and Air pollution, which are considerably more similar to the average of the urban sustainability indicator sets. Hence, the influence of the vision of one actor might be traceable in the choice of indicators made in the development of several indicator sets. In line with the argument presented in the previous paragraph, the analysis of the dendrograms highlights a certain degree of inconsistency in how the CE has been measured through the different indicators sets.

Two main points now merit attention. The understanding that CE indicator sets cover social issues, even if marginally, might represent a positive starting point for including more focus on those issues - a focus which many actors would like to see present in CE discussions. However, adding emphasis on social issues from a CE perspective might bring this concept even closer to sustainability in general, and urban sustainability in particular, when focusing on urban areas. Thus, the real benefit of targeting a CE in comparison with fostering a sustainability transition would not be evident. If social aspects are deemed important for the evolution of the CE perspective, they should focus on social aspects specifically related to core CE thematic groups, such as Waste generation and management, Material resource consumption, and/or Circular initiatives. By doing so, they would offer an innovative perspective, since urban sustainability approaches do not focus on the social aspects of such challenges/issues. CE perspectives should not try to indiscriminately integrate all of the social issues that urban sustainability approaches generally take into account. One of the problems related to the CE approach is that it often aims at broadening its scope by replicating what is already embedded within the urban sustainability discourse. One key challenge for future set developers in the field of CE will be to build indicator sets that are both multidimensional (i.e., which tackle circularity features by simultaneously considering several sustainability dimensions) and concept-specific (i.e., which do not excessively open up the scope, thereby amalgamating CE to the broader notion of sustainability). If CE adopters aim to sustain the concept as up-to-date and innovative, they need to differentiate it from existing approaches (i.e., urban sustainability).

As for practical recommendations for cities engaged in shaping their visions for a transition towards a CE, a clear understanding of what is being targeted is pivotal to avoid aiming at narrow goals that might not be moving cities towards broader sustainability. The CE concept is being widely used nowadays, but there is a risk of using this concept as an alternative, and not as a means, towards sustainability. Much care is needed to compare sustainability and circularity targets and coherently explain city transition plans that are motivated by targeting circularity rather than sustainability. If CE in urban areas is to be seen as a means towards urban sustainability, then CE approaches should be translated into more concrete, focused, and practical operationalization than urban sustainability, the latter being potentially interpreted as a broader, guiding theoretical framework.

5.3. Limitations and further research

It is important to acknowledge some limitations inherent to this research. The sample of retrieved CE indicator sets represents a limited amount of data sets (24). As it is reasonably expected that more assessors will define ad-hoc sets of indicators for measuring CE and urban sustainability in the future, a second iteration of the present study could help to determine how the results stand up to the test of time, in order to understand the degree to which they remain consistent even when more indicators are added to the sample. Also, studies performed on updated versions of the sample used here might elicit trends of change in the way the selected concepts are assessed through time. Second, the analysis of the indicators is subject to a certain degree of subjectivity. Although the researchers applied the same approach to the analysis of all 930 net indicators, a different assessment from other research teams might have produced different results. However, the size of the sample of the indicators corrects for this potential bias. Similar approaches are reported in the literature and their limitations are acknowledged (Ahvenniemi et al., 2017; Merino-Saum et al., 2018).

Regarding ideas for further research, many avenues could be explored. First, indicators could be screened according to typologies directly related to the CE literature (for instance the 10R-strategies; Potting and Hanemaaijer, 2018) or typologies (Moraga et al., 2019). The underlying idea is to better elicit which aspects of the CE are integrated into the sustainability concept. Further research could focus on comparing different concepts using the same approach that has been proposed here, namely using indicators as proxies for their conceptualizations (e.g., green and circular urban areas). In-depth case studies could also be performed, focusing on cities that have developed both circularity and sustainability strategies, to see how these concepts are operationalized when the city context remains unvaried. Finally, there is potential of engaging assessors and practitioners involved in the CE transition to discuss how the findings of this research might help them have a clearer and more informed overview of the goals of their CE strategies. This could help them to align their efforts and to avoid negative interferences between different projects and policies, as the overall goal of these commitments should be a systemic transition to sustainability.

6. Conclusions

Several urban areas around the globe have implemented CE assessments and policy planning. The overall goal of this research was to enquire how the concept of a circular urban area has been operationalized through the use of assessment tools, in comparison with the case of sustainable urban areas. For this objective, an approach was implemented based on the analysis of indicators used by different assessors at the urban scale and multiple perspectives were applied to explore the research questions.

The results show that the concept of CE, when using indicators as a proxy for its conceptualization, is embedded in the broader concept of urban sustainability. However, considering a CE, there is a more detailed focus on certain thematic groups (e.g., waste) and an analysis of several of their different aspects. This is reflected by the use of a multitude of different indicators. In broad terms, a CE focuses more on environmental issues, while urban sustainability covers social aspects in a more extended way. Notably, CE indicator sets do cover some social aspects. If CE adopters aim to maintain the concept as up-to-date and innovative, then they should clearly differentiate it from existing approaches (i.e., urban sustainability), without limiting themselves to replication of those perspectives. Finally, the results show that there is a general consistency in how indicator sets belonging to the CE and urban sustainability groups measure the respective concepts. However, even with a limited sample, some indicator sets that aim at assessing CE are found to be more similar to those measuring urban sustainability (in terms of STEEP categories, SDGs, and thematic groups covered).

The contributions of this research are manifold. This work advances our knowledge on the concept of the CE from theoretical, practical and methodological perspectives. First, by analyzing how the concept of CE in urban areas has been operationalized, insights are offered on how this concept has been interpreted, and what is targeted when aiming at a circular urban area. Second, by comparing the aspects of sustainability that the CE and urban sustainability focus on, insights are offered on the relation between these two multi-faceted concepts and light is shed on their overlap as well as on their differences. This can have practical relevance for those actors involved in urban transitions: they might critically revise their urban agendas to question the suitability and potential of the CE approach in supporting a broader sustainability transition. Third, from a methodological perspective, an approach is refined that proposes the use of indicators as the unit of analysis to elicit peculiarities of concepts such as CE and urban sustainability. It was analyzed how these concepts are made operational through metrics, which is *de facto* a way to delimitate the concepts themselves (Merino-Saum et al., 2020). Developing an indicator set necessarily involves trade-offs between potential metrics. Indicator set developers must decide what counts and what does not count (each indicator has an opportunity cost: if it is included in the final set, it means that other candidate indicators are excluded). In more qualitative conceptualizations, such constraints do not exist, which leads to broader definitions. Hence, by looking at indicators, it can be elucidated how a concept is operationalized in practical terms.

Overall, this research informs the debate on the differences and overlaps between the concepts of CE and urban sustainability, and is expected to support urban communities in finding a match between targeted CE objectives and selected indicators.

Authors contributions

Valeria Superti: Conceptualization, Methodology, Formal analysis, Investigation, Writing - Original Draft, Review & Editing, Visualization, Dr. Albert Merino-Saum: Conceptualization, Methodology, Writing - Original Draft, Review & Editing, Dr. Ivo Baur: Conceptualization, Methodology, Prof. Dr. Claudia R. Binder: Validation, Writing - Review & Editing, Supervision, Project administration, Resources, Funding acquisition.

Declaration of competing interest

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

Acknowledgments

The authors gratefully acknowledge colleagues at HERUS for their comments on a previous version of this paper. The authors acknowledge support from the Swiss Federal Office for the Environment as part of the funding for this project (grant 591517). The authors are also thankful to Mr. D. Baumgartel for the language editing and to Mr. K.S. Hof for support in data visualization.

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2021.128070.

Appendix A

List of the top 5% indicators used in the Circular Economy (CE) indicator sets sample (panel a) and in the urban sustainability (US) indicator sets sample (panel b).

a. CE indicator sets sample		
Indicator	# of CE indicator sets containing the indicator	Related thematic group
Municipal waste treatment by recycling (%)	14	Waste production and management
Municipal solid waste generated (ton)	10	Waste production and management
CO2eq (GHG) emissions (ton)	8	Green House Gases
Jobs in circular economy/sustainability (#)	8	Sustainable/circular initiative
Energy consumption per GDP	7	Conventional Energy
Water consumption (l)	6	Water
Landfilled waste (%)	6	Waste production and management
Municipal Waste treatment by composting (%)	5	Waste production and management
Waste intensity per household (ton)	5	Waste production and management
Green area extension (km^2)	4	Urban Green/blue areas & Urban ecosystems
Construction and demolition waste produced (ton)	4	Waste production and management
WEEE collected (ton)	4	Waste production and management
Total energy consumption (TWY)	4	Conventional energy
Ratio of tot energy derived from renewable sources (%)	4	Renewable energy
Patents (#)	4	Sustainable/circular labels & R&D
Gross Value Added ($)	4	GDP & Added value
Employment rate (%)	4	Employment
Unemployment rate (%)	4	Employment
Potentially toxic material flows (ton)	4	Health & Wellbeing
b. US indicator sets sample	# of US indicator sets containing the indicator	Related thematic group
CO2eq (GHG) emissions (ton)	17	Green House Gases
Municipal Solid Waste generated (ton)	16	Waste production and management
Water consumption (l)	14	Water
Green areas extension (km^2)	13	Urban Green/blue areas & Urban ecosystems
Number of registered crimes (#)	13	Personal safety
Unemployment rate (%)	12	Employment
Disposable income ($)	12	Income/poverty
Trips made by a sustainable mode (%)	11	Sustainable transport
Wastewater treatment rate (%)	10	Water
Employment rate (%)	10	Employment
Poverty/Low income (%)	10	Income/poverty
Concentration of PM10 (ug/m^3)	9	Air pollution
Urban density (hab/km^2)	9	Urban planning
Trips with car/motorbike (%)	9	Conventional transport
Municipal Waste treatment by recycling (%)	8	Waste production and management
Domestic waste treated (%)	8	Waste production and management
R&D expenditure (%)	8	Sustainable/circular labels & R&D
Active population with at least secondary education (%)	8	Education & culture
Length of bike lanes (km)	8	Sustainable transport
Concentration of NO2 (ug/m^3)	7	Air pollution
Green areas/inhabitant (km^2)	7	Urban Green/blue areas & Urban ecosystems
Green areas access (km)	7	Urban Green/blue areas & Urban ecosystems
Total energy consumption (TWY)	7	Conventional energy
Average GDP per year ($)	7	GDP & Added value
Life expectancy (y)	7	Health & Wellbeing
Attendance to municipal elections (%)	7	Participation/engagement
Air pollution index	6	Air pollution
Ratio of tot energy derived from renewable sources (%)	6	Renewable energy
Proximity to basic services (km)	6	Leisure & Urban infrastructure
Pedestrian areas (km^2)	6	Sustainable transport
Volunteers in formal or informal volunteering (#)	6	Participation/engagement

References

Ahvenniemi, H., Huovila, A., Pinto-Seppä, I., Airaksinen, M., 2017. What are the differences between sustainable and smart cities? Cities 60, 234–245. https://doi.org/10.1016/j.cities.2016.09.009.

Alberti, M., 1996. Measuring urban sustainability. Environ. Impact Assess. Rev. 16, 381–424. https://doi.org/10.1016/S0195-9255(96)00083-2.

Allen, M., Poggiali, D., Whitaker, K., Marshall, T.R., Kievit, R.A., 2019. Raincloud plots: a multi-platform tool for robust data visualization. Wellcome Open Res. 4, 63. https://doi.org/10.12688/wellcomeopenres.15191.1.

Blomsma, F., Brennan, G., 2017. The emergence of circular economy: a new framing around prolonging resource productivity: the emergence of circular economy. J. Ind. Ecol. 21, 603–614. https://doi.org/10.1111/jiec.12603.

Bocken, N.M.P., Olivetti, E.A., Cullen, J.M., Potting, J., Lifset, R., 2017. Taking the circularity to the next level: a special issue on the circular economy: taking circularity to the next level. J. Ind. Ecol. 21, 476–482. https://doi.org/10.1111/jiec.12606.

Calisto Friant, M., Vermeulen, W.J.V., Salomone, R., 2021. Analysing European Union circular economy policies: words versus actions. Sustain. Prod. Consum. 27, 337–353. https://doi.org/10.1016/j.spc.2020.11.001.

Caprotti, F., Cowley, R., Datta, A., Broto, V.C., Gao, E., Georgeson, L., Herrick, C., Odendaal, N., Joss, S., 2017. The New Urban Agenda: key opportunities and challenges for policy and practice. Urban Res. Pract. 10, 367–378. https://doi.org/10.1080/17535069.2016.1275618.

Castán Broto, V., 2017. Urban governance and the politics of climate change. World Dev. 93, 1–15. https://doi.org/10.1016/j.worlddev.2016.12.031.

Christis, M., Athanassiadis, A., Vercalsteren, A., 2019. Implementation at a city level of circular economy strategies and climate change mitigation – the case of Brussels. J. Clean. Prod. 218, 511–520. https://doi.org/10.1016/j.jclepro.2019.01.180.
Dantas, T.E.T., de-Souza, E.D., Destro, I.R., Hammes, G., Rodriguez, C.M.T., Soares, S.R., 2021. How the combination of circular economy and Industry 4.0 can contribute towards achieving the sustainable development goals. Sustain. Prod. Consum. 26, 213–227. https://doi.org/10.1016/j.spc.2020.10.005.
Di Maio, F., Rem, P.C., 2015. A robust indicator for promoting circular economy through recycling. J. Environ. Protect. 6, 1095–1104. https://doi.org/10.4236/jep.2015.610096.
Di Maio, F., Rem, P.C., Baldé, K., Polder, M., 2017. Measuring resource efficiency and circular economy: a market value approach. Resour. Conserv. Recycl. 122, 163–171. https://doi.org/10.1016/j.resconrec.2017.02.009.
Elia, V., Gnoni, M.G., Tornese, F., 2017. Measuring circular economy strategies through index methods: a critical analysis. J. Clean. Prod. 142, 2741–2751. https://doi.org/10.1016/j.jclepro.2016.10.196.
EMF, 2013. Towards the circular economy report volume 1: an economic and business rationale for an accelerated transition. https://www.ellenmacarthurfoundation.org/assets/downloads/publications/Ellen-MacArthur-Foundation-Towards-the-Circular-Economy-vol.1.pdf. (Accessed 29 April 2021).
Fatimah, Y.A., Govindan, K., Murniningsih, R., Setiawan, A., 2020. Industry 4.0 based sustainable circular economy approach for smart waste management system to achieve sustainable development goals: a case study of Indonesia. J. Clean. Prod. 269, 122263 https://doi.org/10.1016/j.jclepro.2020.122263.
Feleki, E., Vlachokostas, C., Moussiopoulos, N., 2020. Holistic methodological framework for the characterization of urban sustainability and strategic planning. J. Clean. Prod. 243, 118432 https://doi.org/10.1016/j.jclepro.2019.118432.
Frantzeskaki, N., Castán Broto, V., Coenen, L., Loorbach, D., 2017. Urban Sustainability Transitions. In: Routledge, New York, first ed., ISBN 9780367219086
Fratini, C.F., Georg, S., Jørgensen, M.S., 2019. Exploring circular economy imaginaries in European cities: a research agenda for the governance of urban sustainability transitions. J. Clean. Prod. 228, 974–989. https://doi.org/10.1016/j.jclepro.2019.04.193.
Geissdoerfer, M., Savaget, P., Bocken, N.M.P., Hultink, E.J., 2017. The Circular Economy – a new sustainability paradigm? J. Clean. Prod. 143, 757–768. https://doi.org/10.1016/j.jclepro.2016.12.048.
Genovese, A., Acquaye, A.A., Figueroa, A., Koh, S.C.L., 2017. Sustainable supply chain management and the transition towards a circular economy: evidence and some applications. Omega 66, 344–357. https://doi.org/10.1016/j.omega.2015.05.015.
Ghisellini, P., Cialani, C., Ulgiati, S., 2016. A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems. J. Clean. Prod. 114, 11–32. https://doi.org/10.1016/j.jclepro.2015.09.007.
Gravagnuolo, A., Angrisano, M., Fusco Girard, L., 2019. Circular economy strategies in eight historic port cities: criteria and indicators towards a circular city assessment framework. Sustainability 11, 3512. https://doi.org/10.3390/su11133512.
Grissom, R.J., Kim, J.J., 2012. Effect Sizes for Research: Univariate and Multivariate Applications, second ed. Routledge/Taylor & Francis Group, ISBN 9780415877695.
Halla, P., Merino-Saum, A., Forthcoming. Conceptual frameworks for urban sustainability indicators - an empirical analysis. Submitt. Ecol. Indic.
Hanumante, N.C., Shastri, Y., Hoadley, A., 2019. Assessment of circular economy for global sustainability using an integrated model. Resour. Conserv. Recycl. 151, 104460 https://doi.org/10.1016/j.resconrec.2019.104460.
Henry, M., Schraven, D., Bocken, N., Frenken, K., Hekkert, M., Kirchherr, J., 2021. The battle of the buzzwords: a comparative review of the circular economy and the sharing economy concepts. Environ. Innov. Soc. Transit. 38, 1–21. https://doi.org/10.1016/j.eist.2020.10.008.
Huang, L., Wu, J., Yan, L., 2015. Defining and measuring urban sustainability: a review of indicators. Landsc. Ecol. 30, 1175–1193. https://doi.org/10.1007/s10980-015-0208-2.
Jacobi, N., Haas, W., Wiedenhofer, D., Mayer, A., 2018. Providing an economy-wide monitoring framework for the circular economy in Austria: status quo and challenges. Resour. Conserv. Recycl. 137, 156–166. https://doi.org/10.1016/j.resconrec.2018.05.022.
Jacobs, J., 2016. The Economy of Cities: from the Birth of the U.S. Navy to the Nuclear Age, 13. Vintage. Vintage Books Edition, ISBN 978-0394705842.
Kaur, H., Garg, P., 2019. Urban sustainability assessment tools: a review. J. Clean. Prod. 210, 146–158. https://doi.org/10.1016/j.jclepro.2018.11.009.
Kaza, S., Yao, L., Bhada-Tata, P., Frank, V.W., 2018. What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050. Urban Development Series. Washington, DC: World Bank. https://openknowledge.worldbank.org/bitstream/handle/10986/30317/211329ov.pdf. (Accessed 29 April 2021).
Kennedy, C., Pincetl, S., Bunje, P., 2011. The study of urban metabolism and its applications to urban planning and design. Environ. Pollut. 159, 1965–1973. https://doi.org/10.1016/j.envpol.2010.10.022.
Kirchherr, J., 2019. Research on the circular economy_ A critique of the field. Resour. Conserv. Recycl. 151 https://doi.org/10.1016/j.resconrec.2019.104480.
Kirchherr, J., Reike, D., Hekkert, M., 2017. Conceptualizing the circular economy: an analysis of 114 definitions. Resour. Conserv. Recycl. 127, 221–232. https://doi.org/10.1016/j.resconrec.2017.09.005.
Lee, S., Quinn, A., Rogers, C., 2016. Advancing city sustainability via its systems of flows: the urban metabolism of birmingham and its hinterland. Sustainability 8, 220. https://doi.org/10.3390/su8030220.
Lehtonen, M., Sébastien, L., Bauler, T., 2016. The multiple roles of sustainability indicators in informational governance: between intended use and unanticipated influence. Curr. Opin. Environ. Sustain. 18, 1–9. https://doi.org/10.1016/j.cosust.2015.05.009.
Maclaren, V., 1996. Urban sustainability reporting. J. Am. Plann. Assoc. 62, 184–202.
Manniche, J., Topsø Larsen, K., Brandt Broegaard, R., Holland, E., 2017. Destination: A Circular Tourism Economy. A Handbook for Transitioning toward a Circular Economy within the Tourism and Hospitality Sectors in the South Baltic Region. Centre for Regional and Tourism Research, Denmark. https://circulareconomy.europa.eu/platform/sites/default/files/cirtoinno-handbook_eng-rev.-4.pdf. (Accessed 29 April 2021).
Mccormick, K., Leire, C., 2020. Cities and Consumption: Sharing Cities and Achieving the Sustainable Development Goals. Lund University. https://portal.research.lu.se/ws/files/94761685/Cities_and_Consumption.pdf. (Accessed 29 April 2021).
Merino-Saum, A., Baldi, M.G., Gunderson, I., Oberle, B., 2018. Articulating natural resources and sustainable development goals through green economy indicators: a systematic analysis. Resour. Conserv. Recycl. 139, 90–103. https://doi.org/10.1016/j.resconrec.2018.07.007.
Merino-Saum, A., Halla, P., Superti, V., Boesch, A., Binder, C.R., 2020. Indicators for urban sustainability: key lessons from a systematic analysis of 67 measurement initiatives. Ecol. Indicat. 19, 106879 https://doi.org/10.1016/j.ecolind.2020.106879.
Moraga, G., Huysveld, S., Mathieux, F., Blengini, G.A., Alaerts, L., Van Acker, K., de Meester, S., Dewulf, J., 2019. Circular economy indicators: what do they measure? Resour. Conserv. Recycl. 146, 452–461. https://doi.org/10.1016/j.resconrec.2019.03.045.
Moreau, V., Sahakian, M., van Griethuysen, P., Vuille, F., 2017. Coming full circle: why social and institutional dimensions matter for the circular economy: why social and institutional dimensions matter. J. Ind. Ecol. 21, 497–506. https://doi.org/10.1111/jiec.12598.
Morse, S., 2015. Developing Sustainability Indicators and Indices: Developing SIs. Sustain. Dev. n/a-n/a. https://doi.org/10.1002/sd.1575.
Murray, A., Skene, K., Haynes, K., 2017. The circular economy: an interdisciplinary exploration of the concept and application in a global context. J. Bus. Ethics 140, 369–380. https://doi.org/10.1007/s10551-015-2693-2.
OECD, 2020. The Circular Economy in Cities and Regions: Synthesis Report, OECD Urban Studies. OECD Publishing, Paris. https://doi.org/10.1787/10ac6ae4-en.
Paiho, S., Mäki, E., Wessberg, N., Paavola, M., Tuominen, P., Antikainen, M., Heikkilä, J., Rozado, C.A., Jung, N., 2020. Towards circular cities—conceptualizing core aspects. Sustain. Cities Soc. 59, 102143 https://doi.org/10.1016/j.scs.2020.102143.
Parchomenko, A., Nelen, D., Gillabel, J., Rechberger, H., 2019. Measuring the circular economy - a multiple correspondence analysis of 63 metrics. J. Clean. Prod. 210, 200–216. https://doi.org/10.1016/j.jclepro.2018.10.357.
Parris, T.M., Kates, R.W., 2003. Characterizing and measuring sustainable development. Annu. Rev. Environ. Resour. 28, 559–586. https://doi.org/10.1146/annurev.energy.28.050302.105551.
Pastor, D.E., Erbacher, M.K., 2019. Cluster Analysis. In: Hancock, Gregory R., Stapleton, Laura M., Mueller, Ralph O. (Eds.), The Reviewer's Guide to Quantitative Methods in the Social Sciences. Routledge, New York, ISBN 9781138800137.
Pauliuk, S., 2018. Critical appraisal of the circular economy standard BS 8001:2017 and a dashboard of quantitative system indicators for its implementation in organizations. Resour. Conserv. Recycl. 129, 81–92. https://doi.org/10.1016/j.resconrec.2017.10.019.
Potting, J., Hanemaaijer, A., 2018. Circular Economy: what We Want to Know and Can Measure. Framework and Baseline Assessment for Monitoring the Progress of the Circular Economy in the Netherlands. PBL Netherlands Environmental Assessment Agency, The Hague. https://www.pbl.nl/sites/default/files/downloads/pbl-2018-circular-economy-what-we-want-to-know-and-can-measure-3217.pdf. (Accessed 27 April 2021).
Prendeville, S., Cherim, E., Bocken, N., 2018. Circular cities: mapping six cities in transition. Environ. Innov. Soc. Transit. 26, 171–194. https://doi.org/10.1016/j.eist.2017.03.002.
Reike, D., Vermeulen, W.J.V., Witjes, S., 2018. The circular economy: new or refurbished as CE 3.0? — exploring controversies in the conceptualization of the circular economy through a focus on history and resource value retention options. Resour. Conserv. Recycl. 135, 246–264. https://doi.org/10.1016/j.resconrec.2017.08.027.
Rodríguez, C., Florido, C., Jacob, M., 2020. Circular economy contributions to the tourism sector: a critical literature review. Sustainability 12, 4338. https://doi.org/10.3390/su12114338.
Rossi, E., Bertassini, A.C., Ferreira, C., dos, S., Neves do Amaral, W.A., Ometto, A.R., 2020. Circular economy indicators for organizations considering sustainability and business models: plastic, textile and electro-electronic cases. J. Clean. Prod. 247, 119137 https://doi.org/10.1016/j.jclepro.2019.119137.
Salmenperä, H., Pitkänen, K., Kautto, P., Saikku, L., 2021. Critical factors for enhancing the circular economy in waste management. J. Clean. Prod. 280, 124339 https://doi.org/10.1016/j.jclepro.2020.124339.
Schröder, P., Anggraeni, K., Weber, U., 2019a. The relevance of circular economy practices to the sustainable development goals: circular economy and SDGs. J. Ind. Ecol. 23, 77–95. https://doi.org/10.1111/jiec.12732.
Schröder, P., Bengtsson, M., Cohen, M., Dewick, P., Hoffstetter, J., Sarkis, J., 2019b. Degrowth within – aligning circular economy and strong sustainability narratives. Resour. Conserv. Recycl. 146, 190–191. https://doi.org/10.1016/j.resconrec.2019.03.038.
Schröder, P., Lemille, A., Desmond, P., 2020. Making the circular economy work for human development. Resour. Conserv. Recycl. 156, 104686 https://doi.org/10.1016/j.resconrec.2020.104686.
Soja, E., 2003. Writing the city spatially. Cityscape 7, 269–280. https://doi.org/10.1080/1360481032000157478.

Su, B., Heshmati, A., Geng, Y., Yu, X., 2013. A review of the circular economy in China: moving from rhetoric to implementation. Journal of Cleaner Production 42, 215–227. https://doi.org/10.1016/j.jclepro.2012.11.020.

UN, 2019. World Urbanization Prospects. 2018 Revision (No. ST/ESA/SER.A/420). New York: United Nations. https://population.un.org/wup/Publications/Files/WUP2018-Report.pdf. (Accessed 29 April 2021).

World Economic Forum, 2018. Circular Economy in Cities. Evolving the model for a sustainable urban future. http://www3.weforum.org/docs/White_paper_Circular_Economy_in_Cities_report_2018.pdf. (Accessed 29 April 2021).

Wuelser, G., Pohl, C., Hirsch Hadorn, G., 2012. Structuring complexity for tailoring research contributions to sustainable development: a framework. Sustain. Sci. 7, 81–93. https://doi.org/10.1007/s11625-011-0143-3.