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Closing the gap between EU-wide national bioeconomy monitoring frameworks and urban circular bioeconomy development

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ABSTRACT

The 2018 European bioeconomy strategy sets a new vision for Europe's sustainable development: a transition to regenerative resource usage that embraces circular principles. Similarly, various member states have developed national bioeconomy strategies. To be effective, such strategies require methodologically sound monitoring tools that support the alignment of national and urban policies. Indeed, cities are central to the bioeconomy, mobilizing ever increasing amounts of biogenic materials. To better understand the suitability of national bioeconomy strategies for guiding urban circular bioeconomy transitions, this paper examines the composition, features, and topical coverage of national bioeconomy indicator sets with a threefold analysis: (1) assessment of the integration of circularity principles in the sets and their alignment with existing policy frameworks; (2) appraisal of quality and the fulfillment of the sets' functional purposes; (3) evaluation of the breadth and depth of tackled issues. Of the 27 EU member states, only nine have a dedicated bioeconomy strategy, of which four propose an indicator set. While there is a general lack of sophisticated monitoring, the tools proposed after the publication of the 2018 bioeconomy strategy (Germany and Italy) follow indicator development standards rigorously. They include circularity in their notion of bioeconomy and combine indicators for a comprehensive, substantial, informative and politically relevant analysis. These characteristics strongly improve the potential for alignment and coherence with urban-level bioeconomy monitoring efforts. Although national measuring tools are not intended to cover all urban needs, the findings of this paper give insight into their remaining gaps and highlight improvement pathways for an efficient EU-wide circular bioeconomy transition.

1. Introduction

In recent decades, rising awareness of the destructive environmental impact of current production and consumption models has led to international efforts for sustainable development. On a global stage, the EU has earned the status of ecological leader, thanks to its solid framework of environmental legislation (European Commission, 2018a; Le Cacheux and Laurent, 2015). Among other policy, the bioeconomy strategy aims to power the economy with regenerative resources and has created a level playing field for sustainable innovation on the continent (European Commission, 2012, 2018a).

As a uniform definition of the bioeconomy is still lacking (Temmes and Peck, 2020; Vogelpohl et al., 2021), this paper relies on a definition used by the European Commission (EC) that is widely endorsed by scientists and organizations alike (e.g., Antikainen et al., 2017; World Economic Forum & Ellen MacArthur Foundation, 2017): The bioeconomy encompasses the part of the primary sector relying on renewable resources of biological origin as well as all industrial and economic sectors that use them (European Commission, 2018a). This includes practices like innovative biotechnological interventions leading to the production, usage, processing, and distribution of biological resources (Venkata Mohan et al., 2019). However, while the bioeconomy strategy aims to advance sustainable development (European Commission, 2018a), recent research showed that nature's limited availability of biomass and long regeneration times inherently constrain the prevailing paradigm of economic growth (Giampietro, 2019; Ikram et al., 2021). In fact, Kircher (2022) found that future industrial demand for biomass as feedstock exceeds what can be sustainably sourced. This implies that potential benefits of using bio-based resources to lower greenhouse gas emissions, for example, might rapidly be neutralized or even reversed by their excessive and wasteful usage (D'Amato et al., 2020; Stegmann et al., 2020).

To address such pitfalls, the EU's 2018 strategy recognizes the need for circularity to become an integral component of a thriving bioeconomy, and formulates the ambition of transitioning to a circular

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List of abbreviations

CBE	Circular Bioeconomy

bioeconomy (CBE) (European Commission, 2018a). By combining both concepts, essential steps were made towards improving the sustainability of both policy areas (Carus and Dammer, 2018; Venkata Mohan et al., 2019).

1.1. Measuring and assessing the bioeconomy

Functional assessment systems are crucial to assess the state of the CBE transition and to identify successes and failures of political action (Dietz et al., 2018; Eurostat, 2014). Such monitoring frameworks take the form of indicator sets, thanks to which users can evaluate a combination of measures, facilitate the communication of observed phenomena, and support decision making (Feller-Länzlinger et al., 2010; Gabrielsen and Bosch, 2003). Properly built indicator sets generate insights into the environmental and socioeconomic impacts of policymaking and the drivers and barriers of CBE implementation (European Commission, 2018b).

In response to calls for alignment and policy coherence across the continent, various EU member states have developed national bioeconomy strategies (European Commission, 2019a), translating supranational commitments into national ones (European Commission, 2018a; Robert et al., 2020). However, the extent of alignment between the proposed national strategies and supranational developments is not clear. Furthermore, national monitoring systems may differ due to divergent goals and priorities. Differences may also arise from the variation in methodological, compositional and communicative qualities of indicator sets (European Statistical System, 2019; Eurostat, 2014). No study has yet assessed features, quality and topical coverage of monitoring systems of national bioeconomy strategies, despite their evident impact on CBE policies and development.

1.2. Implementing the bioeconomy

While strategic directions are developed at supranational or national levels, scientists and organizations agree that local governments are crucial to their implementation (e.g. Bezama et al., 2019; Knudsen et al., 2020; Swilling and Hajer, 2017; United Nations Sustainable Development Group, 2020; Woodbridge, 2015). Referring to the successful implementation of bioeconomy strategies, Bezama et al. describe cities as the "smallest representative entity where an integrative approach, for assessing the potential effects of implementing the bioeconomy, can be carried out" (Bezama et al., 2021, p. 18). A quantity of processes that enable the bioeconomy, from resource regeneration to waste and nutrient recovery, take place on urban territory. Cities concentrate physical, institutional, demographic and organizational resources accelerating innovation (Bezama et al., 2021; Ellen MacArthur Foundation, 2019a). They are responsible for 60% of public investments in OECD countries, which significantly influences the development of sustainable practices, key industrial sectors, and urban infrastructure (Romano, 2019). In other words, cities are endowed with all the resources required to advance the bioeconomy.

Not only do cities have the capacity to bring about sustainable development, they also depend on this transition to support energy, resource, and food security for their inhabitants (Hetemäki et al., 2017). Rapidly rising urbanization increases the volume of material flows at the cost of high ecological footprints (Cui et al., 2019): Sixty five per cent of energy consumption, 60% of residential freshwater usage and 75% of worldwide carbon emissions occur in cities (Bezama et al., 2021). Given their high environmental impact and capacity to advance sustainable development, the EC recognizes the vast economic opportunities CBE bears for cities and foresees considerable job creation, financial savings, and reduced emissions (European Commission, 2018a). Circularity in the food sector alone is estimated to bring economic benefits of USD 700 billion in 2050 (Taffuri et al., 2021). Furthermore, 100 Mton of uncollected biomass, most of it unexploited food waste, could be utilized in the EU at no environmental or social cost (Dupont-Inglis and Borg, 2018). Developing the urban bioeconomy, therefore, also means exploiting latent urban assets and metabolic flows (including bio-wastes and byproducts) for economic benefits (Gregg et al., 2020; Taylor Buck and While, 2021).

The transition of a city's economy to a CBE requires targeted action that fosters the desired outcomes: (i) developing a fundamental understanding of the urban flows of organic materials and identifying system-wide solutions to loop them (Ellen MacArthur Foundation, 2017), (ii) acknowledging the complexity of the required systemic changes and (iii) realizing that the transition is rooted in technological advancement (Wilts and Steger, 2019). There is abundant research on the technological aspects of the CBE (Brandão et al., 2021; Gregg et al., 2020; Kang et al., 2020; Mpofu et al., 2021; Näyhä, 2019; Salvador et al., 2021). Bioeconomy impact analysis has also received much research attention (Ferreira et al., 2022). However, studies on bioeconomy transition policy seem to be lacking. Nonetheless, developing the CBE must be supported by an appropriate regulatory environment to give businesses, academics and other stakeholders the tools to overcome barriers and benefit from new opportunities (Ellen MacArthur Foundation, 2019b; European Commission, 2012). Moreover, efforts across policymaking levels must be coherent to achieve timely and collective success and avoid divergent, counterproductive developments (Robert et al., 2020). Zucaro et al. (2022) state that enabling regulatory and legislative frameworks that are coordinated on multiple government levels are necessary preconditions to achieving a CBE.

Despite its crucial and transformative role in sustainable development, the "local" level is mainly tackled in generic terms in the EU's strategy (Giuntoli et al., 2020; Knudsen et al., 2020). The current focus, which is set on aligning national and supranational policymaking and monitoring systems, will therefore have to be expanded to an urban level (Woodbridge, 2015). As UN Habitat points out, "… national governments should strengthen local governments' involvement in the definition, implementation and monitoring of national urban policies" (Knudsen et al., 2020, p. 208). Aligning with national and supranational bioeconomy strategies and measurement tools allows cities to benefit from readily established frameworks and coherently developed instruments (European Commission, 2018b; Woodbridge, 2015). It remains unclear, however, whether national developments in CBE policymaking can bridge the gap between the supranational agenda and local implementation imperatives and therefore support the urban CBE transition.

1.3. Closing the gap between national strategies and urban policymaking

The aim of the paper is to assess the current state, form and adequacy of development of national bioeconomy monitoring systems in the EU and whether CBE-policy monitoring tools can serve urban CBE development. Bridging these gaps is crucial if policymakers are to make progress towards a profound transformation of the economy. The following set of research questions serves as a guide for achieving the research objective:

1. What are the features and compositional rationales of monitoring frameworks proposed by national bioeconomy strategies in the EU and how extensive is their topic coverage?
2. Are current national CBE monitoring tools suitable starting points for the evaluation of urban-level CBE developments?

Insight into the landscape of national bioeconomy monitoring

frameworks will be generated to check whether they meet indicator needs at the urban level. For this assessment, both the relevance of the indicators to urban policymakers and the methodological and functional soundness of the indicator sets will be investigated.

2. Methodology

To analyze the form and content of national indicator sets and to identify their suitability for urban CBE monitoring, an evaluative research design, as defined by Stern (2004) was adopted. The collection and analysis of available indicator sets included the following steps: collecting national bioeconomy strategies in the EU by following a pre-defined procedure, appraising their approach to bioeconomy monitoring, and extracting information from the indicator sets to answer the research questions.

2.1. Collection of CBE strategies and indicator sets

The data to be collected and analyzed for this research was composed of the indicator sets within national bioeconomy strategies of EU member states. The European Commission (2019a) Bioeconomy Country Dashboard and its list of nations with a "dedicated Bioeconomy Strategy at national level" was used to identify the strategies. Although slightly outdated, this is the most recent and holistic review conducted by the EC on national bioeconomy strategy development. Two parameters were then applied as inclusion criteria for the analysis: (1) the nations under analysis had to be EU member states during the period of research; and (2) they had to have an officially adopted bioeconomy strategy. Among the 27 member states, one-third fulfilled both conditions. Therefore, the strategies that constituted the population were those issued by Austria, Finland, France, Germany, Ireland, Italy, Latvia, the Netherlands, and Spain.

Next, each national bioeconomy strategy was downloaded and screened for any information on bioeconomy monitoring systems. For this step, indicator sets in any format were accepted. Three different cases were encountered:

1. **The national bioeconomy strategy included an indicator set.** This set was used for the data analysis. The Finnish bioeconomy strategy proposes an indicator set that differs slightly from the indicators the country actively displays on its statistical database (Natural Resources Institute Finland, 2021). For practical reasons the latter was analyzed.
2. **The national bioeconomy strategy referred to a separate document for an indicator set or further explanations.** These documents were searched for on the same website where the bioeconomy strategy originated. To this end, Boolean strings were used to search only the indicated website, based on keywords retrieved from the bioeconomy strategy and with parsimonious Boolean operators. The strings were created with a timeframe for results spanning from the year the national bioeconomy strategy was issued to the present.
3. **There was no reference to monitoring systems in the bioeconomy strategy.** In this case, the same website as the one that issued the bioeconomy strategy was searched for possible monitoring systems. The following Boolean string was used, whereby the keyword "bioeconomy" was spelled as found in the national bioeconomy strategy and the keyword "indicat*" was replaced with the synonyms "monitor*", "assess*" and "evaluate*": *site:[selected website] "bioeconomy" AND "indicat**". Again, the timespan was set from the year of strategy publication to the present.

2.2. Analysis of the indicator sets

The analysis consisted in scrutinizing the collected national indicator sets and determining whether urban policymakers can use them to assess their city's CBE transition. As no appropriate assessment tools for indicator sets exist, the authors constructed three distinct instruments for this purpose: a factsheet, a quality appraisal grid and a topical assessment framework. To build these instruments, a literature review on CBE, urban sustainability, policy instruments, and indicator development theory was conducted (see Supplementary Material Sections 2.1, 2.2 and 2.3). The development and application of the resulting assessment tools for the analysis is summarized in Fig. 1 and elaborated in the following subchapters.

2.2.1. Factsheet

The factsheet served to appraise the monitoring systems' form and strategic aspects. Besides the title and year of issuance of the respective bioeconomy strategies, the authors evaluated the indicator sets with four criteria (see Supplementary Material Section 2.1):

1. **Strategic goals**: What are the bioeconomy strategy's goals and are they addressed by the indicator set?
2. **Inclusion of circularity**: To what extent is circularity understood to be part of the bioeconomy in the individual strategy?
3. **Indicator framework rationales**: How was the indicator framework constructed and is it linked to both policy and theory?
4. **Single indicators**: What types of indicators are part of the set, how were they selected, and what messages do they convey?

The factsheets served to obtain supportive or constraining arguments for the data interpretation.

2.2.2. Quality assessment grid

The quality assessment grid helped to better grasp whether indicators fulfill essential requirements for coherence and functionality, from describing situations and communicating phenomena to supporting decision and policymaking (Feller-Länzlinger et al., 2010; Gabrielsen and Bosch, 2003). Furthermore, the grid enabled identifying whether indicators were selected purposefully and through rigorous processes to ensure truthful, reliable and meaningful interpretations of results (Eurostat, 2014). Several quality criteria emerged from the literature as essential to compose the assessment grid. The evaluation of the indicator sets was based on a grading of each criterion on a three-point Likert scale (1 = clearly not met; 2 = ambiguous; 3 = clearly met), allowing for one neutral rating and two extremes. The quality assessment gives insight into the indicator sets' quality from the perspective of city-level governance. Table 1 synthesizes the quality evaluation criteria and their sources, while Section 2.2 of the Supplementary Material provides additional information concerning the grid's composition.

2.2.3. Topical Assessment Framework

The authors created a topical assessment framework to better understand the breadth and depth of topics covered by the indicator sets. To do so, the framework's purpose needed to be aligned with the users' needs (Feller-Länzlinger et al., 2010). This led to identifying the primary audience (urban policymakers) and its monitoring objectives (urban transition towards CBE). A set of 54 keywords and key phrases derived from the literature were then collected to compose a framework capable of reflecting the multidimensionality of urban CBE and interconnecting its components (Nardo et al., 2008). From this set, duplicates and ambiguous terms were scrubbed by combining topics and assimilating concepts. This activity produced 36 framework components, each describing one facet of urban CBE (find descriptive list and sources in Section 2.3 of the Supplementary Material). Given the variety of topical areas covered by the framework, these components were thematically grouped into six categories, with pairs of categories falling under one of three aspects of urban CBE (See Fig. 2). The bottom-up approach adopted for the framework creation reduced researcher bias in the inclusion or exclusion of single components. It further enabled discussion of single components isolated from the rest of the framework as well as

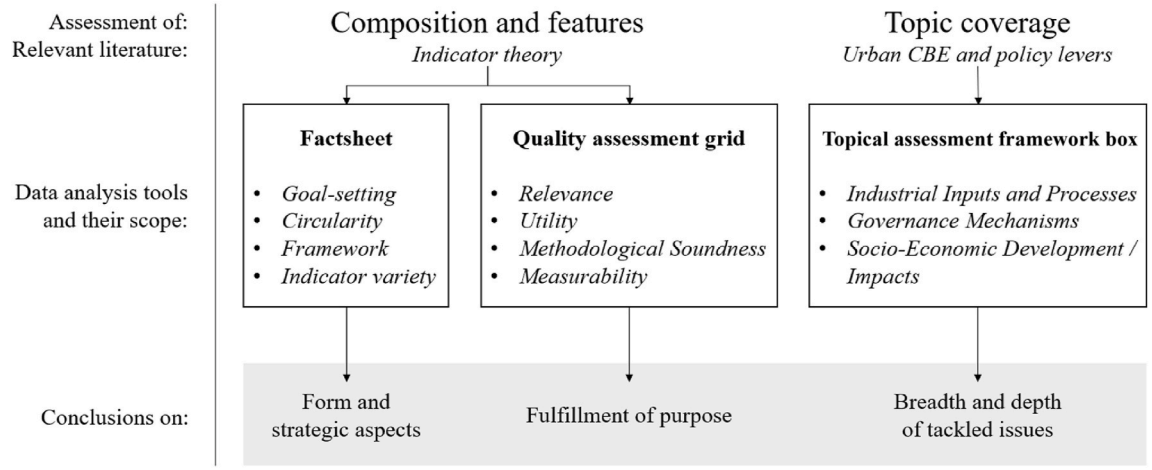

Fig. 1. From theory to assessment instruments - overview.

entire categories or aspects of urban CBE together.

For the analysis, each indicator from the national bioeconomy strategies was matched with one component of the assessment framework (see Supplementary Material Section 2.4). Each match of an indicator with a component of the framework resulted in one point for that component, so that the total points per component reflected the number of times that component is represented within an indicator set. For instance, the indicator "Direct loss of forest area" (Egenolf and Bringezu, 2018, p. 23) drawn from the German indicator set was matched with the component "Land degradation" from the assessment framework. This component, thus received one point. The total points finally gathered for this component reflect the number of times "Land degradation" is assessed by the studied indicator sets. Where available in the bioeconomy strategy or attached documents, specifications regarding the indicators were considered to guide this attribution process. The topical coverage "breadth" was finally assessed by the number of different components covered by an indicator set, while the "depth" is reflected in the quantity of indicators from a set attributed to a single component of the assessment framework.

The three following issues arose during the assessment:

1. The Finnish and Spanish sets were constructed as a series of measures that were applied to a variety of industrial sectors. To avoid overrepresentation of either element caused by this disaggregation of measures onto sectors (eg. "Final production" of "Agriculture" + "Final production" of "Food industry" + "Final production" of "Forestry Products", …), each measure and each sector were only counted once during the assessment.
2. Two items from the Spanish set ("Metric tons of processed waste %" and "Sustainability indicators" (Secretería de Estado de Investigación, 2016, p. 45) lack conceptual clarity with regards to their application. As both are still attributable to a framework component by approximation, they were included in the assessment (See Supplementary Material Section 2.4).
3. Some indicators referred to phenomena in rural areas (e.g., "Access of rural areas to public transport" (Egenolf and Bringezu, 2018, p. 22)) or were not bioeconomy specific (e.g., "Population growth [% year]" (Italian Committee for Biosafety, Biotechnology and Sciences of Life, 2019, p. 82). These were dismissed from the assessment as they go beyond the scope of this research.

Finally, a heat map allowed visualizing the breadth and depth of component, category and aspect coverage, individually and collectively.

3. Findings

3.1. Bioeconomy strategies

It is striking that the development of national bioeconomy strategies is not yet a widespread practice across the EU. While most of the 27 states had some policy initiatives related to the bioeconomy, only nine had adopted a dedicated bioeconomy strategy at the time of the EC's review (European Commission, 2019a).

The availability and scope of measuring tools accompanying these strategies is also highly variable. While the strategies of Germany or Italy include an extensive set of indicators, others do not propose any – or, as is the case with Finland and Spain, provide only a rather simplistic one. Furthermore, only the German and Finnish strategies, and to a lesser extent the Italian one, offer explanations and rationales for their monitoring frameworks, which, as this study shows, have the capacity to vastly improve a set's quality. Although the Austrian and French strategies reference external documents or action plans for their monitoring approaches, these were not found with the systematic search. Meanwhile, the Dutch strategy, a relatively broad policy statement, does not mention any monitoring approach at all. Similarly, the Latvian and Irish strategies do not refer to any monitoring system tailored specifically to the bioeconomy strategy. As a result, the only EU member states proposing an accessible measuring framework for their CBE transitions are Finland, Germany, Italy and Spain. The indicator sets of these countries will be discussed further in the following chapters.

3.2. Indicator sets

This chapter presents the findings from the analysis of the indicator sets' form and strategic aspects, their fulfillment of purpose, and the breadth and depth of tackled issues.

3.2.1. Assessment of form and strategic aspects

Detailed information on the analysis of form and strategic aspects of the indicator sets is presented in the Supplementary Material Section 2.5, while the presence of each aspect in the indicator sets is summarized in Table 2.

The underlying frameworks of the existing national bioeconomy indicator sets broadly follow three designs:

1. **Finland** (Natural Resources Institute Finland, 2021) **and Spain** (Secretería de Estado de Investigación, 2016): A series of measures is applied to a series of sectors, resulting in a matrix of items to assess. The Spanish tool includes an inconsistency, as the measures are also applied to two non-sectoral elements.

Table 1
Quality assessment grid for indicators and indicator sets.

Category	Criterion	Author
Relevance	Aligned with interests of audience	(Feller-Länzlinger et al., 2010; Gabrielsen and Bosch, 2003; Hiremath et al., 2013)
	Representative of: studied issue; area or phenomenon of interest; socio-political or geographic context; local needs; policy target	(European Commission, 2018b; Eurostat, 2014; Gabrielsen and Bosch, 2003; Hiremath et al., 2013; Moreno Pires et al., 2014; Shen et al., 2011; Zavadskas et al., 2007)
	Accurate and reliable	European Statistical System (2019)
	Responsive to change and policy intervention	Eurostat (2014)
Utility	Indicative of development over relevant timespan	(Eurostat, 2014; Gabrielsen and Bosch, 2003)
	Useful for planning and policymaking	Hiremath et al. (2013)
	Comparable with: reference values and policy targets; other indicators; geographical areas	(European Statistical System, 2019; Eurostat, 2014; Gabrielsen and Bosch, 2003)
	Supported by causal explanations	Gabrielsen & Bosch (2003)
	Adaptable to contextual needs	European Commission (2018b)
	Easy to interpret by policymakers, the public and stakeholders	(European Commission, 2018b; European Statistical System, 2019; Eurostat, 2014; Gabrielsen and Bosch, 2003)
	Readily implementable	Hiremath et al. (2013)
Methodological Soundness	Based on sound statistical procedures	(European Statistical System, 2019; Gabrielsen and Bosch, 2003)
	Founded in scientifically constructed framework, based on: existing agreed definitions; classifications; standards; recommendations; best practices	(European Commission, 2018b; European Statistical System, 2019; Eurostat, 2014; Gabrielsen and Bosch, 2003; Hiremath et al., 2013; Wu and Wu, 2012; Zavadskas et al., 2007)
	Supported by policymakers	(European Commission, 2018b; Hiremath et al., 2013)
	Based on documented and accessible methodological procedure including clearly identified assumptions and sources	(European Commission, 2018b; European Statistical System, 2019; Eurostat, 2014; Feller-Länzlinger et al., 2010; Hammond et al., 1995)
	Derived from impartial and independent sources	European Statistical System (2019)
Measurability	Availability of cost-effective measurements and data collection	(European Statistical System, 2019; Eurostat, 2014; Feller-Länzlinger et al., 2010; Zavadskas et al., 2007)
	Calculated from regularly, reliably updated data	(European Statistical System, 2019; Eurostat, 2014; Feller-Länzlinger et al., 2010; Zavadskas et al., 2007)
	Calculated from accessible data	(Bracco et al., 2019; European Statistical System, 2019; Zavadskas et al., 2007)
Indicator Sets	Parsimonious	(Eurostat, 2014; Feller-Länzlinger et al., 2010; Zavadskas et al., 2007)
	Constructed from complementary, coherent indicators	Eurostat (2014)

2. **Germany** (Egenolf and Bringezu, 2018): Strategic and integrative goals are defined in the domains of social, environmental and economic sustainability. These are split into criteria based on the Sustainable Development Goals they support and matched with indicators.
3. **Italy** (Italian Committee for Biosafety, Biotechnology and Sciences of Life, 2019): Measuring categories are set and matched with fitting indicators. No reference is given regarding a political or theoretical origin of the categories.

Among the four, the German set emerged as the most elaborate in terms of quantity and variety of indicators, as well as the explanations provided. It gives a rounded view of the bioeconomy, clearly links the indicators to the strategy's goals, and adheres to sustainability frameworks supported by both policymakers and academia. Italy also follows up on several of its strategic goals in the indicator set. Both sets include measures that cross the boundaries of individual topic areas. They also provide explanations of the objects being measured and the correct application of the indicators by giving explicit statements on how the indicators can be used at various government levels. Furthermore, they both include quantitative and qualitative measures and, as recommended by Eurostat (2014) direct and indirect ones. Descriptive measures are accompanied by performance, efficiency, policy effectiveness and, in the case of Germany, total welfare measures.

Although the Finnish and Spanish frameworks align with the strategy's objectives and goals, the few indicators used do not shed any light on the progress made or decision making impact, if not only ambiguously. Furthermore, both the Finnish and Spanish monitoring systems, using only five or less indicators, merely rely on quantitative, direct and descriptive evaluations.

A coherent, policy-relevant definition of circularity as integral to the bioeconomy (Stegmann et al., 2020) across nations and cities is crucial to supporting collective efforts and synergies towards a continent-wide CBE (Zucaro et al., 2022). Nonetheless, the assessed indicator sets vary in the extent to which they include circularity measures. Italy and Spain point out the importance of circularity in their bioeconomy strategies. Italy includes circularity in the strategy's overarching goals and provides an indicator set with direct measures on energy, water and waste circularity. However, Spain only mentions it in the introduction, and declines to provide further follow-up. The German indicator set most thoroughly commits to its goal of making the bioeconomy more circular by integrating circularity measures in footprint-type indicators and by assessing resource and carbon cycles, as well as economic aspects of the CBE. Finally, Finland does not mention circularity in its strategy at all and consequently does not present any measures for it in its indicator set.

3.2.2. *Quality assessment*

The quality assessment in Table 3 shows that various pitfalls, particularly in the categories "Relevance" and "Utility", affect the quality of Finland's and Spain's indicators. On the other hand, scores in "Methodological Soundness" and "Measurability" are generally high, whereby those strategies with stated data sources (Finland, Germany and Italy) and an attached rationale (Finland and Germany) show a higher level of statistical validity. The Spanish framework's lack of supportive documentation for its indicator set impacted its quality rating, with several criteria that are neither "clearly met" nor "clearly not met" or "ambiguous".

Consideration must also be given to an evaluation of the Spanish framework by the European Commission, 2019b, stating that Spain's national statistics system would not be able to obtain objective numbers about its bioeconomy. A similar assessment of the reliability of the Finnish measures was made by the Natural Resources Institute Finland (Sauvula-Seppälä and Hautakangas, 2019, p. 1). These insights justify the low scores in "Methodological Soundness" for both tools and clearly depict gaps and weaknesses in their development, which ultimately

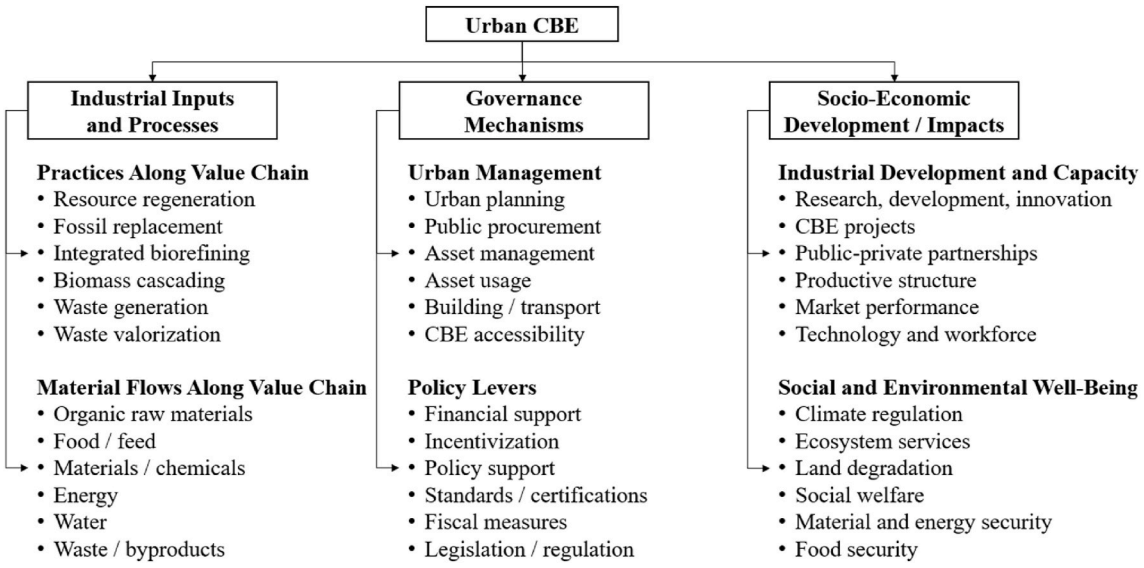

Fig. 2. Structure of the Topical Assessment Framework (3 aspects, 6 categories, 36 components).

Table 2
Form and strategic aspects of indicator sets.

	Finland	Spain	Italy	Germany
Goal-indicator alignment	✔	✔	✔	✔
Inclusion of circularity	x	Unclear	✔	✔
Policy-theory based framework	x	x	Unclear	✔
Indicator variety	x	x	✔	✔
Scalability	Unclear	Unclear	✔	✔
Aggregation	Unclear	Unclear	x	✔
Reliable/steady data source	Unclear	x	✔	✔

make the indicator sets less meaningful at national and urban level alike.

The German and Italian sets scored similarly, with differences in certain criteria being ambiguously represented versus "clearly met". No quality criterion was "clearly not met" by these monitoring systems.

3.2.3. Assessment of topical coverage

As the heat maps on topical coverage in Fig. 3 show, the differences between the Finnish and Spanish group versus the German and Italian trickle down to the breadth and depth of urban CBE topic coverage as well. The few indicators proposed by Finland and Spain concentrate on "Industrial Inputs and Processes" and "Socio-economic Development/ Impacts". These two aspects reflect how both indicator sets are constructed around a set of measures that are applied to a variety of industrial sectors. Furthermore, as the light-colored tiles indicate a low number of indicators pertaining to a given component, it is evident that the measured aspects are rather superficially studied.

Conversely, the German and Italian indicator sets covered the topics more comprehensively, presenting more breadth and depth of analysis. While the Italian set is rather evenly distributed across topic areas, a convergence of indicators in the aspect of "Socio-Economic Development/Impacts" reflects the German tool's strong focus on the three sustainability pillars, which are mainly represented within this aspect of the topical assessment. Concerning the utilization and regeneration of natural resources such as biomass, the German indicator set covers slightly more components than the Italian. Strikingly, despite being among the German strategy's goals to establish a sustainable base of raw materials, the country's tool does not cover related components (German Government, 2020). Similarly, built around the three pillars of sustainability rather than industrial processes and materials, the German framework neglects "Food/feed" and "Energy" flows. This resulted in two crucial aspects of the bioeconomy being omitted. Finally, both the German and Italian sets include at least one indicator referring to waste and valorization options.

When assessing topic coverage across all four frameworks together, a dominant focus on "Social and Environmental Well-Being" seems to emerge. Within this group of components, however, except for the German indicator set, little focus is placed on social issues. Furthermore, within all indicator sets, the components of "Material Flows" are highly represented, though they lack specificity. In fact, while the components are defined in the topical assessment framework to reflect "circularity" (see Supplementary Material Section 2.3), most indicators allocated to these categories do not allow such insights. Similarly, even though their operationalization includes land, buildings, roads and bridges, as well as water and sewage systems as assets, the components of "Asset

Table 3
Quality Assessment of Indicator Sets (The quality criteria were assembled in Chapter 2, grading is based on two extreme (1 = clearly not met and 3 = clearly met) and one neutral grades (2 = ambiguous).

	Finland	Germany	Italy	Spain
Relevance				
Aligned with audience	1	2	2	1
Representative	1	2	2	1
Accurate/reliable	1	3	2	1
Responsive	3	3	3	3
Utility				
Shows development	2	2	3	2
Useful for planning	1	2	2	1
Comparable	1	2	2	N/A
Causal explanations	1	3	3	1
Adaptable to context	2	3	3	2
Easy to interpret	2	3	3	2
Implementable	3	3	3	2
Methodological Soundness				
Sound statistics	1	3	3	1
Scientific framework	1	3	2	1
Supported by policy	3	3	3	3
Stated methodology	2	3	2	1
Impartial sources	3	3	3	N/A
Measurability				
Affordability	N/A	N/A	N/A	N/A
Data regularity	3	2	3	N/A
Data accessibility	3	3	3	N/A
Indicator Sets				
Parsimony	1	2	2	1
Complementary	2	3	3	2
Total	**37**	**53**	**52**	**25**

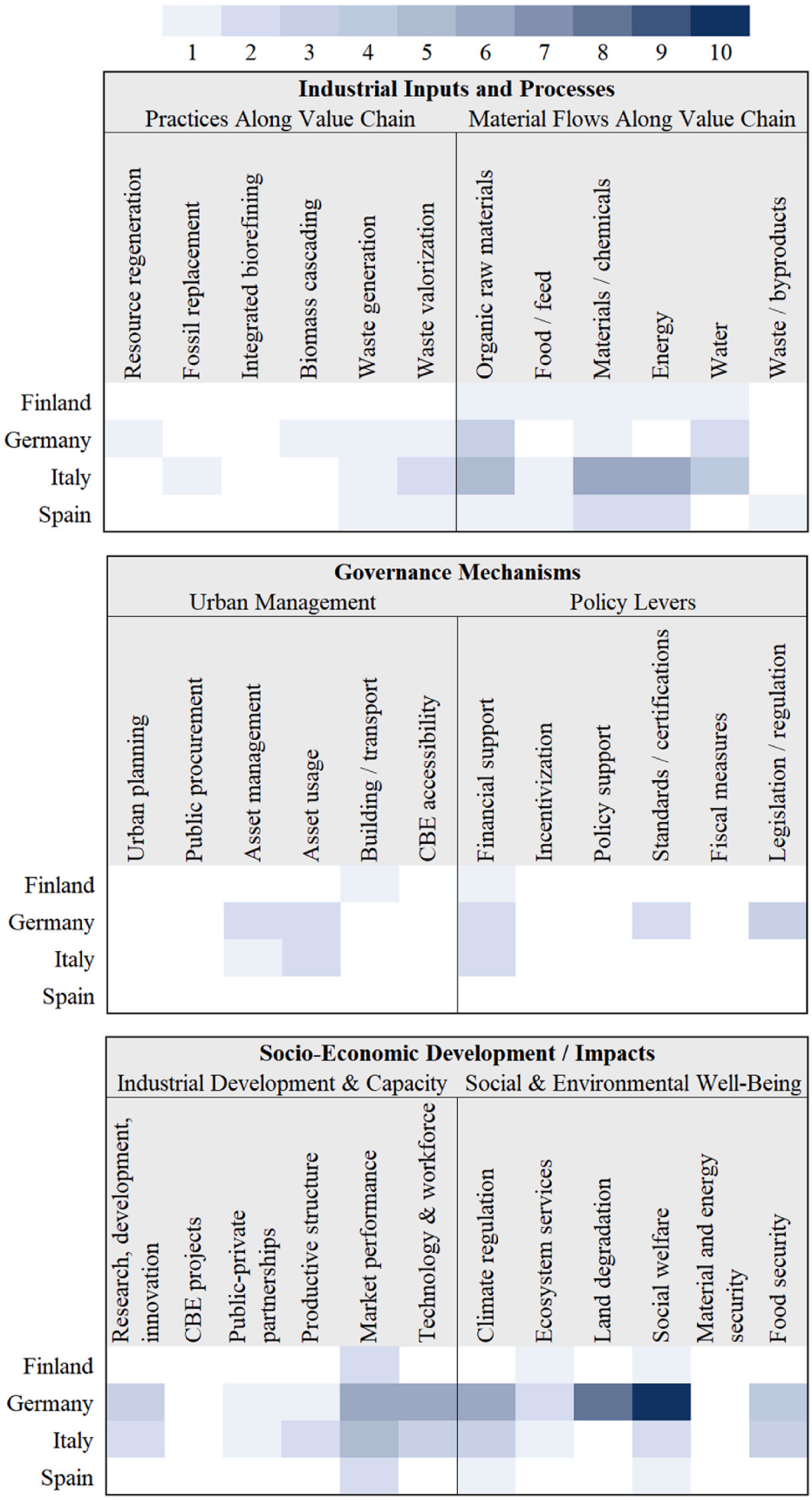

Fig. 3. Heat Maps of the Indicator Assessment (Each match between an indicator from a set and a component of the assessment framework resulted in 1 point for the component. The darker the shade, the more points were attributed to the component; a high number of colored tiles per country thus means that several topics are covered (broad coverage) while dark shaded components indicate multiple references of indicators to this component (deep coverage).

management" and "Asset usage" were exclusively matched with indicators regarding land. The component "Technology and workforce" as well, is only covered by workforce-related indicators and not by technology-related ones.

Components such as "Market performance" overall, but also "Land degradation" and "Social welfare" in the case of Germany, stand out by virtue of the importance given to them by the indicator sets. Further, profound coverage can be observed for "Technology and workforce" and "Climate regulation", while the CBE-essential practices of "Biomass cascading" and "Integrated biorefining", as well as "Resource regeneration" and "Fossil replacement", are significantly underrepresented. Similarly, the category of "Practices along Value Chain", reflecting circularity most directly across the framework, also exhibits low focus.

Finally, some parts of the assessment framework are not covered at all. The aspect with the least coverage across all indicator frameworks is "Governance Mechanisms". In "Socio-Economic Development/Impacts", the lack of "CBE projects" and generally low number of economic indicators besides "Market performance" are evidence of a higher focus on the economic performance rather than industrial structure and development. A final measure that does not appear in any of the frameworks is "Material and energy security".

4. Discussion

4.1. Key insights in the indicator sets

The number of EU member states that have adopted a dedicated bioeconomy strategy so far is conspicuously low, considering that the EU already called for bioeconomy development in 2012 (European Commission, 2012). The absence of more dedicated bioeconomy strategies can partly be explained by several member states having implemented related strategies or similar bioeconomy policy initiatives that do not qualify as "dedicated bioeconomy strategies" to the EC (European Commission, 2019a). Another subset of the EU-27, especially the states with a strategy under development during the 2019 review, may have joined the pioneering countries since.

Among the existing bioeconomy strategies only four include indicator sets, which vastly differ in form, quality and content. The well-built and diverse German and Italian sets allow an interdisciplinary approach to CBE monitoring and integration of various complementary measures within categories of their indicator frameworks (Eurostat, 2014). On the other hand, the Finnish and Spanish sets present several gaps that weaken their adherence to the indicator development best practice of rooting indicator frameworks in theory and policymaking and reduce the indicators' monitoring and policy support functions (Eurostat, 2014; Gabrielsen and Bosch, 2003). Moreover, their lack of indicator diversity limits the potential for multi-perspective interpretation of cause-and-effect relationships (Eurostat, 2014; Haines-Young, 2009). The indicators' combination with qualitative, performance, efficiency, policy effectiveness, and total welfare measures could help uncover such relationships (Gabrielsen and Bosch, 2003).

With regards to the inclusion of circularity measures, a clear disparity can be observed following the time of issuance of the various strategies. Dating from 2014 to 2016, respectively, the Finnish and Spanish strategies were issued during a period in which the circular economy gained increasing popularity and solidification as a concept but was not yet understood to be an integral part of the bioeconomy. The strategies adopted after the EC's official integration of circularity in the bioeconomy (see European Commission, 2018a) both include circular principles in their goals as well as indicators. This hints at a shift in how inherently circular features of the bioeconomy have increasingly been accounted for since 2018. Possibly the late uptake of circularity within bioeconomy strategies is also due to the rapid dissemination of circular economy principles and development in policymaking separate from the bioeconomy itself. Indeed, several sources (e.g., Ellen MacArthur Foundation, 2013) see the bioeconomy as part of the circular economy rather than the other way around (Stegmann et al., 2020) while Kircher (2022) highlights the still ongoing development of bioeconomy concepts towards circularity.

The quality assessment showed that mainly the Finnish and Spanish sets present quality flaws. Partly, the low performance in "Relevance" and "Utility" is due to the assessment grid being built to judge the tools based on the needs of urban policymakers while the indicator sets were built for national governments. Nonetheless, quality criteria such as "Reliable", "Comparable" and "Causal explanations" should be met without regard to the user's goals (European Statistical System, 2019). Furthermore, the complications related to the Spanish set's assessment indicate that an explanation of rationales behind measures, in particular stating their interrelationships, can significantly improve the practical quality of an indicator set. For urban policymakers, more insight in how to utilize a national assessment tool increases the chances of correct application and utilization of instruments as intended.

Finally, the assessment of topical coverage highlights differences in focus set by the various national indicator sets. Within the area of political indicators, Ferreira et al.'s (2022) findings, stating that social bioeconomy impacts have generally been neglected in research compared to environmental and economic ones were confirmed in this study. Accordingly, the strong focus on the analysis of economic impacts of the bioeconomy is not only a phenomenon in the assessed bioeconomy indicator sets (particularly the Spanish and Finnish ones) but has been a recurring theme in research, as well (Ferreira et al., 2022). A skewed perception of CBE development also occurs from a lack of inclusion of indicators on "Policy Levers", which are the primary operating instruments for influencing and monitoring the development of the CBE (Hetemäki et al., 2017; Swilling and Hajer, 2017). Consequently, issues such as adverse subsidies and unpaid externalities, which can drastically hinder the sustainable development of a CBE, cannot be detected with the studied indicator sets. Lastly, lacking indicators on "Material and energy security" present an impactful issue when transitioning an urban economy with its highly concentrated energy and material consumption from non-renewable to regenerative resources while aiming to maintain living standards and economic growth (Hetemäki et al., 2017).

In conclusion the answer to research question 1 is multifaceted. There are vast discrepancies between the four existing national bioeconomy indicator sets: While Italy and Germany provide extensive and versatile tools that combine theoretical and political aspects of the bioeconomy with a high overall quality rating, the Spanish and Finnish indictor sets are rather small and simplistic and lack many essential elements of high quality and functioning monitoring tools.

4.2. Indicator set suitability to urban needs

When considering whether these national CBE monitoring tools are suitable starting points for the evaluation of urban-level CBE developments, one must acknowledge the elaborations in Section 4.1. Similarly to national policymaking, the flaws in the Finnish and Spanish sets prevent a conclusive, multifaceted monitoring approach on the urban level too. With their lack of connections to scientifically and politically relevant frameworks, two essential features of high-quality indicator sets are missing (Eurostat, 2014; Schang et al., 2021), while too much focus is put on economic measures. Ideally, however, the CBE should contribute to all three dimensions of sustainable development at both, national and urban policy levels (Kardung et al., 2021). As such, basing an urban CBE monitoring framework on the Finnish or Spanish approaches results in a tool with unilateral focus, low communicative value and unconclusive assessments of a city's CBE transition.

Conversely, the findings show that the German and Italian monitoring systems propose high-quality and politically relevant tools that, to some extent, are available for urban policymakers to benefit from. According to Gabrielsen and Bosch (2003), tools like the German and Italian ones, offering a variety of interrelated measures are of higher utility due to their potential for adaptation to local contexts and for

weighing indicators from different areas. By incorporating an EU-aligned notion of CBE and corresponding measures, these instruments open the possibility of aligning city-wide, regional, national and international efforts and serve a more holistic and coherent European CBE transition. The benefits of aligning with strategic policy needs are acknowledged in indicator sets related to the CBE, for instance, those of smart cities (Sharifi, 2019).

Nonetheless, despite a better fit of the German and Italian indicator sets, some caution in recommending their use at an urban level is called for. Both sets are based on a locally relevant framework and reflect various measures with differing topical breadth and depth that might be less meaningful at the urban level. Critically, urban CBE indicators derived from national frameworks may reflect a successful outcome, although at the urban level, this is not the case (Zia et al., 2011). Moreover, adapting these indicator sets to urban use comes at the risk of losing important interlinkages between indicators and reducing the communicative value of the tool as a whole. Interlinkages may exist at one scale, but not necessarily at another (Mohtar and Daher, 2016). As such, both instruments include aspects that might challenge their applicability to city-wide CBE monitoring. Nonetheless, despite not providing a rounded and indiscriminately relevant tool to be used by any city across the EU, these tools can serve urban policymakers as solid blueprints for the construction of a tailored CBE indicator set.

The answer to research question 2, therefore, also requires differentiating between the Finnish and Spanish approach and the Italian and German one. Only the latter group issued indicator sets that are versatile and relevant enough to provide a basis from where to start building urban bioeconomy indicator sets. Applying the Finnish or Spanish tools at an urban level might result in misaligned, one-sided and relatively ill-built instruments.

4.3. Research contributions

This research gives a situational overview of how best practices in indicator development and the notion of CBE are currently represented and incorporated in bioeconomy monitoring approaches of EU member states. It identifies issues in topical focus, qualitative weaknesses and the relevance of future action for improvements and developments of indicator sets. As such, the study helps improve CBE monitoring which leads to new business opportunities in the field of cleaner production and ultimately to improved resilience and sustainability of the European economy. This, at a time where global supply-chain and production shortages are caused by multiple simultaneous crises.

4.3.1. Policy implications

An alignment of policymaking and monitoring tools across government levels creates benefits in the form of synergies in data collection and evaluation as well as direct comparability of measures. Without alignment, systemic errors in the CBE transition might remain undetected, lead to inefficiency and wasted resources, and render states, cities and businesses unable to effectively and uniformly work towards reaching consensus in sustainable development (Pillay and Buschke, 2020). Investments in detailed, efficient and streamlined indicators for the CBE transition prevent digressions from indicator best practices and prevent incomplete, and thus dysfunctional monitoring systems. The indicator set assessment conducted in this study, thus, allows policymakers to take corrective action towards a more efficient CBE transition.

4.3.2. Practical implications

The present research also informs national policymakers about their strategies' guiding functions for local CBE development. Policymakers can identify areas of relevance to other policymaking levels and create monitoring sets that are in line with EU-wide requirements and with the measuring capabilities and needs of cities. Future indicator sets can be created to compensate for currently lacking items, such as indicators for governance mechanisms or CBE practices, and replicate valuable features such as policy and theory-based indicator frameworks. In short, the research makes a practical contribution by laying the ground for cross-scale CBE indicators (Bourdic et al., 2012).

Moreover, creating new bioeconomy monitoring frameworks or updating existing ones at the national level by integrating the findings of this research has benefits that trickle down to the private sector. Effectively monitoring the CBE development and aligning it across different scales provides clarity and transparency, which supports the development of business opportunities and innovation that can accelerate reaching strategic goals (Murillo-Luna et al., 2011).

4.3.3. Theoretical implications

Contrary to the claim by Kardung et al. (2021), this cross-country comparison was possible, but required the development of a toolbox based among others on indicator development theory. The systematic and analytical approach to assessing the indicator sets defined in Fig. 1 makes an academic contribution to indicator theory, policy and beyond in two ways: The three-step data analysis process (factsheet, quality and topical coverage) serves as a structured and holistic data analysis method, while the quality criteria and CBE topic coverage assessment framework represent two new data analysis instruments assembled from the available literature. The developed tools, therefore, do not only serve as a basis for assessment and improvement of the national indicator sets. In fact, they are also valuable inputs to the future development of a comprehensive and unified indicator framework for the measurement of global CBE developments across policy levels and regions. Indeed, the proposed methodology can not only be used to assess indicator sets at an EU level but on other continents, single countries or cities as well. Furthermore, while research efforts for assessing existing indicator sets have very much been focused on individual sectors of the CBE so far (biorefineries (Patrizi et al., 2020), forest management (Noss, 1999; Wolfslehner et al., 2016) and waste management (Yuan, 2013)), a vast variety of indicator sets with reference to cleaner production (e.g., urban mining, industrial symbiosis, waste-to-energy strategies, etc.) can be tested with the three tools developed in this article.

4.4. Limitations and opportunities for further research

A variety of limitations that compromise the validity of the findings of this research must be noted. Firstly, the research process showed that a CBE cannot be efficiently measured within the confines of an urban perspective, as city economies inevitably interact with their hinterlands in an interdependent relationship. While the focus on urban areas addresses entities with high impact on sustainable development as described in Section 1.2 of this paper, in the future a similar study could be conducted for entire regions to gain more practicable and conclusive results. Indeed, an approach to urban CBE development that reconnects urban and rural areas might strongly support holistic progress, for instance in terms of material flows or allow to detect CBE inefficiencies in the first place (Cattaneo et al., 2018, for instance, detected a deterioration of agricultural CBE in the Barcelona Metropolitan Region by studying urban-rural production and consumption patterns).

A second limitation concerns the development and usage of the topical assessment tool. While it fulfilled the purpose of informing about the indicator sets' topic coverage, some caveats must be considered. Due to their qualitative nature, different components of the assessment framework can be attributed varying numbers of indicators. This prevents linear comparability of depth of coverage across the components. Another necessary consideration pertains to the choice of attributing each indicator from a strategy to only one, directly related component of the assessment framework, rather than multiple. The rationale for this decision was to avoid interpreting the indicator sets beyond the given elaborations. However, this implies that more topic areas might be represented (either directly or indirectly) in the indicator sets than the heat map actually displays. Further research might be conducted to discover more profoundly how the indicators within national indicator

sets are directly and indirectly interrelated and to what extent they manage to synergistically support policymaking and inform the broader public on CBE development. Furthermore, the topical assessment framework's composition and application might be assessed in a future study with the goal of increasing the validity of the findings.

A final limitation for this study was the data availability. The last systematic review of EU-wide national bioeconomy strategy development was conducted by the EC in 2019 (European Commission, 2019a). Despite being slightly outdated, this list was referred to due to its methodological reliability and because it allows differentiating between what the EC considers to be a "dedicated bioeconomy strategy" versus "bioeconomy policy initiative" or "related strategy". Furthermore, the data collection resulted in a set of four monitoring frameworks, whereby only two of them included thorough elaborations on the various indicators and reflections on the framework compositions. As a result, the usefulness of half of the collected data was significantly compromised. Further research might tackle the study of bioeconomy-related policies in EU member states that do not have a dedicated bioeconomy strategy as identified by the EC or investigate ways to increase applicability and ease-of-use of existing monitoring systems.

5. Conclusion

This research allows to draw various conclusions. Firstly, the CBE monitoring landscape is currently in its early stages, with five of nine bioeconomy strategies lacking an indicator set entirely and two of the remaining ones presenting sets that do not fulfill a policymaker's compositional, qualitative or topical needs. Secondly, the results indicate that the more recent and complex monitoring frameworks (Germany and Italy) follow up on various critical considerations better than the older and simpler ones (Spain and Finland). Such considerations include grounding the underlying indicator frameworks in both theory and policymaking practice, including indicator diversity for a more conclusive monitoring approach, aligning definitions of the CBE with EU-wide policymaking, and finally, covering a more comprehensive range of topic areas. By fulfilling these requirements, the recent sets find relevance in guiding the composition of tailor-made indicator sets for urban policymaking. They allow the notion of circularity to transfer within the bioeconomy from an EU-wide strategy down to an urban implementation plan, fulfilling their educational, policy support, outcome monitoring and informative functions. Nonetheless, despite a better fit of the German and Italian indicator set, recommending their use at an urban level requires caution. Both frameworks are based on a locally relevant framework and reflect various measures with differing breadth and depth that might be less meaningful at the urban level.

While it is not the aspiration of the national frameworks to create an instrument with a perfect fit for urban use, it is vital for EU member states to develop strategies favoring alignment with other policy levels and thus comparability across cities (Zucaro et al., 2022). With well-produced and aligned strategies including efficient and functional monitoring systems, an efficient, rapid and coordinated CBE transition becomes possible. This argument for the formulation of uniform, rapid and efficient policy answers to mounting environmental crises, is facilitated by this study through the identification of strengths, weaknesses and gaps in current indicator sets and by laying the groundwork for future improvement. In the decisive decade for the future of this planet's climate, the question whether action is taken thoughtfully becomes ever more important.

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CRediT authorship contribution statement

Roberto Davide Marcone: Conceptualization, Methodology, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Visualization, Project administration. **Marc Schmid:** Conceptualization, Writing – review & editing, Supervision, Project administration. **Grégoire Meylan:** Validation, Writing – review & editing, Supervision, Project administration.

Declaration of competing interest

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

Data availability

The data collected for this research consists of publicly accessible indicator sets. They are appropriately referenced in the paper.

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Appendix A. Supplementary data

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