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METHOD ARTICLE

REVISED Definition and application of indicators for urban bioeconomy: Analyzing the circularity maturity profile of european cities and regions

[version 2; peer review: 1 approved, 3 approved with reservations]

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Abstract

Background

The European Commission is promoting the Circular Economy (CE) to replace the linear model with one based on recycling and reuse. A genuine commitment to the CE requires that organizations and cities first identify and quantify the value leakages within their resource flows before designing and implementing any CE-related initiatives.

Methods

This study presents an innovative set of Urban Bioeconomy Indicators (UBI) designed to assess and enhance CE initiatives in cities and regions, with a particular focus on biowaste management and valorization. Addressing the need for standardized yet locally adaptable metrics, this research proposes a comprehensive methodology for evaluating urban bioeconomy performance. The study's methodology involved an extensive review of existing CE indicators, followed by a structured selection and adaptation process. This led to the development of 20 indicators across six key dimensions: Waste, Water, Energy, Economy, Society, and Policy. The UBI set uniquely integrates both quantitative and qualitative

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indicators, including 'enabling factors' that capture crucial but hard-to-quantify aspects of CE implementation.

Results

Key innovations of this research include: (1) a specific focus on urban bioeconomy, (2) emphasis on material valorization over energy recovery, (3) introduction of self-sufficiency indicators, and (4) incorporation of qualitative enabling factors. Nevertheless, the indicators are designed to measure both citizen behavior and waste management system performance, providing a holistic assessment of urban CE progress.

Conclusions

By providing a standardized yet flexible methodology, this work contributes to the advancement of urban bioeconomy assessment. It serves as a valuable tool for local authorities to measure, compare, and enhance their bioeconomy performance, potentially laying the groundwork for future urban CE evaluations and policy development.

Plain Language Summary

This study introduces a new set of Urban Bioeconomy Indicators (UBI) to help cities manage and improve how they handle biowaste (organic waste) in a circular economy (a system that reduces waste and reuses materials). The goal is to create standardized but flexible measures that work in different urban areas. To develop these indicators, researchers reviewed existing ones, selected the most relevant, and adapted them. The final set includes 20 indicators in six categories: Waste, Water, Energy, Economy, Society, and Policy. These indicators mix numbers (quantitative data) and descriptive aspects (qualitative data) to capture hard-to-measure factors that influence circular economy efforts. Key contributions of this study include: A focus on the urban bioeconomy (how cities handle organic resources). Prioritizing material reuse over just generating energy from waste. Creating self-sufficiency indicators (measuring how well cities manage resources independently). Including qualitative factors to understand citizen behavior and government policies. This set of indicators helps cities track their progress, compare results, and improve waste management and sustainability policies. It provides a useful tool for decision-makers to support better environmental strategies in urban areas.

Keywords

Circular Economy, Baseline Analysis, Urban Bioeconomy, Bioeconomy Indicators, Waste management, Urban Sustainability, Enabling Factors

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Any reports and responses or comments on the article can be found at the end of the article.

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REVISED **Amendments from Version 1**

This revised version of the manuscript builds upon the initial publication by introducing several clarifications and refinements aimed at improving conceptual coherence, methodological transparency, and readability for a broad audience.

One of the main updates concerns the conceptual framing of the urban bioeconomy, which has been strengthened in the Introduction. While the first version implicitly addressed urban bioeconomy through the context of the HOOP project, the revised manuscript situates the concept more explicitly within existing academic and policy debates. It now outlines how previous studies have largely approached bioeconomy from national or sectoral perspectives and highlights the limited attention given to urban contexts, where biological resources are primarily derived from biowaste and wastewater. Building on this gap, the paper introduces a clear operational definition of urban bioeconomy, which provides the conceptual basis for the proposed indicator framework.

The methodological narrative has also been refined to improve clarity regarding the development and application of the Urban Bioeconomy Indicators. Greater emphasis is placed on the criteria guiding indicator selection and adaptation, including relevance to urban systems, alignment with circularity principles, data availability, and applicability across different city contexts. The role of qualitative indicators and enabling factors is more clearly articulated, underscoring their importance for capturing governance, social engagement, and policy conditions that influence urban bioeconomy transitions.

In addition, the interpretation of results has been enhanced to strengthen the link between the indicator framework and its application to the eight European cities. The revised text provides clearer contextualization of observed differences across cities and explicitly acknowledges key limitations related to data heterogeneity and comparability. Overall, these revisions aim to offer readers a more transparent, robust, and accessible presentation of the framework and its relevance for assessing urban bioeconomy transitions.

Any further responses from the reviewers can be found at the end of the article

Introduction

Over the past few years, the European Commission has been implementing a broad array of policy initiatives related to the Circular Economy. These measures aim to facilitate the transition from a traditional linear "take-make-consume and discard" economic model towards a more sustainable "recycle-and-reuse" approach.

The goal is to mitigate the detrimental impact of economic activities on the environment and natural resources. Genuine engagement with the Circular Economy (CE) necessitates that organizations and cities first identify and quantify the value leakages occurring in their resource flows before designing and implementing any CE-related initiatives.

This value loss assessment requires an understanding of the current circularity level and the points at which these leakages occur, enabling the measurement of the gap between the existing scenario and the desired circular state.

The CE is an umbrella concept that embraces different approaches aiming to extend the value and utility of products and that consider waste as a valuable secondary resource. Although intuitive, the complexity of the CE concept produces an evolving debate on definitions, limitations, and boundaries.[1] This fact has major implications for defining the most appropriate method for the assessment of the current circularity maturity profile of a given organization or city.

The bioeconomy has been widely addressed in policy and academic literature as a strategy to promote the sustainable use of biological resources and reduce dependence on fossil-based materials.[2,3] However, most studies and strategies have adopted a national or sectoral perspective, focusing on biomass production, biotechnology or industrial biorefineries.[4] In contrast, the urban dimension of the bioeconomy, where biological resources are mainly derived from biowaste and wastewater, has received limited attention so far. Only recently have researchers begun to conceptualize the urban bioeconomy as a distinct field, emphasizing the need to integrate biological resource valorization within circular urban systems.[5,6] These emerging studies highlight that the recovery of organic residues and wastewater streams can serve as a cornerstone for new circular bio-based strategies in cities.[7]

In this study, we define the urban bioeconomy as the valorization of urban biowaste and wastewater through circular solutions that enable local bio-based value chains and contribute to resource efficiency, decarbonization, and social well-being at the city level. This operational definition addresses the current gap by explicitly framing cities as active enablers of bio-based circularity, where waste streams are transformed into resources within local economic systems. It provides the conceptual foundation for the indicator framework developed in this paper, which seeks to capture the multi-dimensional maturity of urban bioeconomy transitions across European cities and regions.

In this context, this research established a comprehensive assessment method to analyze city- and region-wide progress towards the CE. To this end, a set of CE indicators will be defined and applied to assess the current level of circularity in eight cities that foster this model through urban biowaste valorization. These indicators will serve as a benchmark for measuring circularity at the European regional level. Developed within the framework of the European Project HOOP [H2020 ID 101000836], these indicators support its goal of unlocking urban circular bioeconomy initiatives and fostering local bio-economies in eight European cities and regions. The project focuses on valorizing the organic fraction of municipal solid waste and urban wastewater sludge, transforming them into high-value products beyond compost and biogas.

To accurately assess whether a specific intervention is achieving the desired change, it is essential to establish a baseline scenario. This allows for impact analysis and comparison with future scenarios, incorporating the application of the indicators to evaluate progress over time. Taking this into account, a baseline analysis could be useful for planning, monitoring and evaluating the circular measures.

According to this, the success of CE will be, to a large extent, measured in relation with the defined baseline. Therefore, a careful and correct baseline specification is crucial to assure an accurate impact estimation. Among all the parameters to be considered, specific variables (e.g., circularity aspect), sources (e.g., industry, public entities, general data bases), geographic resolution, and years covered should be highlighted.[8] Thus, depending on the problem to be dealt with, different thematic pattern scenarios could be built according to the individual issue or topic covered (issue-based scenarios) as well as classified according to the selected viewpoint (macro-, meso- and microlevels).[9]

The baseline analysis offers a macro-level picture (city/region level) picture about the urban circular bioeconomy maturity profile of the 8 different cities.

Having a solid system of indicators for assessing the CE implementation is key in order to achieve sustainable development. At present, there is a lack of a consensual methodology for the evaluation of the CE performance and progress, there is not a harmonized framework, which leads to an availability of a wide variety of indicators that could compromise the robustness of the analysis.[10,11]

According to the Organisation for Economic Co-operation and Development (OECD) report entitled “Inventory on Circular Economy Indicators”,[6] CE indicators could be classified in the following categories: Economy and Business, Environment, Governance, Infrastructure and Technology and Jobs. In said report, the OECD reveals the following: environmental-related indicators prevail, especially energy usage or emissions; solid waste sector prevails over other industrial segments; lack of governance-related indicators; few city-level indicators available. Although the waste axis is overrepresented, most of the indicators in that sector are not defined from a closing-the-loop point of view; there is a lack of monitoring the reduction progress, which is the first approach of the 3R rule.[12,13]

The baseline analysis provides an overview of the current status of the 8 cities and regions previously mentioned, where circular economy measures are being implemented, allowing for the selection of the most appropriate improvements for each of them. The baseline analysis has been run in two levels:

- Baseline studies. Description of each city/region in different dimensions, presenting the main characteristics and the picture based on the six dimensions (Economy, Energy, Policy, Society, Waste, Water).

- Urban Bioeconomy Indicators. A set of indicators have been defined and selected in order to establish the reference point for each city/region.

Methods

The methodology employed in this study followed a pragmatic, criteria-driven selection and adaptation process, focusing on tailoring existing circular economy (CE) indicators to urban contexts within a bioeconomy framework. The development of the indicators was grounded in the analysis of different cities (Table 1) and their circularity-related activities. This allowed for the identification of key quantitative and qualitative indicators, as well as the creation of additional indicators addressing underrepresented categories, particularly in policy, society, and economy.

Review of existing frameworks and data collection

The first stage involved a thorough review of prominent CE indicator sources, primarily the OECD’s “Inventory on Circular Economy Indicators” and the “Indicators for circular economy transition in cities” report from the Urban Agenda for the EU.[3] These sources provided a comprehensive starting point for identifying relevant indicators across various CE dimensions.

Table 1. Description of the Cities and Region Analyzed to Determine UBI.

City	Population (hab)	Area (km ^{2})	Population density (hab/km ^{2})	GDP per capita (€)	Predominant sector	Tourist/ hab	Geography
1	~210,000	~250	~1,600	~40,000	Trade, logistics, financial services and tourism.	3.3	Coastal, near a major European capital with a modern urban planning.
2	~964,000	~2,040	~535	~35,000	Transforming industries, services, construction and tourism.	1.8	Coastal city in Southern Europe, built on hills along a river, with steep streets and ocean views.
3	~365,000	~138	~2,400	~70,000	Non-renewable energy production and ocean technology.	4.1	Coastal city in nordic country, surrounded by fjords and mountains.
4	~460,000	~880	~520	~27,000	Agriculture, tourism	1.2	Inland city in a Mediterranean climate.
5	~120,000	~1,700	~72	~50,000	Social and private forestry, and education.	1.2	Lakeside city in a northern European country, surrounded by forest.
6	~42,000	~59	~710	~38,000	Tertiary sector and industry (metallurgical, mechanical and electronic).	1.2	Inland city part of a metropolitan region with a mix of industry and nature.
7	~280,000	~9,500	~30	~18,000	Agriculture, forestry and phishing.	3	Mountainous region in southeastern Europe, with deep valleys, lakes, and highland plateaus
8	~315,000	~303	~1,050	~55,000	Services (insurance, banks, courts), ICT and universities.	2.1	Mid-sized inland city in the centre of Europe with 5 universities.

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Beyond the existing data available from prior reports, additional information was necessary to complete the assessment of each city. To gather this knowledge, a structured technical questionnaire was distributed to city representatives. This questionnaire included key circularity aspects and was structured along six primary dimensions: Waste, Water, Energy, Society, Economy, and Policy. The questions were categorized into two levels—Primary and Secondary Questions—based on their relevance in establishing a robust baseline.

The key aspects covered in the technical questionnaire vary across the six dimensions previously mentioned. In the Waste sector, the required data highlights the proportion of organic fraction in municipal solid waste (OFMSW) and its diversion to landfills, along with the effectiveness of separate biowaste collection. It also tracks urban wastewater sludge (UWWS) generation, disposal methods, and agricultural reuse rates. Additionally, it includes metrics on municipal waste per capita, recycling rates, and biowaste management efficiency.

For the Water dimension, the focus extends to wastewater production, treatment, and reuse, encompassing household, industrial, and agricultural consumption. The wastewater treatment plant (WWTP) efficiency, the quality of discharged water, the volume of water withdrawn for potabilization, and the proportion of treated water returned to the environment are also assessed. The role of water management companies is also outlined.

In the Energy sector, the focus is on total energy consumption, renewable energy production, and energy recovery from biowaste and sludge. Additionally, it monitors fossil fuel dependence, greenhouse gas (GHG) emissions from waste transport and treatment, and the self-energy consumption of waste and water treatment plants. The survey also records impurities in selectively collected organic waste, which impact energy recovery efficiency.

The Society sector covers demographic and socioeconomic factors such as population density, unemployment rates, and main economic activities. It also tracks employment in waste management, environmental awareness initiatives, and eco-label certifications. This is because these factors influence waste generation, management efficiency and recycling participation.

The Economy sector highlights investments in circular economy projects and Research & Development (R&D) related to biowaste management and sludge treatment. Furthermore, it assesses the economic viability of waste recovery efforts, including job creation in the circular economy.

Finally, the Policy dimension evaluates the implementation of sustainability-related policies, waste treatment fees, and regulatory efforts aimed at enhancing circularity and resource recovery.

Data was collected from both public and private sectors to account for the complex and heterogeneous systems in which cities operate. One of the main challenges encountered during this process was the varying availability and accessibility of data across cities.

Pre-selection and adaptation

The second stage involved pre-selecting indicators from the reviewed sources and adapting them to the urban bioeconomy context of the participating cities and regions. The goal was to ensure that the selected indicators captured the specific characteristics of urban circular bioeconomy, particularly in relation to biowaste valorization and bio-based resource flows. The indicators were distributed along the six identified dimensions (Waste, Water, Energy, Society, Economy, and Policy) to ensure comprehensive coverage.

Optimization based on practical aspects

In the third stage, the pre-selected indicators were further refined based on practical implementation criteria. The key factors considered included:

- Data availability: Indicators were evaluated based on the accessibility and reliability of the required data sources within the participating cities and regions.

- Simplicity: Preference was given to indicators that were straightforward to calculate, use, and understand, promoting ease of implementation and interpretation.

- Comparability: Indicators were designed to allow for meaningful comparisons across diverse city types, considering differences in size, population, and socio-economic contexts.

This refinement process involved selecting and refining conventional indicators while also identifying categories or aspects that were underrepresented in existing frameworks. For example, as it was mentioned previously, the OECD's report highlights the need for measurement of municipal circular economy initiatives or the need to assess energy recovery.[3] As a result, new indicators were specifically developed to address these underrepresented dimensions. Consequently, the set of Urban Bieconomy Indicators was tailored to align with the project's objectives and assumptions. However, this methodology provides a structured approach that can be integrated into other cities interested in adopting HOOP's framework. These additional indicators were designed to enhance applicability and comprehensibility, ensuring that cities with diverse characteristics can effectively implement and benefit from them.

Final criterion application

Finally, at this stage, a set of criteria was applied, considering the complexity of the urban circular bioeconomy. Some of these factors included:

- **Bio-based approach**: Indicators were designed to focus on biowaste and biological resources, aligning with emphasis on the urban circular bioeconomy.
- **Urban scope**: Indicators were tailored to capture the unique dynamics and challenges of urban environments, considering factors such as waste management systems, stakeholder involvement, and policy frameworks.
- **Circularity principles**: Indicators were selected and adapted to prioritize material valorization, waste prevention, and the recirculation of resources within the urban ecosystem.
- **Comparability**: Since the cities and regions have different sizes and number of inhabitants, several indicators have been corrected with the number of inhabitants enabling the comparison.
- **Enabling factors**: Qualitative indicators were incorporated to evaluate enabling conditions such as awareness campaigns, entrepreneurial initiatives, and policy support, which facilitate the transition to a circular bioeconomy.
- **Target of evaluation**: the indicators should allow for assessing the performance and commitment of both the management system and citizenship, as the circular urban bioeconomy depends on both.

The final set of UBI has been implemented into a digital tool available on the HOOP project's web platform. This tool allows users to assess their city's circularity performance by inputting relevant data and generating a customized circularity score. By providing an accessible, open-access, user-friendly interface, this initiative aims to promote broader engagement and facilitate the practical application of the developed indicators. This tool is available at: HOOP Circularity Label.

By building upon existing CE indicator frameworks, analyzing them in relation to the specific needs of the study, and incorporating practical considerations and guiding principles, a tailored set of indicators was developed. These indicators serve as a benchmark for measuring initial status, establishing baselines, monitoring progress, and identifying areas for improvement in cities and regions aiming to implement urban circular bioeconomy initiatives. This analysis establishes the starting point for each city or region to enhance its bioeconomy performance, offering a structured methodology that can be adapted and expanded within broader circular economy transitions.

Results and discussion

Even though CE is not clearly defined, as it is an umbrella concept, there is a need for specific methods to measure its progress, but it has to be done carefully since indicators could lead to incoherent conclusions. It is important that indicators represent two defining characteristics of CE, which differentiate it from linear economy: **slowing the use of resource** loops (e.g., extending product lifespans) and **closing resource loops** (e.g., ensuring material recovery and reuse).[14]

Previous studies have demonstrated that not one, but a set of indicators are necessary to evaluate CE,[14] so the final 20 UBI are presented in Table 2, which were selected to assess key aspects of CE at the urban level. A distinctive feature of this framework is the inclusion of economic, policy, and social indicators, addressing dimensions that are often underrepresented in CE assessments.

Table 2. **HOOP Urban Bioeconomy indicators.**

n°	Indicator	Area	Unit	Explanation
1	Municipal biowaste production	Waste	kg/cap*year	Total amount of biowaste produced per capita (Post-consumer not included). Municipal biowaste production= (organic fraction from MMSW (mixed municipal solid waste) + separately collected urban biowaste + park and gardens waste)/ inhabitants
2	Percentage of biowaste separately collected	Waste	%	Biowaste collected separately with respect to total amount of biowaste (Post-consumer not included). % OFMSW separately collected = [(separately collected biowaste + park and gardens waste)/(organic fraction from MMSW + separately collected biowaste + park and gardens waste)] *100
3	Quality of biowaste streams	Waste	%	OFMSW quality= [100- (percentage of impurities on OFMSW collected separately)]
4	Rate of UWWS re-used	Waste	%	% of UWWS reused
5	Percentage of biowaste used for material recovery	Waste	%	% Total amount of biowaste intended to waste-to-material approach (Excluding incineration and impurities). % biowaste used for material recovery = (Total biowaste valorized/Total biowaste produced)*100
6	n° bioproducts produced from waste	Waste	n°	Quantity of bioproducts (biofertilizers, compost, etc.) produced from biowaste.
7	Biowaste management self-sufficiency	Waste	%	% of biowaste treated inside the City. Indirect indicator of infrastructure availability.
8	Implementation rate of biowaste separate collection system	Waste	% or qualitative	% of the city population with regular biowaste fraction collection (residential).
9	Water reuse	Water	%	% of water from wastewater treatment plants which is reused.
10	Wastewater production	Water	m3/cap*year	Wastewater production= Amount of wastewater generated/inhabitants.
11	Biogas production	Energy	m3/cap*year	Biogas production from urban biowaste, UWWS or wastewater treatment per inhabitant.
12	Costs associated with OFMSW and UWWS management	Economy	€/ton	Costs associated with urban biowaste and urban sewage sludge treatment.
13	Number of R&D projects related to biowaste management and treatment	Economy	n°	Excluding HOOP.
14	Financial mechanisms to reduce biowaste	Economy	Qualitative (yes/no)	Financial mechanisms aimed at reducing the generation of biowaste.
15	Promotion of circular economy entrepreneurial initiatives	Economy	Qualitative (yes/no)	City's support to entrepreneurial initiatives in the circular economy.
16	Awareness rising campaigns about waste	Social	Qualitative (yes/no)	The city/region carries awareness campaigns about biowaste.
17	Coordination entity to engage stakeholders involved in CE	Social	Qualitative (yes/no)	The city/region counts on an entity/ department that coordinates and engages stakeholders involved in circular economy.

Table 2. *Continued*

n°	Indicator	Area	Unit	Explanation
18	Compost applicability in local agriculture/gardens	Social	Qualitative (yes/no)	The produced compost finds applicability in local agriculture/gardens.
19	Circular economy strategies in the city	Policy	Qualitative (yes/no)	Considering only those promoted at city level (EU, national excluded).
20	Innovation public procurement	Policy	Qualitative (yes/no)	The city/region has been involved in projects undertaken using innovative public procurement, namely PCP (pre-commercial procurement) or PPI (public procurement of innovative solutions).

Key findings by dimension

The selection of indicators provides insights into both citizen behaviour and municipal waste management systems. For example, the selective collection rate and its quality serve as indicators of social awareness, while the implementation rate of selective collection systems evaluates the efficiency of municipal infrastructure. One of the key findings from this study is the high heterogeneity among cities and regions regarding circular economy performance. Differences in socio-economic conditions, regulatory frameworks, and infrastructure availability make it difficult to apply a one-size-fits-all approach. Some cities include private-sector waste in their reports, while others focus solely on municipal waste, further complicating direct comparisons.

- **Waste Dimension**: Waste-related indicators are the most represented due to their fundamental role in urban bioeconomy. It was observed that cities with extensive green areas generate higher amounts of biowaste, which influences the results (Figure 1). Additionally, small changes in the composition of municipal waste can significantly alter the estimation of biowaste generation (Figure 2). The selective collection rate and quality of the separated material depend on public awareness and municipal infrastructure, showing strong variability between cities. Furthermore, the biowaste selective collection and recovery indicator excludes organic waste fractions that go to home composting, as from 2027 onwards, this fraction will no longer be considered recycling. This is the case of city 5, which presents the lowest score in this indicator (96 kg/cap*year), as home composting is implemented in 48% of households.

- **Material Valorization**: The percentage of biowaste used for material recovery differs depending on the available local infrastructure (Figure 3). Notably, only City 7 reported that compost does not find applicability in local agriculture or gardens, which may indicate barriers in compost utilization or regulatory constraints

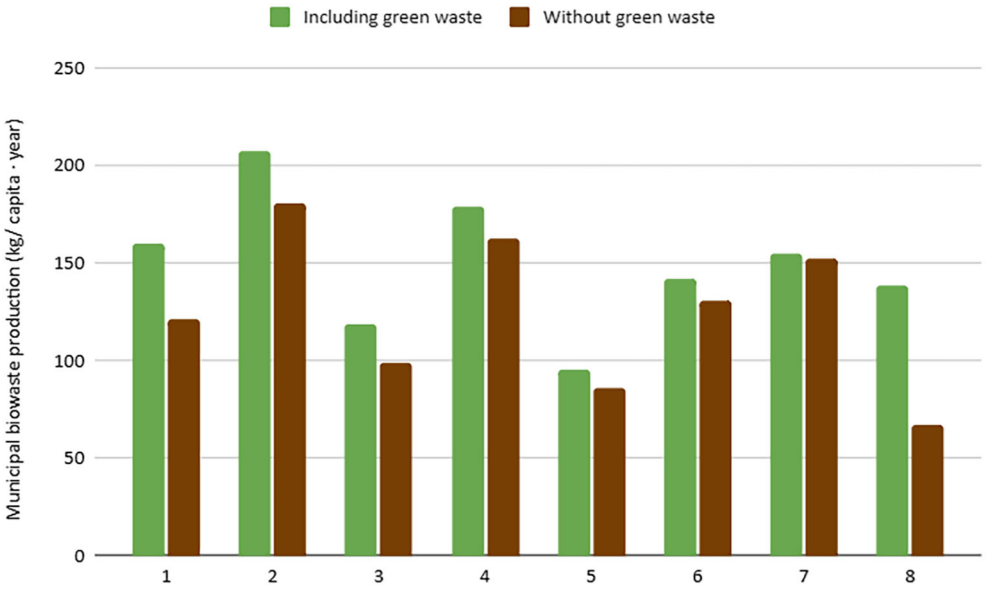


Figure 1. Urban biowaste production, including and excluding generated green waste.

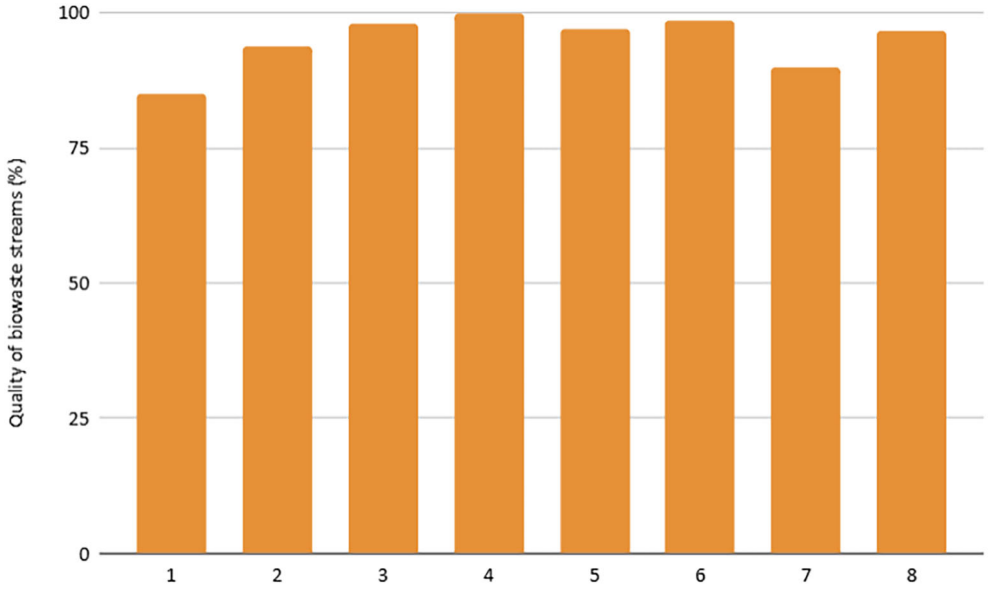


Figure 2. **Quality of biowaste streams.**

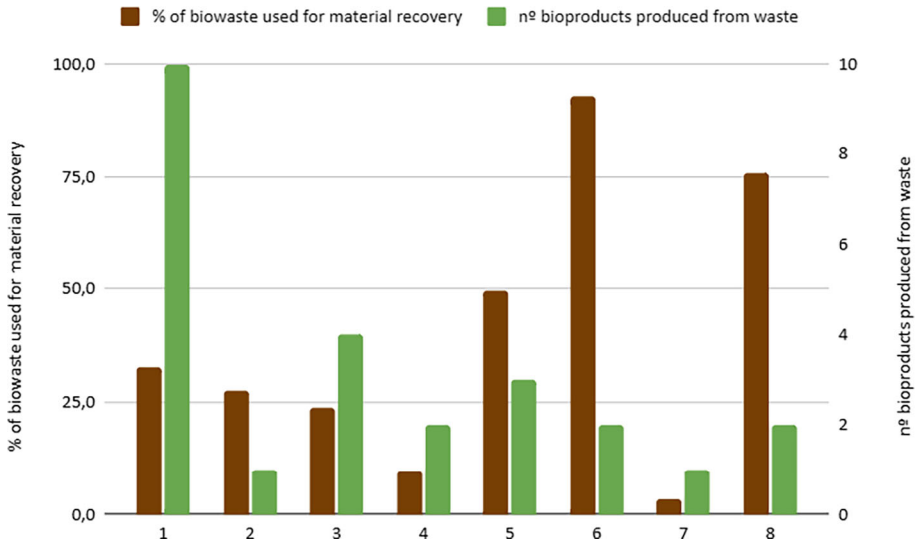


Figure 3. **Percentage of biowaste used for material recovery and number of bioproducts generated from urban biowaste.**

specific to that region. In cities with advanced anaerobic digestion or composting technologies, material valorization reaches 100%. In contrast, those relying on incineration report nearly 0% material valorization, highlighting a gap in waste recovery capacity.

- **Water Dimension**: Water-related indicators are less represented due to the difficulty in defining clear boundaries between water and waste management. This disparity makes data collection difficult, often requiring extrapolations and assumptions. For example, the reuse of water varies drastically among the evaluated cities, with some reaching reuses rates of 11% (city 4), while others do report reduced water reutilization (0.41% and 0.16% for cities 2 and 3 respectively) or no reutilization at all (rest of the cities). This disparity is due to differences in wastewater treatment infrastructure and the implementation of local regulations. Furthermore, the percentage of reuse is also related to the water availability in the region. The city number 4 is an inland city with Mediterranean climate that suffers from water scarcity, explaining the highest reuse rate.

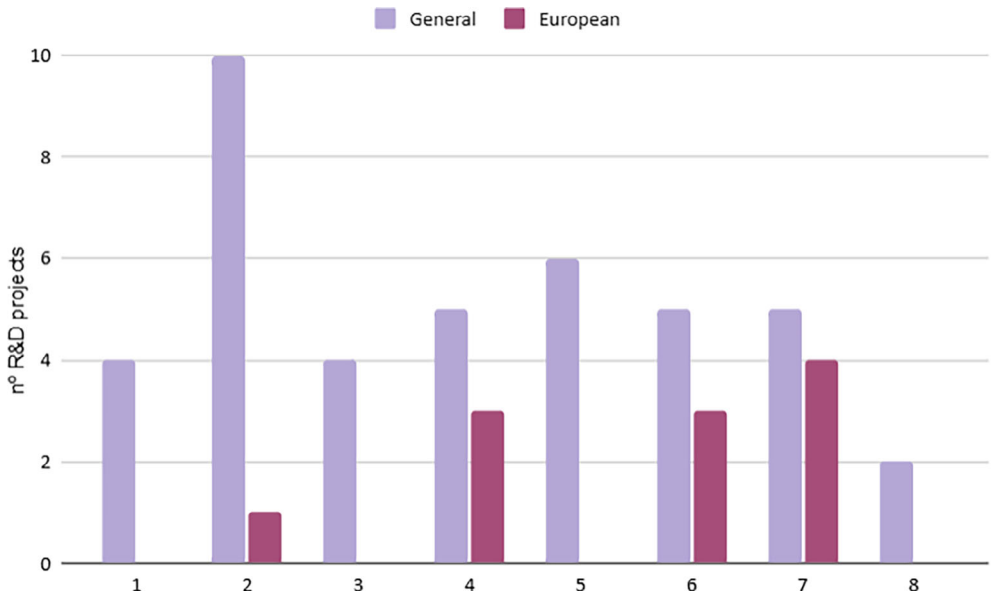


Figure 4. Number of R&D projects.

- **Energy Dimension**: Biogas production is a key indicator within this dimension, but the data show significant differences among cities. Only four of the eight cities (3–5 and 8) generated biogas, producing 7.34, 6.48, 33.16 and 17.56 m3/capita · year respectively. This suggests that the energy conversion capacity of waste is highly dependent on local investments in bioenergy technologies.

- **Economic Dimension**: Investments in R&D show significant disparities between cities (Figure 4). While some cities have implemented financial mechanisms to reduce biowaste generation and promote innovation, others lack effective economic incentives (Table 3). Differences in support for circular economy entrepreneurship also highlight inequalities in access to funding and policy support. Moreover, the lack of standardization between technical and social projects complicates direct comparisons. By correlating the information provided in Figure 4 and Table 3, it becomes evident that the cities that do not promote financial or business mechanisms for economic circularity (cities 2, 4, 6 and 7) are those receiving the highest levels of European funding. Notably, these cities also have the lowest GDP per capita among the seven cities.

- While some cities have implemented financial mechanisms to reduce biowaste generation and promote innovation, others lack effective economic incentives (Table 3). Differences in support for circular economy entrepreneurship also highlight inequalities in access to funding and policy support. Moreover, the lack of standardization between technical and social projects complicates direct comparisons. By correlating the information provided in Figure 4 and Table 3, it becomes evident that the cities that promote financial or business mechanisms for economic circularity (cities 1, 3, 5 and 8) are those involved in more projects and activities of different nature than European projects. Notably, these cities also have the highest GDP per capita among the seven cities.

Table 3. Financial mechanisms and investment in R&D projects related to the circular economy.

		Cities/regions							
Category	**Indicator**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Economic	Financial mechanisms to reduce biowaste	no	no	yes	no	yes	yes	yes	yes
Economic	Promotion of circular economy entrepreneurial initiatives	yes	yes	yes	yes	yes	no	no	yes

Table 4. Key Indicators for Circular Economy Engagement and Strategies in the Cities.

		Cities/regions							
Category	**Indicator**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Social	Awareness rising campaigns about biowaste (y/n)	yes	yes	yes	yes	yes	yes	yes	yes
Social	Coordination entity to engage stakeholders involved in CE (y/n)	yes	yes	no	no	no	yes	yes	yes
Policy	Circular economy strategies in the city	yes	yes	no	no	yes	yes	yes	yes

- **Social and Policy Dimensions**: Qualitative indicators reveal that all cities conduct awareness campaigns on biowaste (Table 4), but only half have coordinating entities to engage key stakeholders in the circular economy. This highlights the importance of public engagement in CE transition as the lack of well-defined political strategies limits the effective implementation of these programs. However, cities exhibit significant differences in their policy frameworks, making cross-regional comparisons challenging.

Limitations in data availability and comparability

A key limitation of this study concerns the heterogeneity in data availability and quality across the eight participating cities. The baseline assessment required compiling information from diverse local sources, resulting in variations in completeness and consistency. This reflects differences in monitoring capacities, governance structures and reporting practices among cities. Moreover, the integration of both quantitative and qualitative indicators introduces challenges for comparability, particularly regarding governance and society related enabling factors, which are inherently context-dependent. Additionally, some of the datasets used during the project were shared under confidentiality agreements, limiting the level of detail that can be disclosed and restricting the extent of statistical harmonization possible across cities. These limitations should be considered when interpreting the baseline results and highlight the need for more standardized and coordinated data collection frameworks in future urban circular bioeconomy assessments.

Policy implications

The indicator framework developed in this study offers several actionable insights for local and regional policymakers aiming to advance circular bioeconomy objectives. First, indicators related to biowaste generation, separate collection performance and material recovery enable evidence-based prioritization of investments in waste management infrastructure and citizen engagement initiatives. Second, governance oriented indicators, such as the presence of coordination entities, awareness campaigns and circular economy strategies, help reveal institutional gaps and support the development of more coherent policy frameworks. Third, the inclusion of enabling factors allows municipalities to evaluate the maturity of their governance arrangements and stakeholder collaboration mechanisms, thereby informing the design of targeted interventions to strengthen local capacities. Overall, the UBI framework can function as a practical decision-support tool for cities seeking to monitor progress, benchmark performance against comparable urban contexts and formulate integrated policy measures that promote a more effective and inclusive transition toward an urban circular bioeconomy.

Conclusions

This study has developed an innovative set of Urban Bioeconomy Indicators (UBI) to assess cities' performance in the circular economy, with a particular focus on biowaste management. By integrating both quantitative and qualitative indicators, this framework enables a comprehensive evaluation across six key dimensions: Waste, Water, Energy, Economy, Society and Policy. The resulting set of 20 indicators, including seven enabling factors, provides a clear perspective on the practices that facilitate a city or region's transition to a CE. These enabling factors are particularly important, as they represent best practices that support the shift toward a more sustainable, bioeconomy-driven circular model. Ultimately, the goal is to empower informed decision-making, allowing cities to implement targeted strategies to enhance their circular bioeconomy performance.

The UBI framework represents a more specialized, locally-focused, and bioeconomy-oriented approach compared to the general reports from the OECD and the Urban Agenda for the EU. Unlike these broader frameworks, the UBI is specifically tailored to address urban bioeconomy and biowaste management. By providing a standardized set of measurements, the UBI offers a tool for tracking a city's progress over time and enables comparisons across different cities or regions. This tailored approach makes it easier to assess the development of a city's bio-based circular economy.

The indicators developed address a critical gap identified in the OECD report, which lacked indicators specifically applicable at the city or regional level. Consequently, the UBI provides local authorities with a valuable tool to measure and enhance their bioeconomy performance. This study's framework could serve as the foundation for a more standardized methodology, an area that has been underdeveloped in current research.[10,11]

The proposed UBI structure categorizes indicators into six dimensions (above mentioned), diverging from the OECD's five-category framework[3] of Economy and Business, Environment, Governance, Infrastructure and Technology, and Employment. This distinction reflects the specific focus on the urban bioeconomy, with the added benefit that the "suggested indicators are only meant to support discussions and further work on CE indicators at the city level".[12] This more focused approach is essential for capturing the nuances of urban bioeconomy systems and their potential for sustainable development.

Moreover, the UBI framework presents additional improvements over existing indicators, offering a more refined and context-specific approach to assessing urban circular economy performance.

1. **Inclusion of qualitative "enabling factors"**: UBI incorporates qualitative indicators in the social and political dimensions, capturing critical elements like public engagement, political commitment, and social acceptance, which are often overlooked in traditional quantitative models.

2. **Focus on material valorization of biowaste**: UBI emphasizes material recovery over energy recovery, aligning with circular economy principles. Indicators such as the "Percentage of biowaste used for material recovery" and "Number of bioproducts produced from waste" promote a more sustainable and resource-efficient approach.

3. **Specific biowaste management indicators**: UBI includes precise indicators on biowaste management, such as the quality and implementation rate of separate collection, offering more detailed insights into waste management effectiveness than general indicators.

4. **Introduction of self-sufficiency indicators**: UBI introduces self-sufficiency indicators to measure a city's capacity to manage its own biowaste, providing a fresh perspective on local waste management that traditional indicators often miss.

5. **Enhanced evaluation of project impacts**: The UBI framework serves as a powerful tool for evaluating the progress and impact of specific circular economy projects implemented in participating cities and regions, allowing for a clearer understanding of the effectiveness of circular economy initiatives and offering a more detailed approach than generalized circular economy indicators that fail to capture local dynamics and project-specific results.

6. **Specialized, locally-relevant approach**: UBI is tailored to address the unique needs of urban bioeconomies, supporting more effective policies, targeted interventions, and the transition to sustainable, bioeconomy-driven urban systems, in contrast to broader, one-size-fits-all models.

7. **Different levels of progression towards CE**: the baseline analysis, applying the set of UBI, shows that cities are at different levels of development across various analyzed dimensions. For example, some cities have been selectively collecting biowaste for decades, while others are just beginning. Furthermore, every city excels in at least one specific dimension.

Data availability statement

No data are associated with this article.

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PubMed Abstract | **Publisher Full Text** | **Free Full Text**

Open Peer Review

Current Peer Review Status: ? ✓ ? ?

Version 2

Reviewer Report 02 March 2026

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Nurliyana Abdul Raof
Universiti Teknologi PETRONAS, Perak, Malaysia

Full Report
Overall, this is a relevant and timely methods paper. The focus on the urban bioeconomy, especially biowaste and wastewater valorisation, is well aligned with current circular economy (CE) priorities at European level. I appreciate the effort to move beyond purely environmental indicators and include enabling factors (policy, social and economic dimensions), which are often missing in CE assessments.
However, since this is presented as a methods article, the main expectation is transparency and reproducibility. At the moment, the paper is strong in concept and indicator design, but some important methodological and technical details are still missing.

Technical soundness
The overall approach (review of existing frameworks → pre-selection → adaptation → refinement based on practical criteria → final set of 20 indicators) is logical and pragmatic. Table 2 is useful, and several quantitative indicators include formulas. **However, for a methods paper, some technical aspects need to be more clearly specified:**

- How exactly were indicators selected from the OECD and Urban Agenda frameworks?
- Was there an expert validation process or structured selection criteria?
- How were inconsistencies across cities (municipal vs private waste, home composting, green waste inclusion) harmonised?

Most importantly, the paper mentions a "circularity score" and a maturity profile, but it does not clearly explain:

- How indicators are normalised
- Whether they are weighted
- How qualitative indicators are combined with quantitative ones
- How the final score or label is calculated

This part is essential and needs to be explicitly described.

Replication
Indicator definitions are provided, which is good. However, the method is not yet fully replicable. To improve this, I suggest:

- Including the **technical questionnaire** as **supplementary material**
- Providing a clear step-by-step explanation of the calculation process
- Adding a simple worked example (for one city) showing raw data

Without this, it is difficult for other researchers or cities to apply the method independently.

Data availability
The manuscript presents results, but the underlying dataset is not provided. Even if some raw data are confidential, the authors should at least provide:

- The final city-level indicator values used in the figures/tables
- Reference year (s)
- General data sources and any assumptions used

If confidentiality applies, this should be clearly stated, and aggregated or processed values should still be shared to allow reproduction of the published figures.

Digital tool clarification (Important)
The manuscript states that the final set of UBI has been implemented in a digital tool available on the HOOP project's web platform, but the link provided cannot currently be accessed.
This is important, since the tool seems to play a key role in generating the circularity score.
I recommend that the authors:

- Briefly describe what type of tool has been used (e.g., web-based dashboard, Excel-based calculator, custom-built software, open-source platform, etc.)
- Explain how the scoring logic is implemented within the tool
- Clarify whether the tool is publicly accessible, and if not, provide at least a methodological description of its backend logic

Without this clarification, it is difficult to evaluate the robustness and transparency of the scoring system.

Major points to address

1. Clearly explain how the circularity score / maturity profile is calculated (normalisation, weighting, aggregation).
2. Provide the technical questionnaire and calculation procedure as supplementary material.
3. Share at least the processed city-level dataset used in the results.
4. Clarify the digital tool (type, accessibility, and scoring logic), especially since the provided link cannot currently be viewed.
5. Define boundary and harmonisation rules more clearly to improve comparability.

Is the rationale for developing the new method (or application) clearly explained?
Yes

Is the description of the method technically sound?
Partly

Are sufficient details provided to allow replication of the method development and its use by others?
Partly

If any results are presented, are all the source data underlying the results available to ensure full reproducibility?
No

Are the conclusions about the method and its performance adequately supported by the findings presented in the article?
Partly

Competing Interests: No competing interests were disclosed.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Reviewer Report 26 February 2026

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Nadia Falah
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The authors have worked diligently to improve the conceptual framework and better explain its limitations, which is a positive step. While we believe further elaboration on the indicator selection process, the formal description of the standardization procedures, and the analysis of non-descriptive results would be necessary, the article demonstrates a sufficiently significant improvement to be considered acceptable for indexing.

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Circular cities, life cycle assesment

We confirm that we have read this submission and believe that we have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Version 1

Reviewer Report 07 October 2025

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The article needs to carry more discussion on the indicators, how they were arrived at, and why are they useful. I don't quite get the indicators and their utility in circular economy. The indicators are not new, and certainly not exhaustive. The authors need to write why they feel the indicators offer a better picture. Figure 1 does not convey any real meaning.

I feel this article is good for academic usage, but not quite useful for practitioners, unless the authors can provide guidelines for practical usage.

Is the rationale for developing the new method (or application) clearly explained?
Partly

Is the description of the method technically sound?
Partly

Are sufficient details provided to allow replication of the method development and its use by others?
Yes

If any results are presented, are all the source data underlying the results available to ensure full reproducibility?
No

Are the conclusions about the method and its performance adequately supported by the findings presented in the article?
No

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Circular economy

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have

significant reservations, as outlined above.

Author Response 30 Jan 2026

Teresa Alvariño Pereira

Thank you for your review and valuable feedback. Regarding the first point of your comments, the indicators presented in the paper were developed within the framework of the HOOP project, following a structured co-creation process. The selection and validation of the indicators were conducted through a technical questionnaire distributed among the eight Lighthouse Cities and their respective Local HOOP Committees. This process involved consultation with a range of local experts and stakeholders, including municipal authorities, public utilities, and private actors, to ensure that the indicators reflected both scientific and operational perspectives on urban circular bioeconomy performance. The detailed results of this consultation are included in an internal confidential deliverable of the project and therefore cannot be publicly available. Nevertheless, the methodology followed standard expert elicitation practices and ensured that the resulting set of indicators was context-specific, comparable across urban settings, and aligned with the objectives of supporting circular bioeconomy implementation at the city level. Regarding your observation that indicators are not new or exhaustive, we fully agree. However, the intention of this work was not to create novel metrics per se, but to identify and adapt the most suitable and operational indicators for assessing circularity in cities with diverse socio-economic and environmental contexts. The selection was therefore based on their relevance, applicability and robustness for urban bioeconomy assessment rather than on conceptual novelty. In this sense, we consider the resulting set to be comprehensive and replicable across cities with similar characteristics. The framework integrates both quantitative and qualitative indicators covering six dimensions, allowing a holistic evaluation of circularity performance and enabling consistent benchmarking between urban contexts. We also agree with the comment that Figure 1 did not convey sufficient meaning. Accordingly, it has been removed from the revised version. Finally, we appreciate your remark that the paper is primarily academic in nature. Nonetheless, the proposed framework is also applicable to practitioners, particularly for cities and regions with similar characteristics to those analyzed in the study. The set of indicators enables an initial evaluation of circularity performance, helping local authorities identify baseline conditions, detect priority areas for improvement, and monitor progress over time. In this sense, the indicator framework is not intended as a purely theoretical exercise, but as a practical decision-support tool that can be replicated and adapted by the municipalities aiming to implement or enhance circular bioeconomy strategies.

Competing Interests: No competing interests were disclosed.

Reviewer Report 07 October 2025

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The manuscript addresses an important and timely topic, proposing a set of **Urban Bioeconomy Indicators (UBI)** to assess and enhance circular economy (CE) initiatives in cities and regions. The focus on urban bioeconomy and the attempt to combine quantitative and qualitative indicators is innovative and of potential value for both academic and policy audiences. The paper is aligned with the European Commission's CE agenda and has clear relevance for local authorities and practitioners.

There are some points that must be mentioned:

1. The proposed UBI framework is well aligned with the existing gaps highlighted in OECD and Urban Agenda reports and represents a genuine innovation. Despite this alignment, the framework lacks a fully systematic methodology for indicator selection. Recent researches apply data-driven methods (machine learning, text analytics) for systematic indicator identification and classification.
2. The integration of both quantitative and qualitative indicators—particularly the inclusion of "enabling factors"—is commendable as it captures social and institutional dimensions often overlooked in CE research. However, the selection and validation of qualitative factors are insufficiently explained, which limits the robustness and comparability of the results. More advanced analytical techniques could transform this process from a subjective exercise into a more rigorous, evidence-based methodology.
3. The development of a digital tool (HOOP Circularity Label) is a significant added value for policymakers and city stakeholders. Nevertheless, the technical functioning, underlying algorithms, and transferability of this tool to other cities are not clearly presented.
4. The use of case studies across eight European cities moves the work beyond the theoretical level and increases its practical relevance. Yet, the analysis remains largely descriptive. Comparative and inferential analyses across cities are missing, which would have allowed stronger conclusions and more generalizable insights.

Some weaknesses and suggestions for improvement

- **Transparency in indicator selection**: The paper states that indicators were chosen through review and adaptation but does not clarify the exact criteria for inclusion or exclusion. A flowchart or comparative table should be provided to demonstrate which

indicators were considered, which were discarded, and on what basis. This would significantly improve the replicability of the study.
- **Data analysis**: The results section is primarily descriptive. More in-depth comparative or statistical analyses are needed to highlight differences and similarities across cities, as well as to identify which dimensions (waste, water, energy, policy, etc.) contribute most to performance variation.
- **Limitations**: Differences in data availability between cities, the uneven quality of collected data, and the challenges of comparing qualitative indicators are critical issues that need explicit discussion. Acknowledging these would add transparency and guide future research.
- **Policy relevance**: While the paper mentions policy implications, it lacks specific, actionable recommendations. A dedicated **Policy Recommendations** section would greatly increase the value of the study for non-academic audiences. For instance, it could highlight which categories of indicators are most relevant for local governments and how they can be operationalized in waste management or urban bioeconomy programs.
- **Definition of urban bioeconomy**: The manuscript introduces the term but does not provide a clear and distinct definition compared to the broader bioeconomy. Since the concept is still emerging, the literature review should systematically trace how previous studies have defined it, what gaps exist, and how this paper arrives at its own definition.
- **Methodological weakness**: The study does not present an updated methodological structure for indicator identification, classification, normalization, and selection. The absence of such a systematic approach in this paper represents a methodological gap, and addressing it would significantly strengthen the contribution and scientific credibility of the work.

The manuscript makes a valuable contribution by highlighting the role of bioeconomy in urban circular economy strategies and by proposing a mixed set of indicators. However, the lack of greater methodological depth in the selection of indicators, insufficient analytical depth and the absence of clear policy recommendations reduce its impact. Substantial revisions—particularly in methodology and conceptual framing—are necessary to enhance the robustness, reproducibility, and policy relevance of the paper.

Is the rationale for developing the new method (or application) clearly explained?

Partly

Is the description of the method technically sound?

Partly

Are sufficient details provided to allow replication of the method development and its use by others?

Partly

If any results are presented, are all the source data underlying the results available to ensure full reproducibility?

Partly

Are the conclusions about the method and its performance adequately supported by the findings presented in the article?

Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Circular cities, life cycle assesment

We confirm that we have read this submission and believe that we have an appropriate level of expertise to state that we do not consider it to be of an acceptable scientific standard, for reasons outlined above.

Author Response 30 Jan 2026

Teresa Alvariño Pereira

We sincerely thank the reviewers for its insightful and thoughtful comments. We acknowledge that several aspects of the paper need clarification and we have addressed each of these points as follows:

- Transparency in indicator selection: As described in the Methods section, the indicators were created within the framework of the HOOP project through a structured co-creation process. Their selection and validation were conducted via technical questionnaires and expert consultations with representatives from the eight Lighthouse Cities and their respective Local HOOP Committees. This participatory process involved a wide range of stakeholders, ensuring that the indicators reflected both scientific knowledge and operational feasibility in different urban contexts. The detailed data and results from these consultations, including the specific inclusion and exclusion criteria applied to the initial list of indicators, are part of a confidential internal project deliverable and therefore cannot be publicly disclosed. Nevertheless, the process followed recognized expert elicitation practices, ensuring methodological rigor and comparability across cities. The final indicator set was thus validated through expert consensus, guaranteeing its relevance, consistency and replicability in similar urban environments.
- Data analysis: We acknowledge that the results presented are primarily descriptive, as the main objective of this study was to establish a baseline analysis for the participating cities and regions. The intention was to provide an initial, harmonized assessment of their circularity maturity profile rather than to perform an in-depth statistical or inferential analysis at this stage. The heterogeneity of the eight Lighthouse Cities, in terms of geographic context, population size, data availability and local governance structures, makes direct statistical comparison challenging and, in some cases, methodologically inappropriate. Furthermore, some of the datasets collected during the HOOP project are confidential and cannot be fully disclosed or subjected to open statistical treatment. Nevertheless, we recognize the value of deeper analysis. While the current manuscript focuses on presenting and validating the indicator framework and baseline results, we hope that future studies by researchers and practitioners will take advantage of the publicly available tools developed by the HOOP project to conduct more sophisticated inter-city or longitudinal analyses.
- Limitations: We fully agree that differences in data availability and quality constitute a key limitation of the study. The baseline assessment for the eight participating cities

required compiling information from multiple municipal departments and local stakeholders, which naturally led to variations in the completeness, level of detail and structure of the data provided. This heterogeneity reflects the differing data management practices, governance structures and monitoring capacities of each city. Furthermore, the framework integrates both quantitative and qualitative variables related to governance, awareness and policy implementation. While this mixed-methods approach is essential to capture the multidimensional nature of urban bioeconomy, it also introduces challenges in terms of ensuring comparability, particularly for qualitative enabling factors, where interpretations can vary across local contexts. Some detailed datasets used during the project were shared by cities under confidentiality agreements and therefore cannot be disclosed or analyzed beyond aggregated levels. This confidentiality constraint also limits the extent to which the study can harmonize certain data elements or perform deeper statistical comparisons. In response to the reviewers' recommendations, the revised manuscript now includes a dedicated paragraph in the Discussion, "Limitations in data availability and comparability", explicitly addressing these limitations, acknowledging: the heterogeneity in data availability across cities, differences in quality and the intrinsic challenges of comparing qualitative indicators across diverse urban contexts.

- Policy relevance: We agree that strengthening the policy relevance of the study can enhance its usefulness for local authorities and practitioners. In response, the revised manuscript now includes a "Policy Implications" subsection in the Discussion section. This addition outlines how the proposed indicators can support municipal decision-making processes, particularly in the prioritization of circular bioeconomy actions and the evaluation of existing waste and resource management strategies. The new subsection highlights which indicator categories are most directly actionable for policymakers, specifically, those related to Waste, Policy and Society dimensions, and provides guidance on how these indicators can be operationalized. By translating the indicator framework into concrete areas of action, the revised manuscript aims to offer a clearer decision-support perspective for municipalities seeking to implement or enhance circular bioeconomy measures. We believe this intensifies the practical value of the study for non-academic audiences.
- Definition of urban bioeconomy: We agree that a clearer and more operational definition of the urban bioeconomy is essential to distinguish it from the broader bioeconomy framework and to clarify the conceptual foundations of our indicator set. In response, we have expanded the Introduction to include a dedicated paragraph that defines the urban bioeconomy as the valorization of urban biowaste and wastewater through circular solutions that enable local bio-based value chains and contribute to resource efficiency, decarbonization and social well-being at city level. This definition builds on the conceptual work developed within the HOOP project and explicitly frames cities as active enablers of localized bio-based circularity. By emphasizing the transformation of urban waste streams into resources within local economic systems, the revised introduction highlights the specificities of the urban context and addresses the conceptual gap noted by the reviewers. This addition also clarifies how the definition underpins the development of the indicators framework presented in this study.
- Methodological weakness: The methodological approach applied in this study was

intentionally designed to fit the objectives and constraints of the HOOP project, which required developing a practical and operational indicator framework applicable across eight highly heterogeneous European cities. For this reason, the work followed a criteria-driven and expert-informed process, rather than a data-driven methodology such as machine learning or text analytics. The indicator development relied on: a comprehensive review of existing circular economy frameworks, a pre-screening based on relevance to urban bioeconomy, an assessment of data availability and comparability across cities and expert consultation through the Local HOOP Committees. This participatory method was essential to ensure that the final indicators reflected both local priorities and operational feasibility. While we acknowledge that more algorithmic or fully systematic approaches may be appropriate in contexts with highly standardized datasets, the diversity of the cities involved, combined with the confidentiality of certain technical inputs shared by local authorities, made such methodologies unsuitable for the scope of this work. The chosen approach allowed us to obtain a set of indicators that is consistent, replicable in similar urban contexts and aligned with the practical needs of municipalities advancing their circular bioeconomy strategies. We appreciate the reviewers' suggestion and consider it a valuable direction for future academic research, particularly once more harmonized and openly accessible datasets become available at the urban level.

Competing Interests: No competing interests were disclosed.

Reviewer Report 06 October 2025

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The article effectively develops and applies the Urban Bioeconomy Indicators (UBI) to assess circular economy progress in c

Replication is partially feasible using the described process and formulas in Table 2. The results illustrate application in eigh

It is suggested that they be stored in a repository.

It mentions the scenario aspect, which is undoubtedly important, but does not elaborate on feedback over time. Conclusion

Access to data would be important for greater transparency.

Overall, this is a valuable contribution to the assessment of urban sustainability and the urgent need to build holistic bioeco

Is the rationale for developing the new method (or application) clearly explained?
Yes

Is the description of the method technically sound?
Yes

Are sufficient details provided to allow replication of the method development and its use by others?
Partly

If any results are presented, are all the source data underlying the results available to ensure full reproducibility?
Partly

Are the conclusions about the method and its performance adequately supported by the findings presented in the article?
Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Bioeconomy

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Author Response 30 Jan 2026

Teresa Alvariño Pereira

We sincerely thank the reviewer for the positive and constructive evaluation of our work. We appreciate the acknowledgement of the study's contribution to advancing the assessment of urban sustainability and the development of holistic bioeconomy indicators. Regarding the comment on reproducibility and data availability, we acknowledge that the raw datasets used in this study cannot be fully disclosed due to confidentiality agreements with the participating cities. This limitation is explicitly related to the nature of the project, as several data inputs were shared internally by municipal authorities for baselines analysis purposes only. Nevertheless, all formulas, indicator definitions and methodological steps are fully described in the manuscript, enabling external researchers to replicate the framework using their own datasets. Regarding the suggestion to provide more detail on scenario development and temporal feedback, we agree that this is an important aspect of circularity assessment. In the context of the HOOP project, the scope of the current work was limited to establishing a harmonized baseline across the eight cities at a single point in time. The

integration of scenario evolution and dynamic monitoring will indeed be a valuable area for future research, particularly as more longitudinal data become available at the urban level. We greatly appreciate the reviewer's constructive feedback and positive assessment, which help reinforce the relevance and clarity of the proposed Urban Bioeconomy Indicator framework.

Competing Interests: No competing interests were disclosed.