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A DECISION-SUPPORT TOOL FOR THE TRANSITION TO SUSTAINABLE URBAN CIRCULARITY

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ABSTRACT

Historically, urban development has followed a linear model in which natural resources are extracted, used, and subsequently discarded, a characteristic of so-called Linear Cities (LC). This model is unsustainable, prompting cities to rethink their operations and make better use of resources. In this context, the principles of Circular Economy (CE) have been incorporated at the urban scale, giving rise to the concept of the Circular City (CC), also known as urban circularity. CCs implement CE guidelines, adapt their structures, regenerate natural systems, and promote local production and consumption to improve resource management and achieve sustainability. However, cities seeking to become circular, mostly located in Europe, face challenges in planning and implementing circular solutions. In the Brazilian context, where the transition is still in its early stages, these challenges are even greater, particularly given the need to identify existing practices that align with CCs. Given this, the present study aims to develop a decision-support tool to assist in the sustainable urban circular transition. The proposed tool, named *CIRCCITY (Circular City Transition Tool)*, was developed using the Design Science Research (DSR) approach. *CIRCCITY* is structured into three components. The first component is a maturity model structured into four levels (Level 0: Linear City; Level 1: Waste Management; Level 2: Circular Economy; and Level 3: Circular City), which enables identification of the current stage of the circular transition. The second component is a set of indicators to monitor the results of circular actions in key sectors (Waste, Agriculture and Food, Local Production and Industry, Energy, Mobility and Transportation, Water and Sanitation, and Space and the Built Environment). The final component consists of a set of indicators to assess economic, social, and environmental impacts. The tool was applied in the city of São Paulo, which scored a Maturity Level of 1 (Waste Management), indicating that efforts remain focused on recycling and energy recovery. Although the city seeks to promote circular business models, these actions remain fragmented. São Paulo needs to make progress in implementing strategies to prevent waste generation and change consumption patterns. Furthermore, the results indicate the need to implement regenerative and adaptive practices in its infrastructure to enable better resource circulation. Thus, the use of the tool demonstrated its effectiveness in supporting public managers at different stages of the circular transition, establishing itself as a structured instrument for decision-making support. Finally, the tool is available on a free digital platform, accessible to urban managers across cities, thereby contributing to the dissemination of knowledge and the advancement of sustainable urban circularity.

Keywords: Circular Economy, Circular Cities, Maturity Models, Sustainability Indicators.

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LIST OF ABBREVIATIONS

ADEME – Agence de la transition écologique

AGEC – Loi Anti-Gaspillage pour une économie circulaire

APUs – Agricultural Production Units

CC – Circular City

CCRI – Circular Cities and Regions Initiative

CE – Circular Economy

CEM – Circular Economy Maturity

CIRCCITY – Circular City Transition Tool

CM-FLAT – Circularity and Maturity Firm-Level Assessment Tool

CPS – Communauté d'agglomération Paris-Saclay

DSR – Design Science Research

ECLAC – Economic Commission for Latin America and the Caribbean

EIB – European Investment Bank

ENEC – National Circular Economy Strategy

ERUs – Energy Recovery Units

EU – European Union

FABHAT – Alto Tietê River Basin Agency Foundation

ICLEI – Local Governments for Sustainability

LC – Linear City

MMA – Ministry of the Environment

MMSC – Smart Cities Maturity Model

OECD – Organisation for Economic Co-operation and Development

PCAET – Plan Climat Air Énergie Territorial

PDE – Strategic Master Plan

PEVs – Voluntary Glass Drop-off Points

PGIRS – Municipal Integrated Solid Waste Management Plan

PLANCLIMA – Climate Action Plan of the Municipality of São Paulo

PLANEC – National Circular Economy Plan

PLANMOB – Municipal Urban Mobility Plan

PMDE – Municipal Economic Development Plan

PMSAI – Municipal Integrated Environmental Sanitation Plan.

PMSB – Municipal Basic Sanitation Plan

PNRS – National Solid Waste Policy

PROAURP – Urban and Peri-Urban Agriculture Program

RMSP – Metropolitan Region of São Paulo

SCMM – Smart City Maturity Model

SCI – Smart City Institute

SDGs – Sustainable Development Goals

SEHAB – Municipal Housing Secretariat

SIOM – Syndicat Intercommunal des Ordures Ménagères de la Vallée de Chevreuse

SLR – Systematic Literature Review

SMCS – Sound Material Cycle Society

UC – Urban Circularity

UCAF – Urban Circularity Assessment Framework

UCCI – Union of Ibero-American Capital Cities

UPAs – Agricultural Production Units

UNECE – United Nations Economic Commission for Europe

WoS – Web of Science

ZPIs – Predominantly Industrial Zones

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1. INTRODUCTION

Urban areas account for only 1% of the Earth's surface, yet they consume a large share of global resources and are hotspots for consumption and waste generation (EIB, 2024a). Linear Cities (LC), as the current model of urban construction and operation is called, are based on the logic of extracting resources, using them to fuel the urban metabolism, and discarding waste. However, this form of development causes negative linear externalities and leads to environmental, social, and infrastructure problems in cities. Population growth, combined with climate change, tends to intensify these problems. This scenario has led to debates on how to transform urban environments to make cities sustainable.

In this context, discussions on urban circularity or circular cities (CCs) have emerged. Although the theoretical concept is not yet fully established in the literature (Schuppler *et al.*, 2026), Girard and Nocca (2019) explain that these terms represent a metaphor for a new way of viewing and organizing cities. CCs can be understood as a set of practical strategies adapted to the local context. Thus, there is no single model of urban circularity, but rather different transition trajectories that reflect specific institutional, economic, and territorial conditions and are therefore open to different interpretations (Schuppler *et al.*, 2026).

Some cities understand circularity as implementing the circular economy at the urban scale, seeking solutions that close material cycles and eliminate waste and pollution (EMF, 2019a). However, this interpretation has been criticized. In this regard, studies indicate that more holistic approaches are necessary to understand what a CC is (Williams, 2019a; Marjanović *et al.,* 2022; Bourdin and Torre, 2024).

In a more comprehensive approach, a CC should implement the following actions: (1) cycle-closing actions (reuse, repair, recycling, etc.); (2) regenerative actions (restoration of natural ecosystems); (3) adaptive actions (aimed at adapting urban infrastructure) (Dąbrowski *et al.*, 2024); and (4) actions to localize production and consumption (which make cities less dependent on the import and export of materials) (Williams, 2019a).

Building upon Williams' (2019a) conceptualization of the CC, this study shifts the focus from defining the characteristics of a CC to understanding how cities evolve toward urban circularity. Accordingly, this study interprets this evolution as an incremental process shaped by the integration of circular practices, governance capacities, institutional arrangements, and

social transformation. This perspective provides the conceptual foundation for the decision-support tool proposed in this study.

From this perspective, urban circularity is understood as a progressive, cumulative, and systemic process toward sustainable urban development. Accordingly, a CC is interpreted not as a fixed state, but as a city that progressively integrates circular principles and practices into its governance, infrastructure, resource management, production and consumption systems, and social development. The level of urban circularity therefore reflects the extent to which these elements have been incorporated over time. Accordingly, cities should not be classified as either circular or non-circular, but rather as progressing through different stages of urban circularity as governance capacities, institutional arrangements, and complementary circular actions mature over time.

In this sense, this study understands the CE as a strategic element of urban circularity, but not as a sufficient condition to characterize a city as circular. Rather, the transition toward urban circularity is achieved through the gradual incorporation of circular principles and practices into urban planning, governance, infrastructure, resource management, and production and consumption systems in order to promote social inclusion, territorial equity, environmental regeneration, and long-term urban well-being.

In practice, urban circularity has increasingly been promoted as a strategy to support sustainable urban development and achieve the *Sustainable Development Goals* (SDGs). The European Union (EU), for example, created the *Circular Cities and Regions Initiative* (CCRI) to promote circular development in cities across the bloc (EU, 2024). Cities in Latin America and the Caribbean have also begun to incorporate urban circularity through the *Declaration of Circular Cities of Latin America and the Caribbean*, published by the *Economic Commission for Latin America and the Caribbean (ECLAC)* in 2021 (ECLAC, 2021).

However, Paiho *et al.* (2021) state that the urban circular transition is complex and requires consideration of the interconnections among various sectors and material flows. Cities engaged in this process face challenges that hinder the creation of efficient solutions. Among these challenges, the following stand out: the diversity of approaches adopted by cities, the difficulty of transferring solutions between different urban contexts, limited financial resources, dependence on political support, the influence of existing institutional structures, and the gaps between strategic planning and its effective implementation (Schuppler *et al.*, 2026).

This scenario poses a significant challenge for public managers, involving not only understanding how to implement urban circularity but also defining which tools to use to guide the transition process, monitor its results, and assess its impact on sustainability. In the context of Brazilian municipalities, this challenge is even more significant, as many have not yet begun their circular transition and require tools to help diagnose their territories.

However, such tools remain scarce, especially given the specificities of the Brazilian context. Thus, the need for studies that develop tools to support urban managers in the circular transition becomes clear. Given this scenario, the present study aims to develop a decision-support tool for the transition to urban circularity.

To achieve this objective and build the tool, the study seeks to answer the following research questions: (1) How has urban circularity been implemented in cities considered benchmarks, and what lessons can be applied to the Brazilian context? (2) What are the support needs of urban managers in the circular transition, and how can a tool be structured to meet these needs? (3) What does the application of the tool reveal about the stage and challenges of the circular transition in a Brazilian city?

To address questions (1) and (2), an exploratory study was conducted to understand the circularity strategies and actions being implemented in leading cities. This exploratory study helped identify the characteristics the tool should have to meet the current needs of urban managers. Finally, to answer research question (3), the developed tool was applied to a selected Brazilian municipality, and a documentary analysis was conducted to assess its current stage of transition toward urban circularity and identify the main challenges associated with this process.

In this study, the proposed tool, called *CIRCCITY* (*Circular City Transition Tool*), is organized into three components. The first component is a maturity model that helps diagnose the city's current situation and supports planning a circular strategy. This component was developed based on the methodologies of De Bruin *et al.* (2005) and Mettler (2010) and underwent a co-creation process with experts.

The second component, which monitors key sectors and helps public managers measure the results of circular initiatives, comprises 37 indicators. Finally, the third component assesses the impacts of these actions on urban sustainability (environmental, social, and economic aspects) and comprises 20 indicators. The indicators for the second and third components were

identified through a systematic literature review (SLR) and selected based on the criteria of consistency, applicability, redundancy, and utility, and validated by experts.

This study selected the municipality of São Paulo because it recognizes, within the scope of its planning, the importance of the circular economy for economic and sustainable development. The application of the tool in the municipality enabled the identification of existing urban circularity actions, as well as the influencing factors and challenges related to the sustainable circular transition. Thus, the study contributes to understanding how urban circularity is being developed in the Brazilian context and demonstrates the tool's potential as a decision-making support instrument.

To expand access to and applicability of *CIRCCITY*, a digital platform was developed that allows users to access its three components, assess their maturity level through a questionnaire, and consult the indicators proposed in this study. Making the tool available online aims to facilitate its use among public managers, researchers, and other actors involved in the circular transition, thereby advancing knowledge and the development of circular strategies, especially in Brazilian cities.

In this sense, this study makes five main contributions to literature. First, it proposes an interpretation of urban circularity as a progressive, cumulative, and systemic transition process toward sustainable urban development. Second, it argues that urban circularity should be understood as a continuum of development, in which cities advance through different levels of circularity rather than being classified as simply circular or non-circular. Third, it explicitly incorporates social inclusion and territorial equity as fundamental dimensions of urban circularity, contributing to a more holistic understanding of the urban circular transition.

Fourth, this work advances literature by proposing a decision-support tool for the transition to sustainable urban circularity. The tool is integrated to support diagnosis, planning, monitoring, and evaluation of circularity impacts in urban areas. Unlike previous studies, which address urban circularity in a fragmented manner, this work proposes a systemic approach that integrates multiple urban sectors and sustainability dimensions into a single analytical framework.

Finally, by applying the proposed tool in the municipality of São Paulo, this study expands knowledge on the urban circular transition in the Global South and demonstrates how

an integrated decision-support tool can support public managers in contexts characterized by institutional constraints, social inequalities, and resource management challenges.

1.1 Objectives

The objective of this study is to develop a decision-support tool to assist public managers in the transition to sustainable urban circularity.

1.1.1 Specific Objectives

- Analyze how urban circularity is being implemented.
- Identify the support needs of public managers in the transition to urban circularity.
- Structure a decision-support tool for the transition to sustainable urban circularity.
- Make the tool freely available through an online platform.
- Apply the tool in a Brazilian municipality to assess its potential for use in real-world contexts.
- Analyze the stage and challenges of the urban circular transition in the municipality of São Paulo.

1.2 Rationale of the study

According to EMF (2019a), cities can facilitate the development of the CE by creating strategies to promote the circular transition. In this sense, some cities have been developing plans and strategies focused on the CE within their territories, also contributing to the dissemination of the concept of circular cities (CCs). Amsterdam, Paris, and London, for example, are analyzed in the literature as reference cases for the circular transition, illustrating how European cities have interpreted and incorporated CE principles (particularly designing out waste and pollution and keeping products and materials in use) into local policies and strategies according to their territorial priorities (Fratini *et al*., 2019).

However, studies on circular cities are still in their early stages, and the concept itself remains under construction in the literature (Girard and Nocca, 2019; Schuppler *et al.*, 2026). Complementarily, Coussa (2025) highlights that the research field is still consolidating, characterized by fragmented approaches and limited integration among the different areas addressing the topic, such as waste management, new forms of urbanization, green ecosystems, and circular governance. Thus, there is a clear need for studies that adopt a more holistic approach, integrating the different dimensions of urban circularity.

Beyond theory, implementing urban circularity also presents challenges. The *Circular Cities Declaration* (2024) notes that although European cities are making progress in adopting circular strategies, the transition still faces significant barriers, including fragmented public policies and difficulty integrating across sectors and levels of governance. Additionally, challenges in monitoring circularity persist, particularly due to a lack of standardized indicators and limited data availability, which hinder the assessment of cities' progress.

Another relevant point is that recent studies indicate that implementing the circular economy at the local level faces various institutional and operational barriers (Bourdin and Jacquet, 2025; De Bantel *et al.*, 2025). According to Bourdin and Jacquet (2025), a lack of understanding of the concept and fragmented governance, which hinders coordination among sectors and administrative levels, are barriers to the advancement of urban circularity.

De Bantel *et al.* (2025), however, found that urban circular economy plans have weaknesses, with a predominance of generic, poorly targeted actions, often focused on awareness-raising and governance, to the detriment of more structural and systemic interventions. Added to this is the absence of standardized indicators, limited data, and the difficulty of linking actions to expected sustainability impacts. For the authors, these factors compromise the effectiveness of the plans and highlight the need for more robust tools to support local planning and management of the circular transition.

Given this context, there is a need to create tools that can assist managers in developing circularity in their territories, as well as monitoring results and evaluating the impact of circular initiatives on urban sustainability, considering environmental, social, and economic aspects. This study aims to address this research gap by developing a tool to support the circular transition that considers it holistically, using a multisectoral approach encompassing all dimensions of sustainability.

Most published works on urban circularity focus on European cities (Petit-Boix and Leipold, 2018; Prendeville *et al.*, 2018; Dąbrowski *et al.*, 2024). Given this, Dąbrowski *et al.* (2024) highlight the need to expand studies on circular cities to other territorial contexts. In Brazil, the topic remains largely unexplored, creating research opportunities to analyze the country's circular transition. Thus, this study addresses another gap in the literature by examining how cities outside the European context interpret and apply the principles of urban circularity while developing a tool to support and assess the circular transition.

The city chosen for the study was São Paulo, a Brazilian municipality of major economic significance in Latin America, with socioeconomic and land-use characteristics very distinct from those of European cities. Therefore, studying the municipality provides insight into the main characteristics of the transition to urban circularity in a context marked by social inequalities, institutional limitations, and resource management challenges, thereby contributing to expanding knowledge on the topic in developing countries.

Finally, this work offers a practical contribution to managers and scholars of urban circularity, as the tool developed will be made available on a digital platform and can be accessed free of charge by researchers and municipalities. Thus, the study is not limited to theoretical contributions; it also provides practical support for decision-making, thereby advancing knowledge dissemination and the implementation of urban circularity.

1.3 Structure of the Thesis

The thesis is structured into eight chapters. Chapter 1 presents the introduction, research objectives, and the study's rationale. Chapter 2 presents the theoretical framework addressing the concepts of CE, urban circularity, indicators, and maturity models. Chapter 3 presents the methodology adopted in the research. Chapter 4 presents the analysis of the implementation of urban circularity in reference cities.

The conceptual maturity model developed in this work is presented in Chapter 5. The results of the indicator analysis are presented in Chapter 6. The application of the tool in the city of São Paulo, as well as the analysis and discussion of the results, are presented in Chapter 7. Finally, Chapter 8 presents the study’s conclusions, its limitations, and suggestions for future research.

2. THEORETICAL FRAMEWORK

This chapter presents the theoretical background of the research, covering the main concepts related to Circular Economy and Sustainability, Urban Circularity, Design Science Research, Maturity Models, and Circularity Indicators. Furthermore, it discusses the relationships among these themes, highlighting the challenges, limitations, and gaps identified in the literature.

2.1 Circular Economy and Sustainability

In recent decades, studies related to the CE have gained prominence in the literature. Alhawari *et al.* (2021) highlight this growth by noting that the number of annual publications on the circular economy increased from 1 in 2004 to 526 in 2020. Europe stands out in scientific output, accounting for 15 of the 20 countries with the highest numbers of publications. China also plays a significant role, ranking as the second-highest publisher on the topic, followed by the United States, Brazil, India, and Australia.

Despite this progress, conceptualizing the CE remains a challenge. Kirchherr *et al.* (2017) identified more than 114 definitions, highlighting the multiplicity of interpretations and the difficulty of consolidating the concept. Furthermore, the authors note that some of the literature associates CE solely with recycling, neglecting practices such as reduction, reuse, and other aspects that are fundamental to sustainable development.

Based on an analysis of the various definitions studied, Kirchherr *et al.* (2017) conceptualized the CE as an economic system that replaces the end-of-life logic with strategies for reduction, reuse, recycling, and material recovery throughout the processes of production, distribution, and consumption. The system operates at different levels (micro, meso, and macro) and seeks to contribute to sustainable development by simultaneously promoting environmental quality, economic prosperity, and social equity, made possible by new business models and more responsible consumption patterns.

EMF (2012) proposes that the CE is based on three interdependent principles that guide the transition from a linear model to a regenerative system, in which natural systems are restored and resources are preserved. The first principle, *design out waste* and pollution, emphasizes the need to eliminate waste and pollution at the design stage to prevent negative environmental impacts before they occur. The second principle, *keep products and materials in use*, seeks to maximize the value and lifespan of products, components, and materials through strategies such

as reuse, repair, remanufacturing, refurbishment, sharing, and recycling. The third principle, *regenerate natural systems*, aims to replace the consumption of finite resources with renewable sources while adopting practices that restore ecosystems, enhance biodiversity, and contribute to the recovery of natural capital.

Among the approaches used to operationalize the CE, the *RESOLVE* framework, proposed by the Ellen MacArthur Foundation, stands out. It organizes circularity into six main actions: *regenerate, share, optimize, loop, virtualize, and exchange* (EMF, 2015). Recent studies indicate that this framework has guided the implementation of the CE across industries and supply chains through strategies aligned with these principles, with a particular focus on technological solutions, efficiency, and process optimization (Sell *et al*., 2023).

Despite the broad scope of these principles and actions, their implementation has often focused on downstream strategies, particularly recycling and material recovery, reinforcing the misconception that the CE is primarily concerned with waste management. Instead, the CE should be understood as a broader approach focused on maintaining the value of products, components, and materials throughout their life cycle (Cobra *et al*., 2023). In this context, greater emphasis should be given to practices such as maintenance, repair, and reuse, as they play a key role in extending product lifespans, reducing the demand for new resources, and maximizing the value of existing products, components, and materials.

These different interpretations of the CE are reflected in the various discourses identified in the literature. For Calisto Friant *et al.* (2020), the CE is not a single paradigm, but rather a diverse field of discourse. The authors identify four types of discourse related to the circular economy: the first, the *Technocentric Circular Economy*, focuses on technological and market-based solutions to increase resource efficiency. The second typology, termed the *Reformist Circular Society*, incorporates social and governance aspects but remains aligned with the logic of the current economic system. The third typology is the *Transformational Circular Society*, which proposes structural changes in production and consumption systems, prioritizing socio-environmental justice and ecological limits. Finally, the fourth typology is the *Fortress Circular Economy*, focused on security and resource control in contexts of scarcity, with an emphasis on resilience and risk management.

Although the prevailing discourse in the CE debate is technocentric (Calisto Friant *et al*., 2020), many studies already question the model's contribution to sustainability. Furthermore, the similarities and differences between the CE and sustainability are not yet clear

in the literature (Kirchherr *et al.*, 2017), since some authors use the CE as a synonym for sustainability and, in other cases, as a condition for achieving sustainable development (Walker *et al.*, 2022).

Given these ambiguities, Geissdoerfer *et al.* (2017) identify three types of relationships between the CE and sustainability: Conditional (in which CE is a condition for sustainability), Beneficial (in which CE contributes positively to sustainability), and Trade-off (in which CE can generate positive or negative effects on sustainability).

Scholars who argue that CE can contribute to sustainability assert that by applying circularity principles, organizations can achieve economic, environmental, and social gains. According to Cecchin *et al.* (2021), one of the criticisms of sustainability is the lack of a clear strategy with the current model, whereas CE offers a more tangible approach to achieving it.

The potential contribution of the CE to sustainability has also been discussed in relation to the SDGs (Schroeder *et al.*, 2019). The SDGs comprise 17 global goals adopted by the United Nations in 2015 under the 2030 Agenda, which aim to establish interconnected goals and targets to eradicate poverty, protect the planet, and promote peace and prosperity for all by 2030 (United Nations, 2024).

For Ortiz-de-Montellano *et al.* (2023), implementing circularity strategies can help achieve the targets of the 17 SDGs, with the greatest contributions in SDG 8 (decent work and economic growth), 12 (responsible consumption and production), and 13 (climate action). This is because the implementation of CE is directly related to the restructuring of production and consumption systems, promoting greater resource efficiency, innovation in business models, and job creation. Furthermore, by reducing raw material extraction and waste generation, CE significantly lowers greenhouse gas emissions, directly addressing climate change.

However, authors who question the CE's contribution to sustainability point to potential negative rebound effects. One of the main concerns is that studies on CE focus on economic and environmental aspects rather than promoting a holistic view (Geissdoerfer *et al.*, 2017; Walker *et al.*, 2022). The lack of studies that consider all pillars of sustainability (economic, social, and environmental aspects) hinders the systemic assessment of the CE's impact. Vanhuyse *et al.* (2021) and Luthin *et al.* (2023) highlight that the social dimension continues to receive little attention in studies of the circular transition.

Calisto Friant *et al.* (2020) conclude that, despite the various economic and environmental benefits associated with circular policies and business models, discourses on the CE still do not provide a holistic and systemic understanding of the social implications and sustainability of the circular transition. For the authors, the contemporary discourse on CE remains centered on economic and market solutions, which is insufficient to address the complexity of current challenges. In this sense, they argue that circularity should be understood as a broader social transformation that also involves ecological and political dimensions.

In this context, some researchers have been conducting in-depth studies on the negative rebound effects of CE. Castro *et al.* (2022), for example, identified several side effects of CE in the literature, such as increased waste generation, growth in informal employment, and increased emissions and energy consumption. Thus, rebound effects can become significant obstacles to addressing environmental (Zink and Geyer, 2017) and social challenges.

Metic and Pigosso (2022) emphasize that further research is needed to improve the understanding of rebound effects, particularly their environmental and social impacts. It is known that these effects may occur, making it essential to develop strategies to mitigate them during the transition to a circular economic model (Zink and Geyer, 2017).

Given this, it can be inferred that the CE has the potential to contribute to sustainability, but its outcomes are not guaranteed, as they depend on its implementation. Thus, the strategic planning of CE initiatives, as well as the use of tools to assess their impacts, is essential to minimize rebound effects and support an effective transition toward sustainability.

2.2 Public Policies and the Development of the Circular Economy

The transition to a circular economic model cannot occur without public policies that encourage and enable its implementation. According to Losa (2025), these policies are among the most effective instruments for encouraging companies to adopt circular practices because they create conditions conducive to the shift from the current linear model to a circular economy.

Public policies can be understood as a coordinated set of decisions and actions carried out by different levels of government to respond to collective demands and achieve effective results in addressing socially recognized problems (Souza, 2006). In this context, there has been a growing trend toward developing policies to promote CE and reduce the impacts associated with the linear model of production and consumption (De Melo *et al.*, 2022).

The European Union (EU) has stood out in developing policies that encourage the CE. From a European perspective, this economic model is understood as a strategy to promote a competitive, sustainable, low-carbon economy that is more resource-efficient and self-sufficient (EU, 2015). It is noteworthy that the bloc is highly dependent on primary materials sourced from other regions of the world. In this context, closing material cycles can help reduce vulnerability to economic fluctuations associated with resource imports. Thus, public policies aimed at the transition to the CE respond to these structural demands of European society.

In this scenario, the EU has introduced several policy initiatives to foster the transition to a CE. One of the most significant milestones was the publication of *Closing the Loop: An EU Action Plan for the Circular Economy* in 2015, which established priorities for key areas, including plastics, food waste, biomass, critical raw materials, and construction. In 2019, the *European Green Deal* expanded this approach by integrating the CE as a central element of economic efficiency, linking micro- and macroeconomic dimensions and highlighting its relevance at the local level. Subsequently, in 2020, the new action plan for the CE reinforced an approach focused on the entire product life cycle, incorporating aspects related to design, sustainable consumption, greater consumer participation, practices such as industrial symbiosis, and information and certification systems (Dubeux and Campos, 2020).

Although European public policies are often considered global benchmarks, they still present significant limitations. Gaps in the current institutional framework, fragmentation, and a lack of coherence among policy instruments hinder the effectiveness of the transition to a circular economic model. Furthermore, public policies focused on CE predominantly adopt recycling-centered approaches, with less attention to higher-value strategies such as prevention, reuse, repair, and remanufacturing, which remain underutilized in the European context (Losa, 2025).

Outside the EU, other countries have been creating and implementing strategies focused on the CE. China, for example, stands out for the development of circular policies, which are regarded as state policy and a national strategy led by the central government (De Melo *et al.*, 2022). In 2005, the country published the document *Opinions on Accelerating the Development of the Circular Economy*, which proposed a policy framework, basic principles, tasks, and objectives for the CE. Subsequently, in 2008, the *Circular Economy Promotion Law* was enacted, marking another important milestone for CE in China. The circular model has been implemented in China to address a range of environmental problems stemming from rapid

industrialization, including air and water pollution. In this context, the Chinese CE is strongly oriented toward industrial efficiency, industrial symbiosis, and reducing pollution resulting from accelerated industrialization (Bleischwitz *et al.*, 2022).

Another Asian country pioneering the promotion of the CE is Japan, which incorporated the concept of the *Sound Material Cycle Society* (SMCS) in 2000. In an SMCS society, the consumption of natural resources is reduced, and environmental pressure is minimized as much as possible (a concept similar to CE). Since then, Japan has moved toward a sustainable circular system based on the 3Rs principles (Arai *et al.*, 2023). In 2020, another milestone for the Japanese CE was announced: *The Circular Vision*, which aims to increase Japanese competitiveness through CE, respond to society's demands regarding environmental issues, and align with the SDGs. According to Herrador *et al.* (2022), the country is developing CE in the right direction and providing solid institutional support.

In Latin America, Colombia stands out as one of the leading countries in promoting the CE and plays a significant role in coordinating a regional agenda. The country has incorporated circularity as a development strategy, linking it to innovation, competitiveness, and sustainability, and advancing the integration of this concept into public policies and national initiatives (EMF, 2021c). Chile is also cited by Dubeux and Campos (2020) as a model for other countries in the region to study. According to the authors, the country aims to boost the economy through the CE while improving resource efficiency.

Given the economic and social characteristics of Latin America, the CE offers potential that extends beyond more efficient resource use. In the region, circular principles are being incorporated into the strategic public policy agenda and aim to reconcile economic development, social inclusion, and the reduction of environmental impacts. This potential is linked to issues such as high social inequality, informality in production chains, pressure on natural resources, and limitations in waste management, which pose structural challenges for Latin American countries (EMF, 2021c).

In this context, Brazilian public policies focused on the CE face the challenge of not only promoting closed-loop systems and economic gains but also developing solutions appropriate to the country's socioeconomic context. Although the *National Solid Waste Policy* (PNRS), aligned with CE principles, has been in effect since 2010 (Brazil, 2010), the country has only recently begun developing specific policies to transition to a circular economic model.

In 2024, the *National Circular Economy Strategy* (ENEC) was published, marking an important milestone for the country's circular transition. The ENEC establishes guidelines such as the elimination of pollution and the reduction of waste, the maintenance of the value of materials and the regeneration of the environment, reducing dependence on natural resources, promoting sustainable production and consumption patterns, extending the life cycle of materials, and ensuring a fair, inclusive, and equitable circular transition, taking into account inequalities of gender, race, ethnicity, and socioeconomic status (Brazil, 2024).

The publication of the ENEC paved the way for the launch of the *National Circular Economy Plan* 2025-2034 (PLANEC) in 2025. The plan is an instrument that outlines goals, actions, and indicators for implementing the circular economy strategy at the national level. Thus, it defines specific objectives, proposed actions, and key actors for each of the five established pillars: (1) creation of a regulatory and institutional environment conducive to the circular economy; (2) promotion of innovation, culture, education, and skills development; (3) reduction of resource use and waste generation; (4) proposal of financial instruments; and (5) promoting intergovernmental coordination and the engagement of workers in the circular economy (Brazil, 2025).

Thus, the CE, as a public policy in Brazil, is still under development, with the country taking its first steps toward strengthening regulatory, financial, and governance instruments. It is worth noting that the circular transition in Brazil begins with waste management, as outlined in the PNRS, and then progresses to incentives for circular practices (tax incentives, special financing, technical support, price regulation, etc.) through the ENEC. Despite these advances, a large part of CE policies still retains a sectoral character and shows limited integration with urban planning.

Furthermore, Seles *et al*. (2025) argue that the implementation of circular practices in the Brazilian context still faces significant institutional barriers, including outdated regulations and the lack of government incentives capable of fostering the adoption of circular practices and business models. Such limitations hinder the consolidation of the CE in the country and highlight the need to strengthen the regulatory environment and support instruments for the circular transition.

Similarly, when analyzing PLANEC, it is evident that little attention is given to the urban level of CE implementation, which is limited to setting a goal of creating a national industrial symbiosis program that facilitates the exchange of resources (co-products and by-

products) between companies and sectors (Brazil, 2025). Thus, the plan lacks specific actions to incorporate CE principles into urban planning and to strengthen the circular transition in the country.

Beyond the formulation of public policies, it is necessary to develop mechanisms capable of supporting their implementation, monitoring, and evaluation. The effectiveness of CE strategies depends not only on the definition of objectives and guidelines but also on the ability to track their outcomes, identify limitations, and promote adjustments throughout the implementation process. In this context, decision-support instruments play an important role in reducing uncertainties, fostering institutional learning, and strengthening the governance of the circular transition (Guzzo *et al*., 2022).

Given this context, this study can contribute to the development of public policies aimed at implementing CE at the urban level, helping fill a gap in incorporating the urban dimension into CE operationalization and reinforcing the need for more systemic approaches and tools that support public managers in planning, monitoring, and evaluating the circular transition.

2.3 Urban Circularity

The implementation of the CE at the macro level, especially on an urban scale, has been growing in recent years, driven by the strategic role of cities in resource management and the promotion of sustainability. These factors have increased interest in the academic literature on the topic (Coussa, 2025).

According to EMF (2019a), cities are fundamental to the circular transition, as they have the autonomy to regulate, incentivize, and promote the CE. Furthermore, they possess infrastructure, services, and utilities with circular potential. In this context, urban managers can foster circular businesses, implement solutions to close material cycles, define strategies, and coordinate different stakeholders.

In light of this, cities have been developing plans and strategies focused on the circular transition, many of which aim to promote urban sustainability by implementing circular solutions (De Bantel *et al.*, 2025). Thus, CE presents itself as an approach capable of addressing challenges such as climate change and population growth by proposing strategies focused on resource efficiency, waste reduction, and urban sustainability (Herrador, 2024).

Despite cities' growing interest in becoming circular, the concept of the CC remains vague in the literature (Girard and Nocca, 2019; Schuppler *et al.*, 2016). Different authors have

interpreted CCs in distinct ways. For Paiho *et al.* (2020), the CC is based on closing, decelerating, and narrowing resource cycles through strategies such as conservation, increased efficiency, sharing, servitization, and virtualization.

Prendeville *et al.* (2018), on the other hand, highlight that CCs apply CE principles in partnership with various urban actors, such as citizens, companies, and other stakeholders. For the authors, this movement aims to close cycles and build cities prepared for the future. For Ferreira and Fuso-Nerini (2019), however, the concept of urban circularity should encompass the main aspects of CE, adapting them to the urban perspective.

Although these perspectives differ in their emphasis, they collectively suggest that CCs involve more than the implementation of isolated CE initiatives. Instead, they require integrating circular principles across urban systems, governance processes, and resource flows, multiple stakeholders, and the specific characteristics of cities.

To translate these principles into practice, many cities have adopted the *RESOLVE* framework (Marjanović *et al*., 2022). For example, the European cities analyzed by Williams (2017) tended to adopt the *RESOLVE* framework to support their transition toward circularity. However, the framework was not originally developed for urban systems. In light of this, Prendeville *et al*. (2018) proposed an adaptation of the framework, in which each principle can encompass different types of actions to be implemented on an urban scale.

In the proposal by Prendeville *et al.* (2018), the *Loop* principle (closing cycles) includes actions such as waste separation and recycling, upcycling, and bioeconomy initiatives. The *Share* principle involves the shared use of goods, reuse, and repair. The *Optimize* principle, on the other hand, encompasses actions aimed at resource efficiency, such as building rehabilitation and the adoption of technological solutions. Under the *Virtualize* principle, actions such as creating digital platforms for monitoring and service delivery stand out.

In the same proposal, the *Regenerate* principle focuses on environmental restoration through renewable energy, such as rooftop solar panels, the creation of green spaces for biodiversity, and the promotion of urban agriculture. Finally, the *Exchange* principle encompasses, among other examples, the electrification of public transportation and the adoption of circular processes in construction and demolition (Prendeville *et al.*, 2018). It is observed, however, that this approach tends to prioritize technical dimensions of circularity, with less attention given to the socio-spatial complexity of urban systems.

Despite the adaptation, Williams (2019a) has questioned the implementation of urban circularity as outlined in the *RESOLVE* framework. For the author, this approach is insufficient to characterize a CC. Although *RESOLVE* is useful as an initial guide for resource management, the framework was developed for economic systems, such as companies or industrial sectors. Thus, the framework does not account for the complexity of urban systems. Marjanović *et al.* (2022) also question the framework's use to ensure a holistic circular transition in urban environments.

Williams (2021a) highlights that urban systems are complex, involving multiple actors, sectors, and resource flows, and depend on diverse infrastructure and services. Cities are governed at the local level but are influenced by decisions at different scales and aim to provide social benefits to the population. Furthermore, the framework was developed with a focus on production, whereas cities are simultaneously spaces of production and consumption, in which residents' behavior directly influences circularity (Williams, 2021b).

Another relevant point is that *RESOLVE* disregards the territorial dimension, which is strategic for urban circularity. Urban infrastructure plays a central role in the circulation of materials, water, and energy that fuel the urban metabolism. Finally, the need to adapt structures over time is also not addressed by the *RESOLVE* approach (Williams, 2019a).

Given this scenario, Williams (2019a) proposes a conceptual framework for CCs, the *Circular City Approach*, adapted from the *RESOLVE* framework and incorporating the aspects discussed above. This approach presents three principles: reducing resource consumption and waste generation, preserving natural capital and ecosystem services, and eliminating the city's negative externalities (economic, environmental, and social). These principles must be achieved amid the constant change of urban systems, since demands, consumption patterns, and supply needs are not static. A comparison of the frameworks is presented in Table 1.

Table 1 - Comparison between the *Circular City Approach* and the *RESOLVE* framework.

Category	Aspect	RESOLVE	Circular City
Principles	**Preserving natural capital**	The preservation and enhancement of natural capital through the management of finite stocks and the balancing of renewable resource flows.	The ecosystem that sustains the city is constantly regenerated, preserving natural capital and essential ecosystem services.

Source: Williams (2019a) (continued)

Table 1 - Comparison between the *Circular City Approach* and the *RESOLVE* framework.

Category	Aspect	RESOLVE	Circular City
Principles	**Optimizing resource use**	Optimizing resource utilization by circulating products, components, and materials in use at their highest utility at all times, in both technical and biological cycles.	Resource consumption is reduced (through sharing, optimization, localization, and substitution), and all remaining waste produced by urban activities is recycled. Urban infrastructure is also adapted and renewed for new contexts to avoid waste.
	Eliminating negative externalities	Promote system effectiveness by identifying and addressing negative externalities related to resource use.	Eliminate the negative environmental, economic, and social externalities associated with resource waste in the city.
Scope	**System**	Economic	Urban ecosystem
	Resources	Materials, energy, water.	Materials, energy, water, land, and infrastructure.
	Complexity	Less complex: a single company or industrial sector.	Very complex, involving multiple actors, diverse resources, and infrastructure systems.
	Scale	National/international (companies or industrial sectors).	All scales (with a special focus on cities/locations).
	Focus	Focus on production systems.	Focus on lifestyles, social practices, and supply systems.
	Sector	Single sector.	Multisectoral, intersectoral.
	Activity	Manufacturing, supply, transportation, and disposal related to the production, distribution, and disposal of goods/resources.	Travel, shopping, leisure, education, manufacturing, construction, and agriculture (related to consumption, development, and the city's operations). .
Action	**Loop**	Keep components and materials in closed loops through reuse, recycling, recovery, and remanufacturing, prioritizing internal loops.	Closing material cycles through recycling, recovery, and reuse of resources.

Source: Williams (2019a) (continued)

Table 1 - Comparison between the *Circular City Approach* and the *RESOLVE* framework.

Category	Aspect	RESOLVE	Circular City
Action	**Adapt**	N/A	Plan and design cities to enable the adaptation and renewal of urban infrastructure.
	Regenerate	Switch to renewable energy and materials; restore ecosystem quality and return recovered biological resources to the biosphere.	Regenerate natural capital and urban ecosystem services.
	Location	N/A	Map resource flows and activities (consumption and production) within the city-region to develop symbiotic local capital and encourage pro-environmental behavior.
	Substitute	Virtualize and substitute, dematerialize resource use by providing utilities virtually. Replace products/services with options that consume fewer resources.	Replace non-renewable resources with renewable resources in the supply chain; resource-based activities with service-based activities; physical activities with virtual ones; and non-durable infrastructure with durable infrastructure.
	Share	Keep the product cycle short and maximize product utilization by sharing it among different users.	Share resources in cities across a range of activities (e.g., living, working, traveling).
	Optimize	Increase product performance and efficiency; eliminate waste in production and the supply chain; leverage big data.	Optimize resource consumption by producers and consumers through efficient technologies and by addressing resource surpluses in the urban system.

Source: Williams (2019a).

Williams' (2019a) conceptual approach is based on the application of two types of actions: circular actions and supporting actions. The author identifies three fundamental circular actions: loop, regeneration, and adaptation. According to Williams (2021a), the combination of these actions allows the urban system to renew itself, reducing resource consumption and waste generation. In addition, four supporting actions can be used to support urban circularity: optimization, sharing, substitution, and localization.

When comparing the two frameworks, it is evident that while *RESOLVE* provides an important foundation for implementing CE, the CC approach offers a more systemic, territorial, and urban-sustainability-oriented vision. The actions outlined by Williams (2019a) enable the

city to move beyond closing cycles by incorporating elements such as adapting urban infrastructure, regenerating natural systems, and localizing production and consumption flows.

Marjanović *et al.* (2022) noted that urban circularity strategies remain heavily influenced by the *RESOLVE* framework and a systems-based view of the CE. However, the authors emphasize that urban circularity is still in its early stages and that the development of circular urban systems occurs gradually. In this sense, *RESOLVE*-based approaches tend to represent the early stages of the circular transition, while more comprehensive proposals, such as Williams (2019a), move toward a more systemic, integrated, and mature vision.

Given the current state of the literature, and even without a definitive concept of the CC, it can be inferred that urban circularity is not equivalent to the CE implemented in cities. In this sense, Pegorin, Caldeira-Pires, and Faria (2024) argue that the mere presence of circular economy projects does not, by itself, characterize a city as a CC. However, such projects may represent important steps within a broader and gradual transition toward urban circularity. Complementarily, Marjanović *et al.* (2022) highlight that urban circularity involves the reorganization of the urban system as a whole, in contrast to the notion of urban circular economy, which refers to the development of circular flows restricted to the city's economic system.

This limitation is also highlighted by Bourdin and Torre (2025), who argue that the CE at the local level cannot be implemented solely on economic or sectoral grounds, as is often the case in industrial systems. For the authors, it is essential to consider territorial dimensions, local dynamics, and interactions among actors for the effective implementation. In this sense, the authors emphasize that the circular transition depends on contextualized and territory-based approaches. These factors highlight the importance of territorial governance and local relationships in the organization of circular systems.

Aina *et al.* (2026) also analyzed the circular trajectories of cities and argue that initiatives have evolved from isolated, sectoral actions, often focused on recycling and waste management, toward more integrated, multisectoral approaches. These actions involve governance, technological innovation, urban planning, citizen engagement, and sociocultural transformations. Similarly, Falah *et al*. (2026) argue that many CC initiatives remain heavily oriented toward recycling and material recovery, maintaining a waste-management-centered approach. According to the authors, building more advanced CCs requires urban strategies that go beyond the logic of closing cycles and recovering materials, incorporating actions related to

prevention, the redesign of urban systems, the extension of the useful life of urban resources, and the holistic transformation of material, energy, and consumption flows in cities.

Given these different perspectives, it becomes evident that the literature has not yet reached a consensus on the concept of the *Circular City* or on how the practices that support the urban circular transition should be understood. Building upon the conceptual contributions discussed throughout this section, particularly those of Williams (2019a), this study adopts the interpretation that urban circularity should be understood as an integrated and evolutionary process rather than as the implementation of isolated circular economy initiatives.

Thus, in this study, urban circularity is understood as an integrated and evolutionary process in which the urban environment is viewed as a complex socioeconomic system in which the circular use of resources is combined with actions to adapt urban structures, localize production and consumption flows, and regenerate natural systems. Urban circularity also incorporates social and territorial dimensions that are often neglected in the CE. It is important to note that, based on the discussion above, this study understands the CE as a strategic element of urban circularity, but not as a sufficient condition to characterize a city as circular.

Accordingly, circular practices are understood as the set of actions and strategies implemented by different urban actors that support the transition toward urban circularity. They comprise the practical mechanisms through which the principles of urban circularity are progressively incorporated into urban planning, governance, infrastructure, resource management, and production and consumption systems. In this sense, while the principles of urban circularity define the objectives to be achieved, circular practices represent the operational mechanisms through which these objectives are progressively implemented throughout the urban circular transition.

Finally, based on the literature discussed above, particularly Marjanović *et al*. (2022), this study assumes, assumes that the construction of sustainable CCs occurs through an evolutionary process in which different approaches and levels of circularity integration are progressively developed over time. Thus, this study understands that a CC is not implemented uniformly but is built upon different levels of integration among policies, infrastructure, actors, and urban systems. This evolutionary understanding of urban circularity provides the theoretical and conceptual basis for the maturity model and the integrated decision-support tool proposed in this research. Rather than classifying cities as either circular or non-circular, this study recognizes urban circularity as an evolutionary process in which cities exhibit different

levels of integration of circular principles and practices over time, thereby providing the rationale for assessing urban circularity through different maturity levels.

2.4 Benefits and Challenges of the Urban Circular Transition

Implementing circularity can yield various benefits for city sustainability. Williams (2021b) classifies these advantages into three categories: ecological, social (including health and community), and economic. Among the ecological benefits, the following stand out: reduced resource consumption, restoration of urban ecosystem services, decreased greenhouse gas emissions, increased capacity to adapt to climate change, and the promotion of environmental awareness.

In the social sphere, circular actions can improve public health by expanding green spaces and reducing pollution, and strengthen local communities by fostering social engagement and capacity building. Economic benefits, meanwhile, include reduced production costs, economic value creation, economic diversification, and job creation (Williams, 2021b).

In this context, urban circularity is presented as a means of achieving the SDGs at the local level, with a greater contribution to SDG 11 (*Sustainable Cities and Communities*) (Falah *et al.*, 2025; Paiho *et al.*, 2020), SDG 12 (*Responsible Consumption and Production*), and SDG 13 (*Climate Action*) (Paiho *et al.*, 2020).

However, implementing urban circularity does not always yield positive outcomes, particularly when it is based on an interpretation focused solely on creating an urban circular economy. In this regard, Dong *et al.* (2021) highlight that, although CE at the urban level contributes to several SDGs, it can generate trade-offs that need to be identified and mitigated, risking compromise of urban livability and quality of life (Superti *et al.*, 2021).

The literature identifies various rebound effects associated with CE in urban areas. Increased waste collection, for example, can exacerbate precarious working conditions when it relies on informal waste pickers, contributing to social exclusion (Dong *et al.*, 2021). Furthermore, organizational changes can generate negative impacts, such as the loss of quality jobs, reduced labor rights, and health risks (Chen, 2021; Vanhuyse *et al.*, 2022).

Vanhuyse *et al.* (2022) emphasize that, although the circular economy is often associated with job creation, these initiatives do not always guarantee decent working conditions. According to the authors, many of the jobs created offer low wages, and there is

also a reliance on informal or volunteer work. Thus, urban circularity can negatively impact the achievement of SDGs 1, 8, and 10 (Dong *et al.*, 2021).

In this sense, ensuring a fair and effectively sustainable circular transition is a challenge. In addition to the obstacles mentioned, Paiho *et al.* (2020) identify other barriers to urban circularity. The authors classify these barriers into four groups: business, political, technical, and knowledge-related challenges. Complementarily, Williams (2019b) highlights sociocultural, economic, regulatory, institutional, environmental, and technical challenges associated with implementing circular initiatives.

Campbell-Johnston *et al.* (2019), in analyzing Dutch cities that are pioneers in implementing circularity, identified barriers classified as hard and soft. Hard barriers include technological limitations, systems integration, knowledge of material flows, financing, project scalability, and the costs of virgin materials. Soft barriers, on the other hand, include difficulties in measuring CE, regulatory complexity, a prevalence of a linear mindset, and limitations in planning and organizing circular activities.

Given this scenario, these challenges highlight the need for instruments that provide structured support for the urban circular transition. Such instruments should assist not only in strategic planning but also in the continuous monitoring of the implemented actions and the assessment of their impacts over time. Furthermore, they must account for the complexity of urban systems by integrating diverse sectors, stakeholders, and dimensions of sustainability to guide decision-making and reduce risks associated with rebound effects and fragmented initiatives. Given the need to structure the urban circular transition, maturity models emerge as a means of organizing and guiding this process.

2.5 Experiences in Implementing Urban Circularity

Despite the challenges of the urban circular transition, various initiatives are emerging worldwide to advance CC development. In China, for example, efforts toward circular urban development are evident. One of the first cities in the world to attempt to implement circular solutions was Shanghai, which in 2005 published the *Shanghai Circular Economy White Paper* (Su *et al.*, 2021). In their study of 40 Chinese cities, Wang *et al.* (2018) noted that Chinese national policies strongly incentivize CE strategies in these cities. In the Chinese context, urban circularity is no longer limited to post-consumer recycling but now encompasses circular value chains that integrate inter-industrial systems.

In a study of the city of Rizhao, China, Li *et al*. (2021) found that the city's CE is characterized by an economic development model that minimizes waste and promotes sustainability. According to them, CE has yielded positive results and increased Rizhao's sustainable development index. However, the authors emphasize that to build a more effective strategy, it is necessary to create policies that optimize the use of local renewable resources, the efficient use of non-renewable resources, and the circular structure of industries. For the authors, a strategy that considers these aspects can enhance the economic, social, and environmental benefits of CE.

Marjanović *et al.* (2022) studied a CC implementation project across five cities in Alberta, Canada. The authors noted that even before the project, the cities already had several CE initiatives in place. According to the researchers, CE actions are inspired by the RESOLVE framework and focus on closing the material loop. Waste reduction and elimination are encouraged through regulatory measures in the business sector. These actions are promoted through circular procurement policies, bans on plastic use, and incentives for waste reduction.

The city of Charlotte, in the United States, was the first American city to commit to developing a circular economy. In 2018, the study *Circular Charlotte - Towards a zero-waste and inclusive city* was published, analyzing the amount of materials lost in the waste system and presenting guidelines for the circular economy. The plan focuses on waste management and seeks to encourage and make recycling viable. At the same time, the publication notes that the next steps toward making the city circular are: working with the commercial and industrial sectors, engaging non-governmental organizations, promoting sustainable energy, urban agriculture, repair, and upcycling, raising awareness about the CE, and encouraging changes in consumption patterns (Charlotte, 2018).

In developing countries, the transition to a circular economy is occurring slowly. In Indonesia, where the CE is in its early stages, the starting point for urban circularity is waste management, with a focus on reducing waste generation. Additionally, the country's government has been creating mechanisms to transform waste into resources. However, all stakeholders must be involved in developing the CE (Nurdiana *et al.*, 2021).

In 2022, UCCI (*Union of Ibero-American Capital Cities*) published the *Manual on the Circular Economy in Ibero-American Cities*, which seeks to adapt the concept of urban circularity to the regional context and addresses specific cultural, social, and structural aspects that may hinder the circular transition. The extractive economy, deep social inequalities, and

the presence of waste pickers (often informal and precarious) are characteristics that cities must consider in the circularization process. Taking these aspects into account, the manual identifies priority areas for urban circularity in the region, including: industry, the bioeconomy, construction and civil engineering, urban infrastructure (water, energy, and mobility systems), and well-being and social inclusion (UCCI, 2022).

In the Latin American context, Brazil published the *Guide to the Inclusive Circular Economy for Cities and Regions* in 2025. The document aims to support local governments in incorporating CE principles into urban and regional planning, presenting guidelines and opportunities for the circular transition in cities and regions. It highlights topics such as waste management, local food production, circular construction, mobility, water, energy, governance, and social inclusion, emphasizing the need to promote more regenerative, resilient, and inclusive urban systems. Furthermore, it reinforces the importance of valuing socially vulnerable groups, such as recyclable material collectors, and of developing strategies tailored to local specificities and needs (MMA, 2025).

The European Union also presents various documents and initiatives focused on the circular transition in cities, which will be analyzed in Chapter 4. The greater focus on European cities in this study is related to the bloc's efforts to promote circularity in the urban context, making these cities references for understanding the circular transition and for the development of CC in Brazil.

An analysis of international experiences shows that the implementation of urban circularity varies across contexts, reflecting the specific economic, institutional, territorial, and social characteristics of each. At the same time, it is evident that building a CC involves multiple sectors and presents challenges, reinforcing the need for tools that support public managers in planning, monitoring, and evaluating this process.

2.6 Maturity Models

Maturity models are used to measure the quality of a process (Wendler, 2012), enabling the identification of the optimal path for evolution from an initial stage to a more advanced stage, passing through a series of intermediate stages. For each intermediate stage, requirements are defined that, when met, enable attainment of a higher level (Maier *et al.*, 2012).

According to Klimko (2001), maturity models have specific properties. The first is that development occurs across a limited number of maturity levels (typically 4 to 6). The second is

that the levels are characterized by specific prerequisites that must be met. Finally, the levels are ordered sequentially, from an initial phase to a higher level of development.

In CE studies, maturity models are used to assess progress toward a circular economy. Aguiar and Jugend (2022), for example, proposed a maturity matrix for CE adoption in product development. Gorecki (2019), on the other hand, analyzed maturity in the construction industry and proposed the *Circular Economy Maturity* (CEM). Sacco *et al.* (2021), in turn, developed the CM-FLAT (*Circularity and Maturity Firm-Level Assessment Tool*), aimed at evaluating companies' performance regarding the CE.

Regarding the relationship between sustainability, the CE, and urban areas, models focused on smart cities stand out. Aragão *et al.* (2023), for example, developed the MMSC (*Smart Cities Maturity Model*), which classifies cities' degree of intelligence based on social and technological indicators. Arruda (2019), on the other hand, proposed the MMSC (*Maturity Model for Smart Cities*), incorporating indicators related to the SDGs. Another example of a maturity model focused on cities is the SCMM (*Smart City Maturity Model*) proposed by the *Smart City Institute* - SCI (SCI, 2022).

It is also worth noting Damianou *et al.* (2023), who proposed a planning model for smart and circular cities, with a macroeconomic approach focused on decision support. Despite these contributions, the model presents a more conceptual and strategic approach, neither defining maturity levels nor offering an operational tool directly applicable to urban managers, particularly in governance, cross-sectoral integration, and the social dimensions of urban circularity.

Thus, the literature review revealed that most maturity models related to the circular economy focus on organizational contexts or approaches geared toward smart cities, with few initiatives specifically aimed at supporting the urban circular transition in an integrated and systemic manner. In this regard, there is a gap in the literature regarding the development of maturity models designed to support decision-making in the circular transition.

Furthermore, these models can assist managers in monitoring urban indicator performance (Aragão *et al*., 2023), thereby advancing the circular transition. The creation of CC-specific maturity models, capable of structuring levels of evolution and guiding urban planning in an integrated and long-term manner, can facilitate the circular transition and support

public managers' decision-making. Such tools also allow for continuous monitoring of the transition, supporting the evaluation of public policies and evidence-based decision-making.

In the literature, various methodologies for constructing maturity models are described. In the work by Pigosso *et al.* (2013), the proposed model was developed in three main phases: (1) Theoretical Development; (2) Empirical Development; and (3) Theory Testing. The model by Aguiar and Jugend (2022) was also developed in three phases: (1) Planning; (2) Development; and (3) Evaluation.

To create a maturity model focused on the development of resilient cities, Gimenez *et al.* (2017) adopted an interactive process that incorporated multiple research methods and was divided into three phases. In phase (1), Stakeholder Validation, the authors utilized a literature review and semi-structured interviews with representatives from European cities. In phase (2), Identification of Maturity Stages, the researchers analyzed the semi-structured interviews and reviewed reports. In phase (3), Validation of the Evolution of Maturity Stages, the researchers conducted semi-structured interviews with representatives of the studied cities to validate the maturity levels.

It is evident that most maturity models are developed using the following logic: (1) collection of information on the subject under study, (2) development of maturity levels, and (3) validation of the model. This structure can be related to the cycles of *Design Science Research* (DSR). The information collection stage is similar to the rigor cycle, as it involves consolidating existing scientific knowledge and understanding the problem under study. The development of maturity levels, on the other hand, is associated with the design cycle, during which the proposed artifact is constructed. Finally, the model validation stage is part of the relevance cycle, as it assesses the model's applicability and usefulness in real-world contexts or among experts.

In this context, Mettler (2011) highlights that maturity models can be understood as artifacts of DSR, with their development and application closely connected to the processes of construction, evaluation, and evolution of the artifact. Thus, DSR proves to be a suitable approach for developing maturity models, as it combines the construction of applied solutions with systematic processes for evaluating and refining the resulting artifact.

2.7 Design Science Research (DSR)

DSR is a research approach focused on the construction and evaluation of artifacts developed to solve relevant organizational and social problems, reconciling scientific rigor and practical relevance (Hevner *et al*., 2004). According to Lacerda *et al*. (2013), this approach has as its central elements the definition of problem classes and the development of artifacts that offer generalizable solutions to these problems, thereby advancing knowledge in the field.

In this context, the problem class refers to the grouping of similar problems that share common characteristics, enabling the development of artifacts and solutions applicable to different situations and contexts (Lacerda *et al*., 2013). Thus, DSR seeks to develop artifacts that go beyond resolving a specific problem and contribute to broader, recurring situations.

Regarding the operationalization of DSR, this occurs through a structured process involving problem identification, the definition of solution objectives, artifact development, its demonstration, the evaluation of its utility, and, finally, the communication of results, with continuous refinement throughout the process (Lacerda *et al*., 2013; Delport; Von Solms and Gerber, 2024). Figure 1 illustrates the phases of DSR.

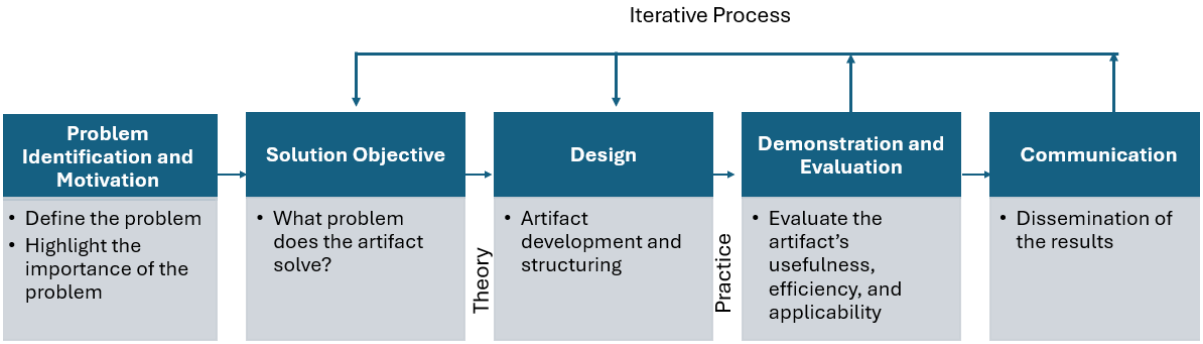


Figure 1 - DSR process. Source: Adapted from Peffers *et al*. (2007).

A study that uses DSR can also be understood through its cycles, which represent the dynamics of knowledge generation throughout the research. According to Hevner *et al*. (2004), DSR is structured into three main cycles: the relevance cycle, the rigor cycle, and the design cycle, as shown in Figure 2. The interaction between the relevance, rigor, and design cycles enables integration among the practical context, the theoretical foundation, and the artifact

development process, ensuring that the proposed solution is both applicable and scientifically grounded.

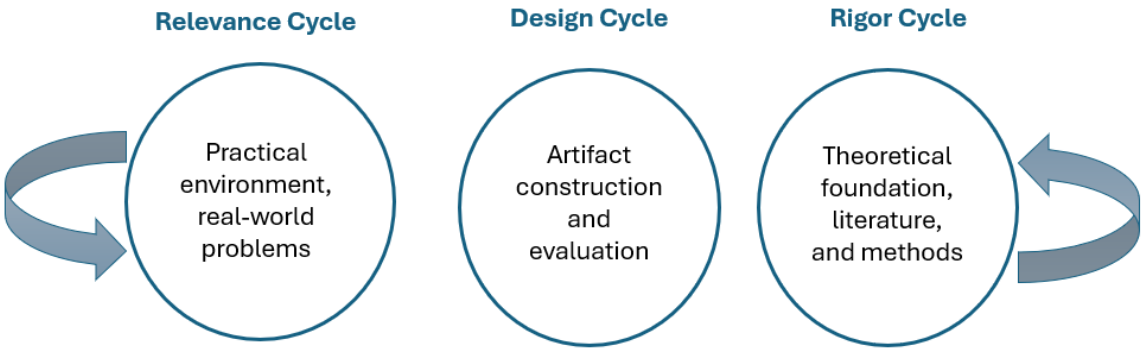


Figure 2 - DSR Cycles, highlighting the interaction between the relevance cycle, the rigor cycle, and the design cycle. Source: Adapted from Hevner *et al*. (2004).

The relevance cycle connects the research to the real-world context, defining the problem and solution requirements based on practical needs. The rigor cycle, on the other hand, relates the study to the existing theoretical framework, utilizing prior knowledge, models, and methods established in the literature to ground the development of the artifact. Finally, the design cycle corresponds to the process of constructing, applying, and evaluating the artifact, characterized by its iterative nature, in which the solution is continuously refined. Thus, the DSR cycles highlight the integration between theory and practice, allowing knowledge to be developed in an applied and scientifically rigorous manner (Hevner *et al*., 2004).

According to Lacerda *et al.* (2013), artifacts can be classified into different types, such as constructs, models, methods, and instantiations. Constructs refer to the concepts and language used to describe a given problem. Models, on the other hand, represent relationships between elements and aid in understanding reality. Methods, in turn, correspond to procedures or steps for problem-solving, while instantiations are the practical application of the developed artifact in a real-world context.

In the context of this study, the DSR was adopted to develop a solution to the lack of integrated tools to support sustainable urban circular transition. Thus, this approach enables the construction of a tool with scientific rigor, relevance, applicability, and adaptability across different contexts.

2.7 Circularity Indicators

An indicator can be understood as a factor or variable that allows one to understand, simply and reliably, the performance of something, reflect on changes, or evaluate the performance of an agent (OECD, 2014). It is, therefore, a quantitative or qualitative measure that provides relevant information about an object under analysis, aiding the decision-making process.

In CE studies, indicators are used to support the circular transition (Moraga *et al.*, 2019). With the development of policies and the rise of CE initiatives, there has been growing academic interest in developing indicators to monitor CE. These indicators are known as circularity indicators or C-indicators. Although they are important for the development of CE, academic studies on the topic, as noted by Saidani *et al.* (2019), indicate that the field is expanding and highlight the need to create tools to measure progress and manage CE at different levels.

Moraga *et al.* (2019) sought to understand what circularity indicators specifically measure and concluded that most focus on material preservation, particularly recycling. The authors emphasize that, although recycling is important in the circular model, it is not the only aspect to be monitored in a sustainable CE. Furthermore, they found that no single indicator can provide all the information necessary to understand the development of CE.

Chrispim *et al*. (2023), in their analysis of various CE assessment tools, found that most focus on resource efficiency, recycling, and waste management. In contrast, elements such as the social dimension, stakeholder engagement, industrial symbiosis, and consumption prevention and reduction strategies remain underrepresented. According to the authors, assessing circularity requires more holistic approaches that integrate multiple dimensions of sustainability and capture the complex interactions involved in the circular transition. These findings reinforce the need to develop more comprehensive assessment instruments, particularly when dealing with complex systems such as cities.

At the macro level, indicators play a fundamental role in the development of strategies and public policies for cities, regions, and countries, as they make it possible to assess whether the transition promotes not only circularity but also positive environmental, economic, and social sustainability outcomes (De Pascale *et al*., 2021). Despite their relevance, few urban-

scale Circular Economy plans include consistent indicators capable of monitoring and evaluating the sustainability impacts of circular actions (De Bantel *et al*., 2025).

The literature also points to gaps in measuring the social impacts of urban circularity (Bîrgovan *et al.*, 2022; Nurdiana *et al.*, 2021; Vanhuyse *et al.*, 2021). According to Girard and Nocca (2019), many of these aspects are only partially measurable, requiring qualitative and subjective indicators that have not yet been consolidated, which hinders the assessment of the circular transition and sustainability.

Similarly, current indicators have limitations in capturing environmental impacts (Bîrgovan *et al.*, 2022; Falah *et al.*, 2025; Kopp *et al.*, 2024). According to Kopp *et al.* (2024), although cities adopt circularity with environmental ambitions, their indicator systems remain limited, territorialized, and focused on waste streams, and are insufficient to capture systemic impacts, indirect effects, and global externalities.

Falah *et al.* (2026) analyzed 241 urban circularity indicators using the 10R framework and identified a strong predominance of indicators associated with downstream strategies, particularly recycling and material recovery. The study's results indicated that upstream strategies, such as reduction, rethinking, and refusal, were underrepresented among the indicators analyzed. Furthermore, the authors observed that strategies related to extending the useful life of products, such as repair, reuse, remanufacturing, and reconditioning, remain significantly underrepresented in urban monitoring systems. For the authors, this scenario highlights a trend in the operationalization of urban circularity that remains strongly associated with waste management, hindering the assessment of more systemic and preventive urban transformations.

Given this scenario, although circularity indicators are fundamental, they still have limitations in measuring, in an integrated manner, the environmental, social, and economic aspects in the urban context. This gap highlights the need for more comprehensive and systemic approaches to support the assessment and planning of urban circularity.

Thus, it is evident that existing approaches have significant limitations, whether due to the absence of a framework for assessing the evolution of urban circularity over time or to the difficulty of systematically integrating planning, monitoring, and impact assessment. Given this, there is a clear need for tools that articulate these dimensions in an integrated manner, allowing not only the diagnosis of cities' current stages but also guidance for their evolution,

monitoring the performance of the implemented actions, and evaluating their effects on sustainability. A detailed study of urban circularity indicators is presented in Chapter 6.

2.8 Reflections

The theoretical framework has shown that the topic of CE has been gaining prominence in academic literature over the past decades. However, the relationship between the CE and sustainability has been increasingly questioned. In this study, the CE is understood to have the potential to promote environmental, social, and economic benefits, but these outcomes are not guaranteed. In this sense, the possible rebound effects associated with the circular transition must be identified, monitored, and mitigated.

The literature review also revealed that many studies on the CE remain focused on technocentric approaches, often associated with resource efficiency, recycling, and the optimization of production processes. In the urban context, this limitation becomes even more relevant, since cities are characterized by complex, multisectoral, and territorially integrated socioeconomic systems. Thus, urban circularity cannot be understood merely as the implementation of the CE in cities.

Actions focused on the CE, particularly those related to closing material loops and resource recovery, are important for advancing the circular transition. However, cities are complex, dynamic, and multisectoral systems in which factors such as urban infrastructure, governance, land use, mobility, housing, consumption patterns, social inequalities, and access to resources also directly influence circularity. In this sense, urban circularity involves the integrated reorganization of urban systems, considering territorial specificities, local dynamics, and interactions among different urban actors.

Thus, strategies related to infrastructure adaptation, the regeneration of natural systems, the localization of production flows, and the strengthening of more resilient and inclusive urban systems become fundamental elements for building CCs. Furthermore, the analyzed literature indicates that the urban circular transition unfolds through a gradual maturation process, with varying levels of circularity integration across public policies, urban sectors, actors, and infrastructure systems.

Finally, although circularity indicators are fundamental to supporting the circular transition, limitations remain in the integrated measurement of circularity's impacts on

sustainability. Thus, the study of such indicators can assist public managers in identifying rebound effects and developing strategies that promote genuinely sustainable circularity.

3. METHODOLOGY

This chapter addresses the methodology used to develop this study. It presents the research classification and details the stages involved in developing the proposed tool.

3.1 Research Classification

This research is classified as applied. As explained by Mello *et al.* (2013), such research seeks to solve real-world problems, has practical relevance, and its results are immediately applicable. In this study, we seek to address the lack of tools to support urban managers in the circular transition. The tool will be applied in an urban area, underscoring the study's applied nature.

Regarding the objectives, the research is exploratory and descriptive. The research is exploratory, as it seeks to familiarize itself with the problem to understand it and identify possible solutions. It is also descriptive, as it seeks to characterize a phenomenon. As for the approach, the study is mixed-methods, using both qualitative and quantitative methods (Mello *et al*., 2013). The combined approach provides a better understanding of the research problems than either approach alone (Miguel *et al*., 2010). The research method adopted is modeling, as it seeks to construct a decision-support model (artifact) focused on the urban circular transition.

The study employs the Design Science Research (DSR) approach. DSR focuses on building solutions to real-world problems through the development of artifacts. Unlike traditional approaches, which focus on explaining and describing phenomena, DSR is prescriptive, seeking to propose and validate solutions for identified problem classes (Lacerda *et al*., 2013). In this context, the research is not limited to analyzing urban circularity but also involves designing an artifact to support decision-making in the circular transition.

Furthermore, in this study, the problem class concerns the lack of structured instruments to support urban managers across different cities in the transition to sustainable urban circularity. The proposed solution to this problem is to build a decision-support tool. The phases of the DSR describe the research development process, including problem identification, definition of solution objectives, artifact development, demonstration, evaluation, and communication of results. Thus, the DSR is well-suited to the objectives of this study, as it enables the development of an applied solution to a complex and still largely unexplored problem.

From the DSR perspective, the decision-support tool proposed in this study is an artifact developed to address the identified problem of the lack of instruments to support the transition to sustainable urban circularity. The artifact was designed to assist public managers in diagnosing, planning, monitoring, and evaluating urban circularity, integrating multiple urban sectors and dimensions of sustainability.

In the present study, the relevance cycle is associated with identifying gaps in tools to support the transition to urban circularity. The rigor cycle relates to the theoretical foundation of urban circularity and the analysis of circularity implementation in European cities. Finally, the design cycle refers to the development, application, and evaluation of the proposed tool.

The artifact developed in this research can be classified as a decision-support method, according to the classification presented by Lacerda *et al*. (2013). This is because it consists of a guiding framework comprising stages, criteria, and instruments for diagnosing, monitoring, and evaluating the transition to sustainable urban circularity. It consists of three complementary components: (1) a maturity model focused on the diagnosis and planning of the circular transition; (2) a set of indicators for monitoring key sectors; and (3) a set of indicators for assessing the environmental, social, and economic impacts related to urban circularity.

Figure 3 presents the methodological structure of the research, relating the DSR cycles to the phases of the study's development.

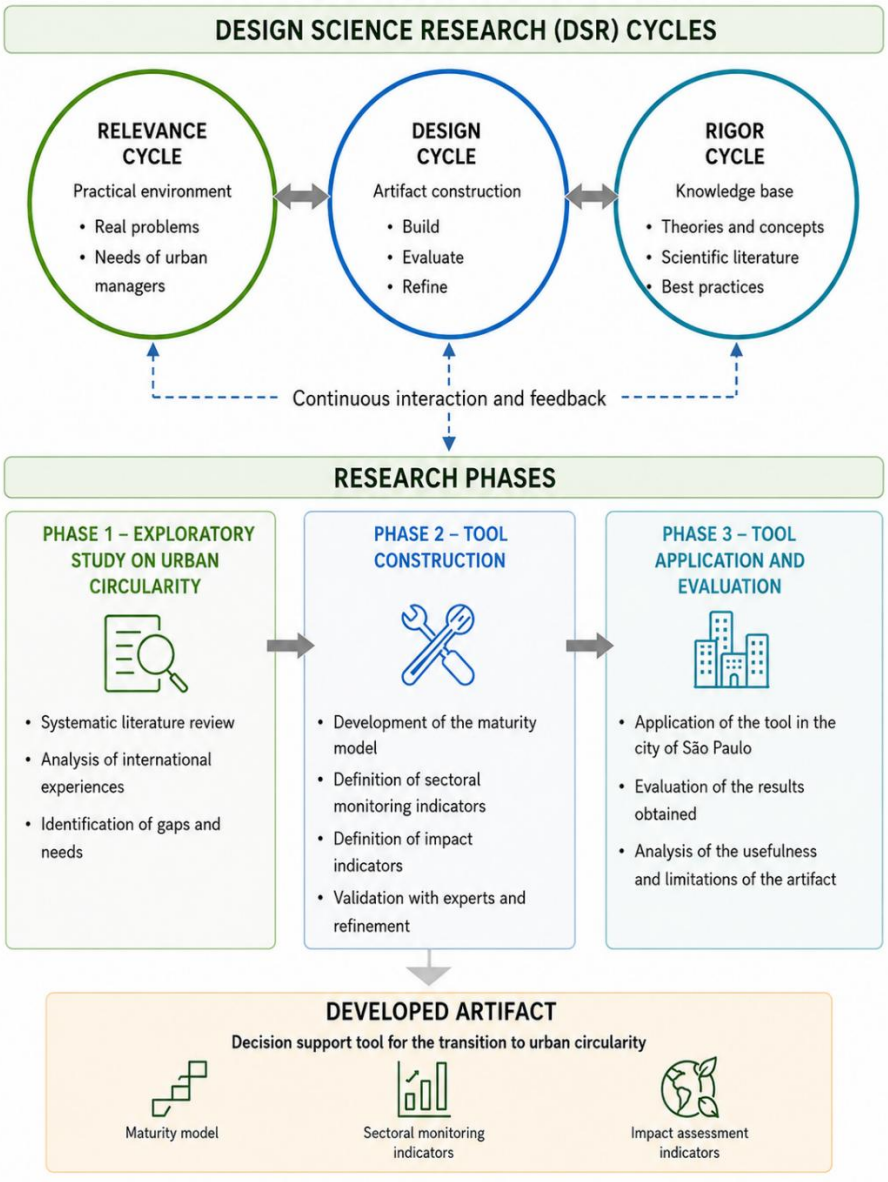


Figure 3 - Application of the DSR in this study.

Source: Developed by the author, with the assistance of ChatGPT – OpenAI (2026).

In light of the above, this study was conducted in three phases (Figure 4), namely: (i) an exploratory study on urban circularity, aimed at filling gaps in the literature and providing a foundation for the proposed tool; (ii) development of the tool, including modeling, structuring, and validation; and (iii) application of the tool in the city of São Paulo, selected for its data availability and pioneering role in environmental issues. This structure highlights the sequential and iterative nature of the research, aligned with the principles of DSR.

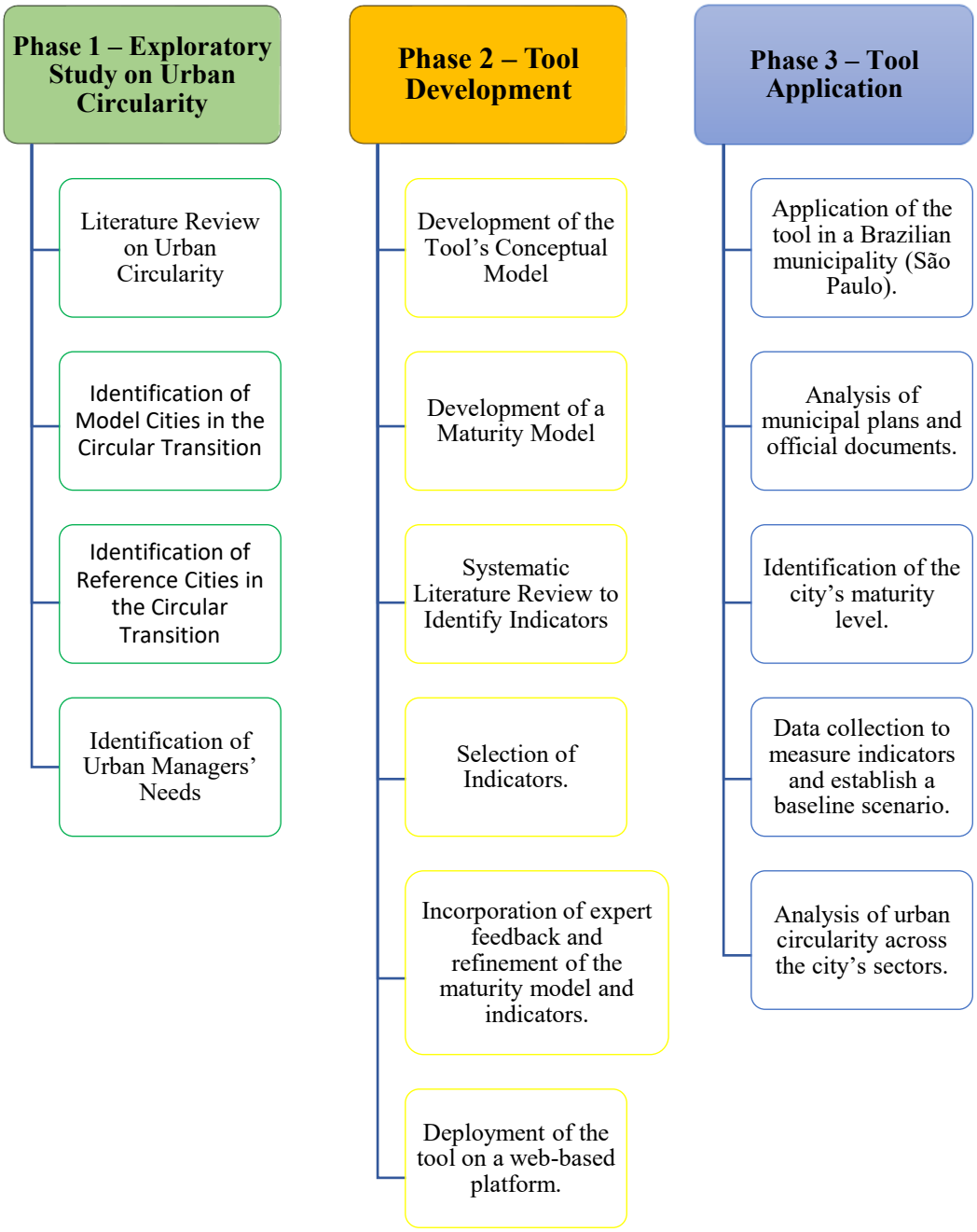


Figure 4 - Phases of the study's development.

Figure 5 summarizes the methodology used in this study, illustrating the research phases, their objectives, and their relationship with the DSR cycles. A detailed description of the methodology is presented in the following sections of this chapter.

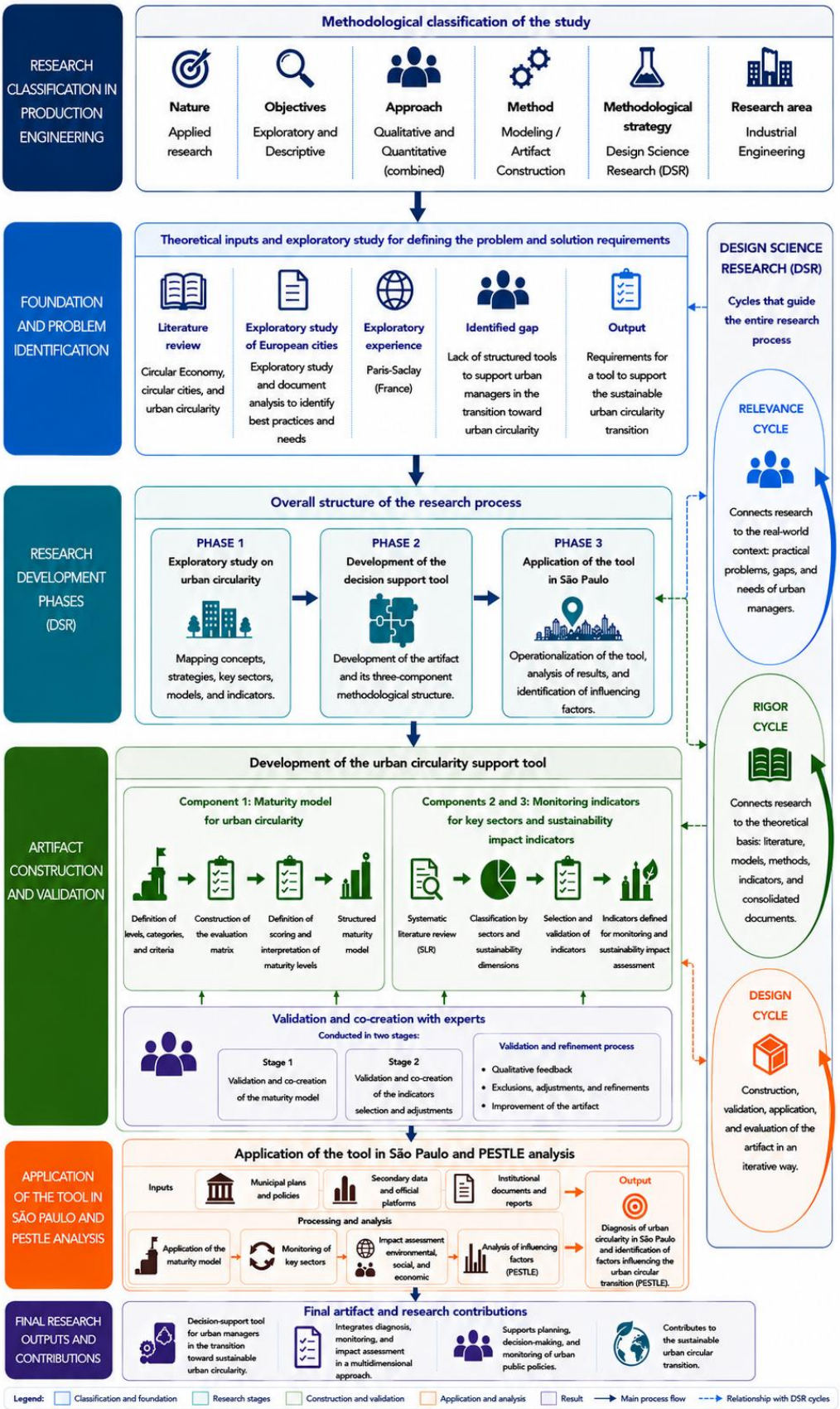


Figure 5 - Methodological summary of the research.

Source: Developed by the author, with the assistance of ChatGPT – OpenAI (2026).

3.2 Description of the phases of the study's development

The following section details the methodology used to develop each phase of this study's preparation.

3.2.1 Phase 1 - Exploratory Research on Urban Circularity

In addition to the literature review, an exploratory study was conducted through a documentary analysis of the implementation of urban circularity. This study sought to understand how urban circularity is being implemented in practice, identifying the circular actions adopted in reference cities. To this end, plans and strategies from different cities were analyzed, along with documents from organizations working on the urban circular transition.

The cities were selected based on their frequency in the literature and the availability of structured circular transition plans. The following documents were analyzed:

- Paris: *Paris Circular Economy Plan* (2017) (City of Paris, 2017);
- Rotterdam: *Rotterdam Circularity Programme - From Trash to Treasure* (2019) (Rotterdam, 2019);
- Helsinki: *The City of Helsinki's Roadmap for Circular and Sharing Economy* (2020);
- Prague: *Circular Prague* (2019) (Prague, 2019);
- Copenhagen: *Circular Copenhagen* (2020) (Copenhagen, 2020);
- Amsterdam: *Amsterdam Circular 2020–2025 Strategy* (2020) (Amsterdam, 2020);
- London: *London's Circular Economy Route Map* (2017) (London, 2017).
- *Circular Cities Declaration – 2022 Report* (Circular Cities Declaration, 2022).
- *Circular Cities Declaration – 2024 Report* (Circular Cities Declaration, 2024).
- *A Catalogue of Circular City Actions and Solutions – The Circular City Centre* (2022) (EIB, 2022).
- *A Catalogue of Circular City Actions and Solutions – The Circular City Centre* (2024) (EIB, 2024b).

The literature review sought to identify how urban circularity has been interpreted and implemented in different urban areas, considering the principles adopted, the prioritized sectors, the circular strategies implemented, and the governance mechanisms used by the cities analyzed. In addition, the documents enabled the mapping of actions to close material cycles, regenerate natural systems, adapt urban infrastructure, promote local production and consumption, and foster integration across urban sectors.

The study also contributed to identifying the main key sectors addressed by urban circularity strategies, as well as understanding how cities structure their plans, define priorities for action, set goals, and develop mechanisms for monitoring the circular transition. Based on this analysis, recurring patterns, gaps, and challenges in the implementation of urban circularity were identified, which informed the structuring of the tool proposed in this study.

During this thesis, two academic visits were made to the *Industrial Engineering Laboratory* at *CentraleSupélec*, *Université Paris-Saclay* (LGI). These visits provided an opportunity to monitor the development of a Circular Economy Plan for the *Communauté d'agglomération Paris-Saclay* (CPS) in France. The CPS is an administrative entity for a French urban area located south of Paris, the capital of France. The territory already has various strategies, guidelines, and actions aimed at the CE, as well as a project in partnership with the LGI.

The exchange enabled participation in events, meetings, and discussions with CPS members, which helped clarify how an urban area manages its circular development and the next steps in its transition. The research also involved attending workshops organized by the CPS with various partners to develop a CE plan in the urban area.

In addition, an event on the CE in São Paulo was also attended. In May 2022, the author of this study attended (virtually) the presentations of the 1st *Circular Economy Week in São Paulo*. This participation contributed to understanding the initial urban circularity strategies developed in the municipality. Participation in CE-related events in two urban areas at different stages of development was fundamental to the development of the support tool proposed in this study.

This direct observation of circular initiatives in urban areas across different contexts and stages of development helped identify elements relevant to developing the circular transition support tool in this study. Thus, the exploratory study was strategic for the development of the proposed tool, enabling an understanding of the differences between conceptual approaches in the literature and the strategies effectively implemented in practice. Based on this empirical engagement with urban circularity initiatives, it was possible to develop an interpretation oriented toward the needs and challenges faced by public managers in the context of the circular transition.

In addition, the exploratory phase contributed to the DSR's relevance, rigor, and design cycles. The relevance cycle was addressed by understanding the problems, challenges, and needs associated with implementing urban circularity in real-world contexts. The rigor cycle was supported by a literature review and the analysis of documents related to urban circularity strategies. The design cycle, in turn, was developed based on practical observations of initiatives, plans, workshops, and experiences related to the circular transition, enabling the identification of requirements, key sectors, and elements necessary to structure the tool proposed in this study.

3.2.2 Phase 2 - Development of the Urban Circularity Support Tool

Figure 6 presents the methodology used to construct the components of the proposed tool; a detailed description of this methodology is provided in the following sections of this study.

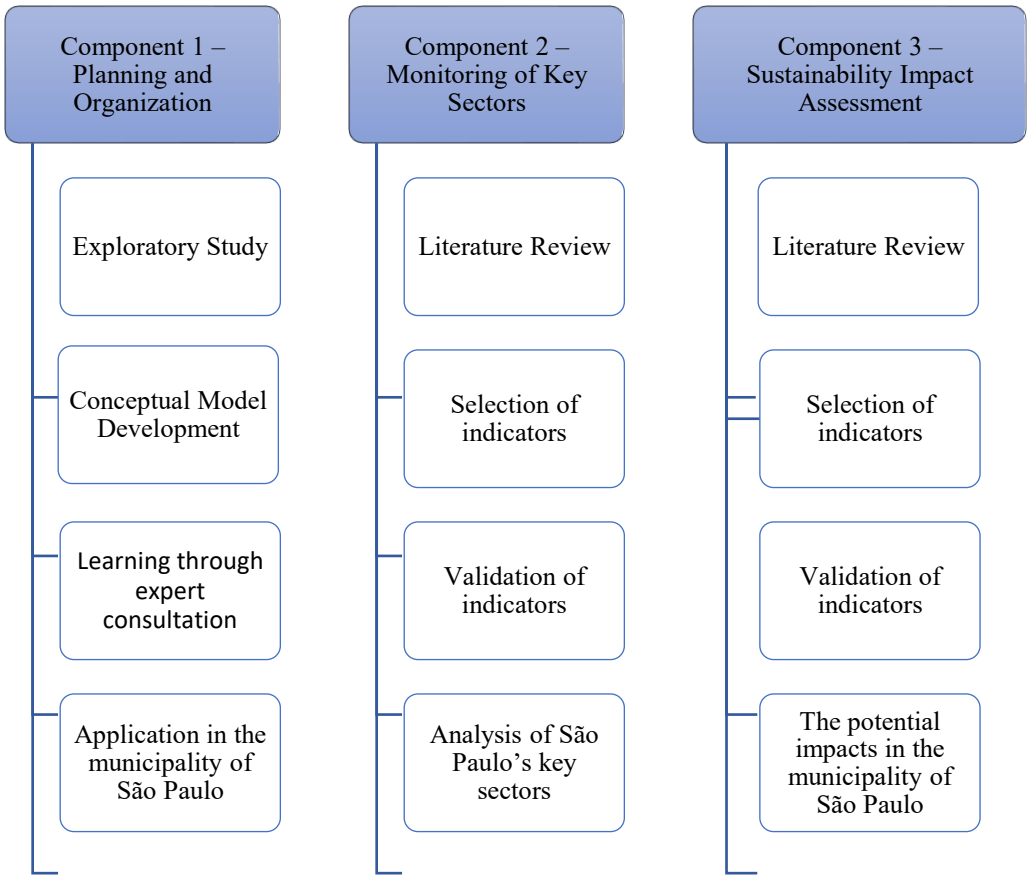


Figure 6 - Development of the support tool for urban circularity.

Two independent expert consultation processes were conducted during the development of the *CIRCCITY* tool. The first focused on the co-creation of the maturity model (Component

1), whereas the second aimed to validate the indicators proposed for Components 2 and 3. As these stages pursued different objectives, separate expert panels were assembled based on specific inclusion criteria.

Component 1 - Formulation of the Maturity Model for Circular Urban Areas

As shown in Chapter 2, the construction of maturity models follows a logic of planning, development, and application. However, De Bruin *et al*. (2005) and Mettler (2010) presented more detailed methodologies for developing such tools. De Bruin *et al*. (2005) proposed six stages for designing a generic maturity model.

The first stage proposed by De Bruin *et al.* (2005) is *Scope*. In this stage, model developers must identify the model's focus (domain) and how it differs from existing models. Within the scope, potential stakeholders for developing the maturity model are also identified. In the second stage, called *Design*, modelers must propose the framework, that is, the architecture of the model that will serve as the basis for subsequent stages. In the *Design stage*, certain decisions must be made, such as the target audience and the actors responsible for applying the model.

With the initial framework in place, the third stage, called *Populate*, aims to identify what should be measured in the maturity assessment and how to measure it. Components and subcomponents for the maturity assessment are identified. In the *Test stage*, the proposed model is evaluated for relevance and rigor. Surveys can be used to validate the model. In *the Deploy stage*, the model should be made available for use to verify its generalizability. This stage will facilitate broader acceptance and standardization of the model.

Finally, the last stage proposed by De Bruin *et al.* (2005) is *Maintain*, which aims to track the model's evolution. To enable this tracking, a repository must be created to collect information over time. One way to make the model available is to create a web interface. The model's relevance is ensured only through its maintenance over time.

A generic framework for creating maturity models was also proposed by Mettler (2010). According to the author, a model can be developed using five steps and eighteen decision parameters. Step 1, "*Identify a need or new opportunity*", consists of the decision parameters novelty and innovation. In step 2, "*Define scope*", the decision parameters are breadth, depth, and innovation.

In step 3, "*Design model*", the parameters are the maturity concept, definition of the objective, definition of the process, product design, method application, and interviewees. In step 4, "Design evaluation," the parameters are the evaluation theme, period, and evaluation method. Finally, step 5, "Reflect evolution," includes the following parameters for defining the model: theme of change, frequency, structure of change, and dissemination (Mettler, 2010). In this study, the structures proposed by Mettler (2010) and De Bruin *et al.* (2005) are adapted and used.

The structure presented in Figure 7 for developing the maturity model aligns with the DSR principles.

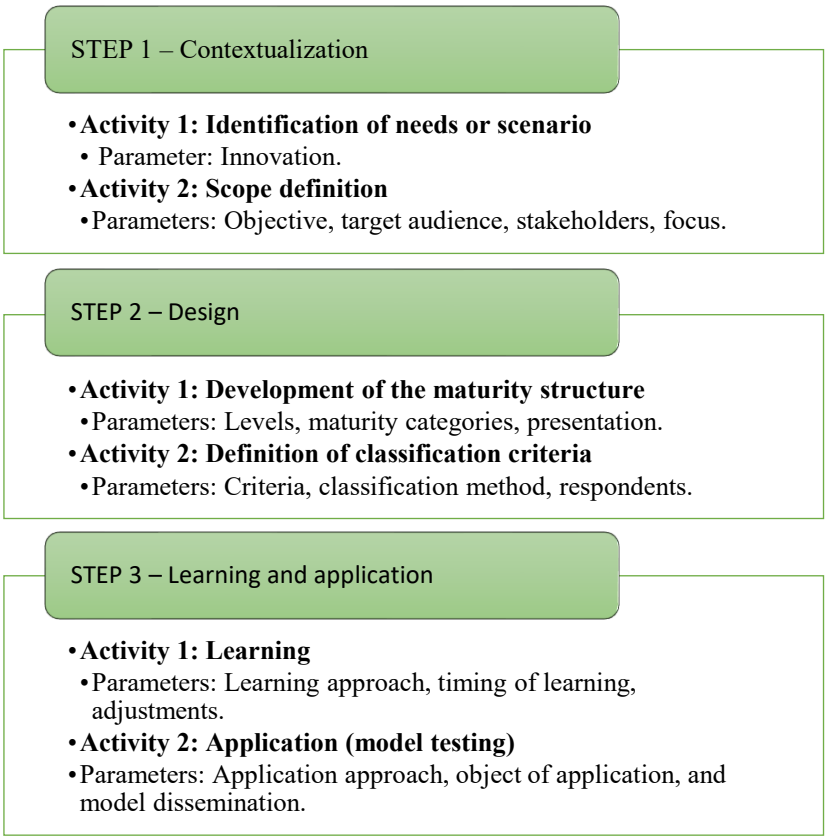


Figure 7 - Stages of constructing the maturity model.

Stage 1 (contextualization) is linked to the relevance cycle because it seeks to understand the research problem, the needs of public managers, and the context of the urban circular transition, and defines aspects such as the objective, target audience, stakeholders, and the model's focus. Stage 2 (design), on the other hand, pertains to the design cycle, involving the development of the maturity model's structure, the definition of levels, categories, and classification criteria, and the construction of mechanisms for evaluating the artifact.

Finally, stage 3 (learning and application) relates to the design and rigor cycles by incorporating processes of refinement, learning, and practical application of the model, allowing the evaluation of its utility, coherence, and potential for use in real-world contexts of urban circularity. Thus, the stages adopted in this study reflect the iterative logic of DSR.

It is worth highlighting the articles that contributed most to the development of the maturity model: *Circular Cities* by Williams (2019a) and *The Urban Circularity Assessment Framework (UCAF): a Framework for Planning, Monitoring, Evaluation, and Learning from CE Transitions in Cities* by Vanhuyse (2023). These articles helped define the categories and maturity levels of the proposed model. Another important document for identifying the categories, maturity levels, and structure of the model was *City Governments and their Role in Enabling a Circular Economy Transition: An Overview of Urban Policy Levers*, published by EMF (2019b).

To support the co-creation and validation of the maturity model (Stage 3), experts were intentionally selected using purposive sampling based on predefined inclusion criteria. Participants were required to demonstrate at least one form of recognized expertise in Circular Cities, Circular Economy at the urban scale, urban sustainability, urban governance, or closely related fields. Eligibility was assessed based on publicly available information regarding the participants' academic and professional experience. Evidence of expertise included at least one of the following: peer-reviewed publications, participation in research projects, professional experience in developing or implementing urban CE initiatives, or demonstrated involvement in urban planning or public policy related to the circular transition.

Given that urban circularity is still an emerging research field and that most documented experiences and academic advances have originated outside Brazil, particular emphasis was placed on the participation of international experts. Potential participants were identified through authors of peer-reviewed scientific publications, research groups dedicated to Circular Economy and Circular Cities, academic networks, and professional networking platforms (*LinkedIn*). This strategy enabled the inclusion of researchers and practitioners with complementary academic and professional backgrounds, thereby increasing the diversity of perspectives considered during the conceptual development and validation of the maturity model.

The final expert panel consisted of 18 specialists who participated in the co-creation process of the maturity model. The experts' profiles are presented in Appendix A. Further details about the expert panel are provided in Chapter 5.

Experts who accepted the invitation to participate were involved in the third stage of the maturity model development, which consisted of an iterative process of conceptual refinement and validation through expert co-creation. They received a preliminary version of the maturity model and were invited to critically evaluate its conceptual structure, comprehensiveness, clarity, and applicability by completing a structured validation questionnaire. Their comments and suggestions were incorporated to iteratively refine the model before proceeding with the subsequent stages of the *CIRCCITY* tool development. The questions used in this study are available at: https://goo.su/vblHEwu.

However, beyond simply verifying the experts' validation of the proposed model, the consultation process was also conceived as a learning experience. In this context, the questionnaire sought to understand, based on the experts' experience and knowledge, which aspects of the model could be improved. Thus, the methodology adopted to construct the maturity model also took the form of a collaborative process for refining it (co-creation), aligned with the principles of DSR.

Thus, in addition to the pre-structured, closed-ended questions answered by the experts based on defined options, spaces for descriptive comments were included in the questionnaire. These spaces allowed the experts to present their opinions, suggestions, and arguments regarding the proposed model. Among the open-ended questions, those focused on improving the clarity of the maturity model description, the structure of the matrix, the possible inclusion or exclusion of categories, and additional comments to refine both the model and the matrix stood out.

It is worth noting that the evaluation of the artifact developed in this study was conducted in accordance with DSR principles, through validation, co-creation, and real-world application processes. In this sense, consultation with experts contributed to the refinement of and analysis of the conceptual consistency, relevance, clarity, and usefulness of the proposed components, strengthening the DSR design cycle through iterative processes of refinement and learning.

Concurrently, the application of the tool in the city of São Paulo enabled verification of its capacity to support the diagnosis, planning, and monitoring of urban circularity in a real-world context, contributing to the assessment of its applicability and potential to inform decision-making. Thus, the evaluation of the artifact was conducted based on experts' perceptions and the analysis of results from applying the tool, allowing an assessment of its suitability, coherence, and applicability to the context under study, as well as its contribution to supporting the sustainable urban circular transition.

Components 2 and 3 - Identification of circularity indicators in urban areas

To understand how urban circularity is being measured, a systematic literature review (SLR) was conducted. The SLR is a rigorous scientific method that seeks to identify, select, critically evaluate, and synthesize the available scientific literature on a given topic. As such, it enables a broader and more precise level of understanding than a traditional literature review (Pati and Lorusso, 2018). The SLR has gained popularity with the development of tools that enable data mining (Alhawari *et al*., 2021).

In studies related to the CE, the SLR has been used by several authors, such as Alhawari *et al.* (2021), who sought to analyze the definition of CE and suggest directions for future research. Panchal *et al.* (2021) also conducted an SLR to understand whether CE performance contributes to sustainable development. Salvador *et al.* (2020), on the other hand, used the SLR to understand circular business models and the factors influencing their application.

In this study, the SLR is used to identify the main publications on indicators for assessing urban circularity. The purpose of the review was to understand what the literature considers important to measure when assessing urban circularity, which sectors are being analyzed, and to compile a list of indicators related to the topic. It also sought to evaluate whether these indicators could capture the CE's impact on urban sustainability.

To conduct the systematic review, the Scopus and Web of Science databases were used. The search in these databases was conducted across the title, abstract, and keyword fields, using the following search terms: *(Urban Circularity or Circular Urban Areas or Circular City or Circular Urban Metabolism) AND (Indicator or Assessment)*. The search was conducted in March 2023.

To filter the studies, the following criteria were used: articles published since 2014 in English-language scientific journals. A total of 382 documents were found in the *Scopus* database and 476 in the *Web of Science* (WoS) database.

In the Scopus database, the fields of *Environmental Sciences, Engineering and Computer Science,* and *Decision Sciences* were selected. In the WoS, the fields of *Environmental Sciences, Green Sustainable Science and Technology, Urban Studies, Regional Urban Planning, Urban Planning, and Computer Science* were selected. The selected fields differed because the databases did not offer the same options. The field of Computer Science was selected for its potential to help assess urban circularity through digital platforms.

After applying these filters, the number of articles in the Scopus database was reduced to 191, and in the WoS database to 278. Duplicate articles were then identified, and 28 records were excluded from the analysis. Next, the titles and abstracts were reviewed. Thus, a total of 93 articles were selected for full-text reading.

Although many articles presented interesting discussions on CE monitoring in urban areas, for the final analysis, only articles that presented a set of indicators, rather than merely conceptual discussions, were considered. Thus, a final set of 47 articles was obtained.

In addition to academic studies published in scientific journals, organizations such as the OECD (*Organization for Economic Co-operation and Development*), UNECE (*United Nations Economic Commission for Europe*), ADEME (*Agence de la transition écologique*), the *Nordland Research Institute*, and ICLEI (*Local Governments for Sustainability*) have dedicated themselves to understanding CE in urban environments and have published materials related to the topic. These materials were considered in this study. In total, 63 studies comprised the list of indicators. These studies are presented in Appendix B of this thesis.

Figure 8 presents the PRISMA diagram, which clearly and systematically illustrates the process of identifying and selecting studies considered in the SLR. The results of the SLR are presented in Chapter 6.

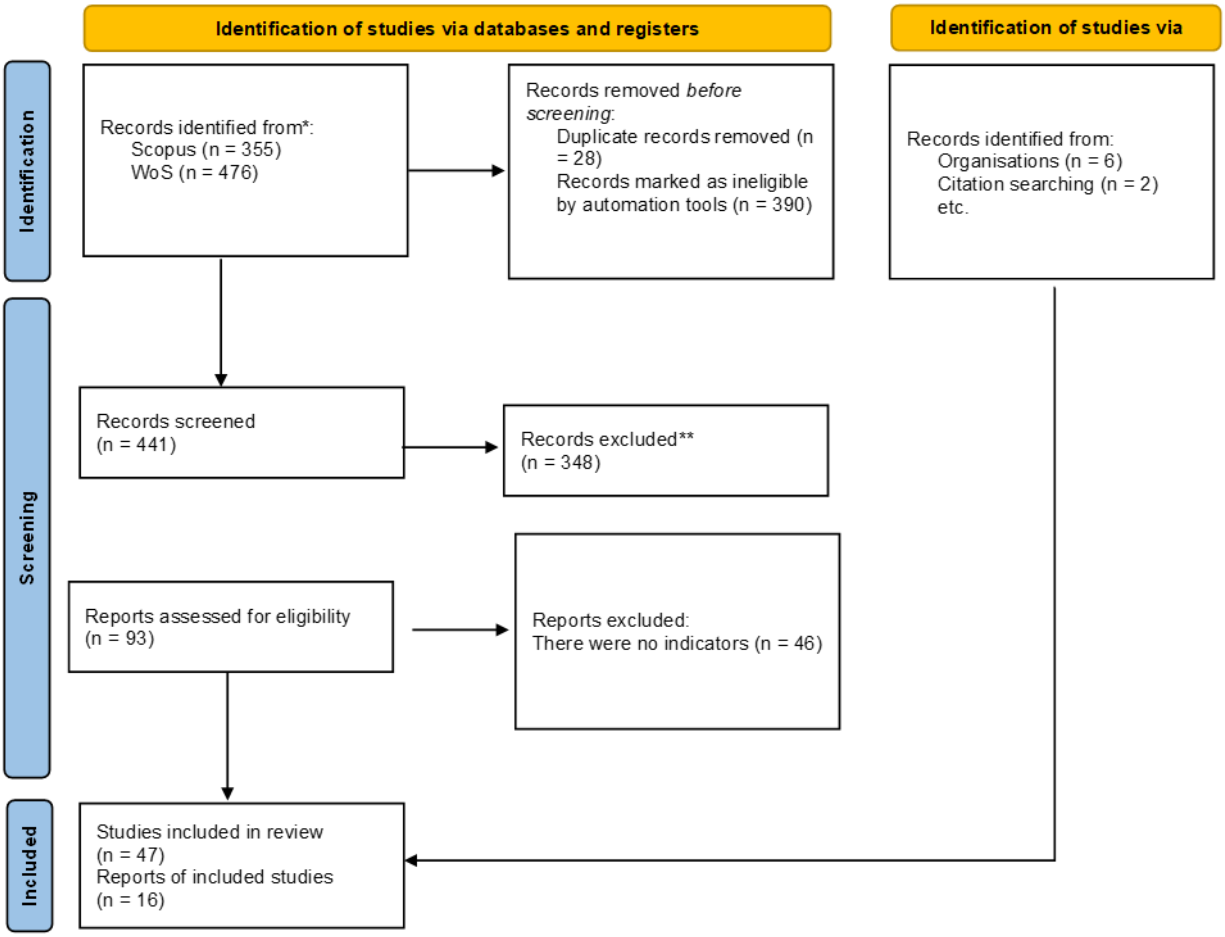


Figure 8 - PRISMA diagram. Source: adapted from Page *et al*. (2021).

Once the indicators had been listed and analyzed, a set of indicators was selected to monitor the results of circularity actions in key sectors. The selection of indicators was based on the following criteria:

- **Consistency Criterion:** This selection criterion aims to identify indicators that provide relevant information for monitoring key sectors or for assessing the sustainability of urban circularity initiatives. It thus eliminates indicators that do not help managers gain an overview of the topic.
- **Applicability Criterion:** This selection criterion aims to determine whether the indicator can be applied, that is, measured in each context (whether data for measurement already exists or can be collected).
- **Redundancy Criterion:** This criterion assesses whether the information obtained through this indicator is not already present in another selected indicator. Therefore, it seeks to eliminate redundant indicators.

- **Usefulness Criterion:** This criterion seeks to assess whether the information provided by the indicator is truly useful to an urban manager. Even if a given indicator provides information that can contribute to an overview of urban circularity, it is necessary to select indicators that provide effectively useful information.

The flowchart in Figure 9 illustrates the decision-making process for selecting indicators.

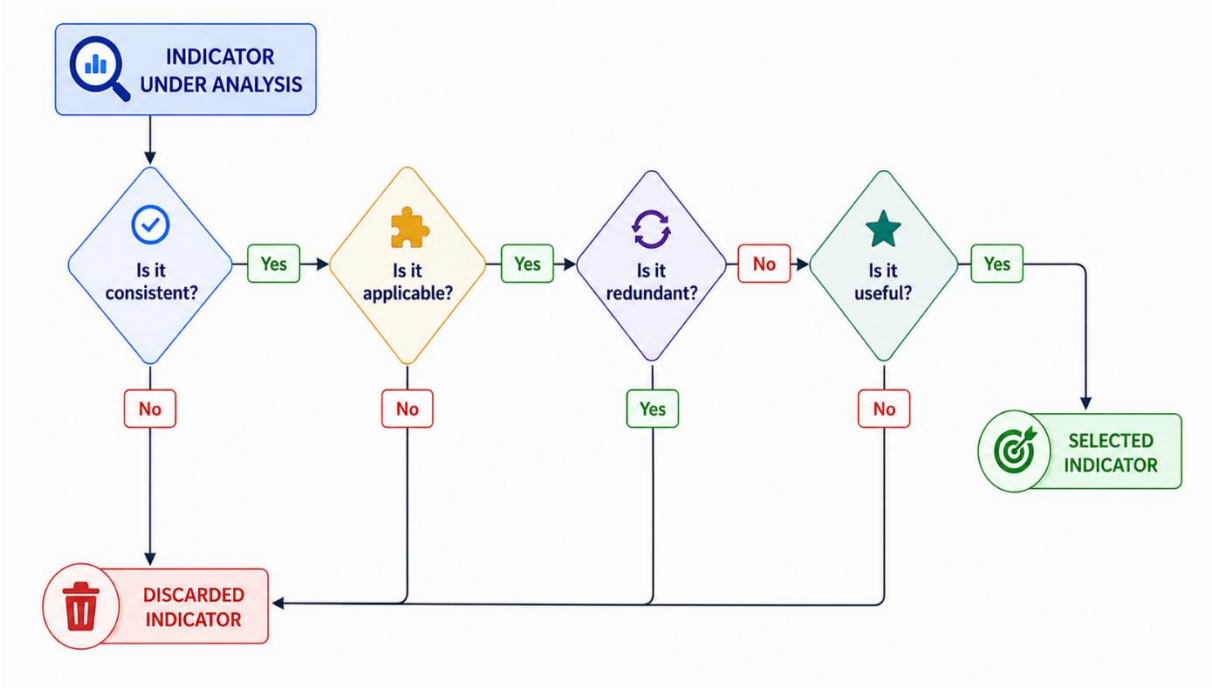


Figure 9 - Flowchart for indicator selection.

Source: Developed by the author, with the assistance of ChatGPT – OpenAI (2026).

Once selected, the proposed set of indicators was validated through a second expert consultation as part of the DSR iterative process. Unlike the first expert consultation (Component 1), which focused on the conceptual development and validation of the maturity model, this stage aimed to assess the quality and suitability of the proposed indicators. To support this process, experts were intentionally selected using purposive sampling based on predefined inclusion criteria.

The inclusion criterion required participants to demonstrate at least one form of recognized expertise in Circular Economy indicators, sustainability assessment, urban planning, environmental management, public policy, infrastructure, or closely related fields. Eligibility was assessed based on publicly available information regarding the participants' academic and professional experience. Evidence of expertise included at least one of the

following: peer-reviewed publications, participation in research projects, professional experience in developing indicator systems or sustainability assessment frameworks, or demonstrated involvement in urban planning, environmental management, or public policy related to the circular transition.

Since the proposed indicators encompass the seven key sectors of urban circularity and the three sustainability dimensions, experts from different disciplinary backgrounds were intentionally invited to ensure a multidisciplinary evaluation. Potential participants were identified through authors of peer-reviewed scientific publications, research groups dedicated to urban CE, urban sustainability, academic networks, and professional networking platforms (*LinkedIn*). This strategy enabled the inclusion of researchers and practitioners with complementary academic and professional backgrounds, ensuring that the indicators were evaluated from different technical perspectives regarding their relevance, clarity, applicability, consistency, and usefulness across different urban contexts.

The final expert panel consisted of 22 specialists who participated in the validation and refinement of the indicator sets proposed for Components 2 and 3. The panel included experts with expertise across all key sectors and sustainability dimensions, ensuring multidisciplinary coverage during the evaluation process. The experts' profiles are presented in Appendix C.

For this consultation, the *Likert* scale was used. This scale is widely used in scientific research to measure the degree of agreement or disagreement among respondents on specific statements, enabling an assessment of experts' perceptions of the relevance, clarity, and applicability of the proposed indicators. The *Likert* scale has been widely used in the validation of sustainability indicators, as noted in the studies by Ebbinghaus *et al.* (2025) and Silva *et al.* (2023). In the field of CE, Galatti and Baruque-Ramos (2022) and Valls-Val *et al.* (2023) also employed this scale to validate indicators.

In this study, experts were sent a spreadsheet containing indicator matrices for each key sector and each sustainability dimension. For each indicator, the matrix included one column detailing the measurement method and another detailing its intended use. The experts were asked to answer the following question for each indicator: Does this indicator accurately and effectively measure the established objective, and is it suitable for validation? Responses were to be provided using a five-point *Likert* scale (strongly agree, agree, neutral, disagree, and strongly disagree).

Figure 10 presents an example of the matrix provided to the experts. The complete material used in the validation process is available at: https://goo.su/g7I5j9.

Indicator	How to measure	Does this indicator accurately and effectively measure the established objective, and can it be validated?
1. Generation of urban solid waste.	Total of solid waste generated = amount of household waste + urban cleaning waste). Unit: t.	

Figure 10 - Example of a matrix developed for expert consultation.

In addition, space was provided for the experts to record comments and suggestions for each indicator, as well as to indicate whether each indicator should be included or excluded. Thus, rather than merely identifying the degree of agreement with each indicator, the consultation enabled the refinement and collaborative development of the set of indicators based on the experts' contributions.

In this study, an indicator was considered relevant when the sum of the strongly agree and agree responses exceeded 50% of the total responses, a criterion similar to that adopted by Silva *et al.* (2023). Indicators with agreement levels below 50% were automatically excluded from the final set. Indicators with agreement levels above 50% were also excluded when the experts' comments revealed conceptual weaknesses or significant limitations affecting their applicability.

Following the agreement analysis, the indicators were reviewed in light of the experts' comments and suggestions. Where appropriate, modifications were incorporated to improve the clarity, conceptual consistency, and applicability of the indicators. This iterative refinement process resulted in the final set of indicators proposed in this study.

3.2.3 Phase 3 - Application of the Tool

The city of São Paulo was selected for the application of the proposed tool. This choice is due to the municipality's pioneering role in enacting environmental regulations and the city's current commitment to promoting CE. São Paulo was the first city to establish a strategic partnership with the Ellen MacArthur Foundation to promote CE at the local level (EMF, 2021a). These characteristics make the city suitable for the tool's application.

Furthermore, São Paulo is one of the main economic hubs in Latin America, featuring diverse economic activities with potential for CE. The city has a high population density,

generates large amounts of waste, and has intense demand for natural resources, which reinforces the need for strategies that promote more efficient use of these resources. São Paulo also has a complex urban infrastructure, a diversified industrial and service sector, and an active innovation ecosystem, including universities and research centers. These factors favor the development and implementation of circular solutions and indicate the city's potential to lead the urban circular transition in Brazil, thus justifying the application of the tool.

The model was applied in the city of São Paulo based on a review of documents and secondary data obtained from municipal plans, reports, and platforms. Thus, the application developed in this study is exploratory and demonstrative in character, seeking to assess the tool's operational feasibility, consistency, and analytical potential in an urban context. This approach aligns with the principles of DSR, which involves iterative cycles of development, demonstration, evaluation, and refinement of the artifact, thereby enabling its progressive evolution and future application in real, participatory contexts.

To apply the tool in the municipality of São Paulo, municipal plans available on the City Hall's official website were consulted. Among the documents analyzed, the following were particularly relevant: the 2020 Municipal Agenda 2030, the 2014 *Municipal Integrated Solid Waste Management Plan* (PGIRS), the 2021 *Climate Action Plan of the Municipality of São Paulo* (PlanClima), the 2015 *Municipal Urban Mobility Plan* (PlanMob), the 2014 *Strategic Master Plan* (PDE), the 2019 *Municipal Basic Sanitation Plan* (PMSB), the 2022 Municipal *Economic Development Plan* (PMDE), as well as the 2025 diagnostic reports prepared for the revision of the *Municipal Integrated Solid Waste Management Plan* (PGIRS) and the *Municipal Integrated Environmental Sanitation Plan* (PMSAI).

The use of municipal plans, which guide the planning, management, and development of various sectors in the city of São Paulo, enables an understanding of how well the municipality aligns with the principles of urban circularity and helps assess its level of maturity in the circular transition. Furthermore, municipal plans are important sources of information, as they enable identification of whether the principles of circularity are incorporated into public policies, programs, and municipal actions.

Data from the municipality of São Paulo available on various platforms were also used, such as *Observa Sampa* (a platform for monitoring municipal indicators and public policies), *GeoSampa* (the geographic information system of the city of São Paulo), *Infocidades*, the *PDE Monitoring and Evaluation Platform*, the *São Paulo City Hall Open Data portal* (a public

repository of databases produced by the municipal administration), *Sampa Mais Rural* (data on agriculture), and *Green Sampa* (an acceleration program focused on businesses developing solutions in the green economy and socio-environmental impact).

In addition, information available on the *official website of the City of São Paulo* was consulted, which compiles data and reports produced by various municipal departments. These platforms serve as official sources of municipal data, enabling the collection of reliable information to monitor outcomes and assess the impacts of implementing circular strategies.

The application of the tool in São Paulo enabled the identification of the main factors influencing the transition to urban circularity in the municipality. These factors were subsequently structured according to the PESTLE framework (Political, Economic, Social, Technological, Legal, and Environmental).

A similar methodology has been used in the literature to identify influencing factors, barriers, and opportunities in the transition to the CE, as demonstrated by Gallego-Schmid *et al.* (2024). This approach allowed the categorization of influencing factors, facilitating the understanding of dynamics that may act as barriers or drivers of urban circularity and contributing to a more structured and integrated analysis of the urban environment.

4. IMPLEMENTATION OF URBAN CIRCULARITY

This chapter presents the results of the exploratory research on the implementation of urban circularity, identifies key sectors for urban circularity, and outlines the structure of the proposed tool.

4.1 Urban Circularity Plans

As noted in the literature review, the implementation of urban circularity varies in both perspectives and objectives. To understand this phenomenon, plans and strategies from cities considered benchmarks in the field were analyzed, as presented in Chapter 3.

The choice of European urban areas is justified because the continent hosts a large share of initiatives and public policies focused on the topic. Petit-Boix and Leipold (2018), who studied policies across the globe, noted that most circular initiatives are concentrated in Europe. Furthermore, in 2021, the European Union launched the *Circular Cities and Regions Initiative* (CCRI) to support cities and regions in implementing the CE at the territorial level. The initiative is among the actions outlined in the *Circular Economy Action Plan*, launched in 2020 and part of the *European Green Deal*, presented in 2019 (EU, 2024), thereby creating a favorable environment for the development of urban circularity.

Driven by this favorable regulatory environment, European cities have begun to publish circular plans and strategies tailored to their territories. In this context, they have, in a sense, become laboratories for experimenting with urban circular development. For this reason, understanding the plans and strategies of these cities makes it possible to identify the needs of urban managers and the characteristics the tool must possess to support decision-making regarding the urban circular transition.

Table 2 summarizes the results of the study on the circular transition plans of European cities, highlighting the objectives and key characteristics of the plans and strategies analyzed.

Table 2 - Analysis of model city plans.

Plan	Objective	Key Feature
Paris Paris Circular Economy Plan of 2017.	The objective of the CE plan is to implement a territorial strategy for sustainable economic development, mobilizing producers, consumers, and public and private actors to transform production and consumption models in the region.	The social dimension emerges as one of the pillars of the CE, serving to promote social inclusion and generate local jobs. The CE should not only reduce environmental impacts but also produce social and territorial benefits.
Rotterdam Rotterdam Circularity Programme—From Trash to Treasure (2019)	Create a zero-waste society as quickly as possible. Extend the useful life of products and use waste as raw materials.	Waste is a valuable treasure; implementation involves closing the loop on specific material flows, such as construction (extending the lifespan of buildings and reusing demolition materials) and green flows (reducing food waste and recovering organic waste).
Helsinki The City of Helsinki's Roadmap for Circular and Sharing Economy (2020)	Conserving increasingly scarce natural resources, reducing waste generation, and contributing to the fight against climate change by decreasing the use of virgin raw materials and the resulting reduction in emissions associated with material production.	Links the CE to the sharing economy, as sharing enables more efficient use of existing resources and reduces the need for new products.
Prague Circular Prague 2019	To promote a prosperous, healthy, and resilient city by offering citizens a more sustainable way of life and creating opportunities for business innovation through the transition to more circular production and consumption models.	Adoption of an analytical approach based on mapping the city's material flows, which allowed for the identification of priority sectors (construction, household consumption, and urban services) and guided the implementation of circular actions through collaboration between public and private actors. It considers urban sectors beyond waste management and infrastructure, citing mobility, water, and sanitation.
Copenhagen Circular Copenhagen 2020	The strategy focuses on transforming waste into resources and keeping materials in circulation for as long as possible, reducing raw material extraction, CO_2 emissions, and waste generation.	The strategy aims to shift from a produce-consume-dispose culture to a sustainable system where materials continuously circulate within the economic cycle. It prioritizes circularity focused on waste management and urban material flows.

(continued)

Table 2 - Analysis of model city plans.

Plan	Objective	Key Feature
Amsterdam Amsterdam Circular 2020-2025 Strategy (2020)	Reduce dependence on virgin raw materials sourced from outside the city, lessen environmental impacts, and make the city more resilient.	Aligned with the concept of Doughnut Economics, which proposes a development model that balances social well-being and environmental limits. It seeks regenerative and distributive growth, reducing environmental impacts throughout production chains and promoting an inclusive urban economy.
London London's 2017 Circular Economy Route Map	Reducing dependence on resources, protecting businesses and consumers from fluctuations in raw material prices, creating a more stable economic environment, and stimulating new circular business models, strengthening the city's economy.	Strong emphasis on economic benefits. Circularity is seen as a driver of growth and business innovation. Creation of new business models based on reuse, repair, remanufacturing, and sharing.

Based on the summary of the plans presented in Table 2, European cities are charting distinct paths for implementing urban circularity. In this context, Fratini *et al.* (2019) analyzed how three major European cities (Amsterdam, Paris, and London) envisioned urban circularity within their territories. According to the authors, in practice, these cities understand and approach CE in distinct ways. In Amsterdam, CE is strongly linked to technological development, innovation, and ecological modernization. Through the CE, the city seeks to localize production and minimize dependence on resources from other countries, and little attention has been given to changes in current consumption patterns.

In Paris, the CE takes on an approach centered on social issues. Paris focuses on creating an inclusive environment, generating jobs, encouraging environmentally responsible business models, promoting sharing, and changing attitudes and practices. There is strong participation from various stakeholders (NGOs, citizens, companies, public authorities, etc.). In London, by contrast, the circular transition is strongly linked to businesses and the financial sector. These actors seek business models that promote sharing, extend the useful life of products, and recover value from products at the end of their useful life. The sectors in which these circular businesses operate are construction, food, textiles, electronic equipment, and plastics (Fratini *et al.*, 2019).

Calisto Friant *et al.* (2023) analyzed the CE policies of Amsterdam and Copenhagen and noted that although these cities are benchmarks in implementing urban circularity, their policies still have limitations. According to the authors, the policies of both cities are based on a

technocentric approach, in which problems related to resource use are considered solvable through technology, innovation, and increased efficiency, and are driven by economic growth. The authors argue that fundamental aspects for truly sustainable circularity are missing, such as greater attention to social justice and democratic governance.

In this regard, it is important to develop tools to help urban managers identify structural gaps in the implementation of truly sustainable circularity strategies. Such tools can guide the transition process, tracking progress and the path toward sustainability, moving beyond strategies that focus solely on closing material loops. These tools can be useful for both cities that are more advanced in the circular transition and those just beginning their journeys.

In this context, maturity models are useful tools for assessing the stage of urban circularity development, identifying areas for improvement, and supporting action planning. The exploratory study thus highlights the importance of a model capable of assessing the evolution of cities, from linear systems toward more advanced levels of sustainability. This analysis enabled the identification of implementation patterns, structural gaps, and priority sectors, which served as the basis for constructing the proposed tool.

Finally, it is observed that, although there have been advances in incorporating CE principles at the strategic level, approaches still vary in terms of the scope and depth of actions, with a predominance of strategies focused on closing cycles and waste management, and less emphasis on structural aspects, such as infrastructure adaptation, which constitutes a strategic action for CCs, as pointed out by Williams (2019a).

4.2 Key Actions and Sectors for Urban Circularity

Petit-Boix and Leipold (2018) analyzed 300 circular initiatives in 83 cities across countries and classified them by focus. The categories proposed by the authors were: infrastructure (which involved actions related to local food production, energy efficiency, sustainable mobility, sustainable construction and materials, and water conservation and reuse); social consumption (actions related to the repair and reuse of materials, food waste management, and sharing initiatives); industries and businesses (which included actions related to industrial symbiosis, sustainable public procurement, remanufacturing, the use of recyclable materials, and the recovery of materials, nutrients, and energy); and urban planning (actions related to land use and zoning, and sustainable planning).

Coussa (2025) analyzes the application of urban CE based on four main axes: waste management (municipal solid waste, construction and demolition waste, electrical and electronic waste, and wastewater); new forms of urbanity and urban systems (living labs, reuse of materials in construction, nature-based construction solutions, and urban innovation policies oriented toward circularity); green ecosystems and nature-based solutions (industrial symbiosis, circular bioeconomy, urban agriculture, green roofs, and water reuse); and spatial and public policies (regulatory instruments, assessment and monitoring, urban planning, and public engagement).

Circular actions have also been analyzed from a multisectoral perspective, in which sectors are understood as functional systems that underpin urban activities and within which CE actions can be implemented (Ferreira and Fuso-Nerini, 2019; EIB, 2024a). Ferreira and Fuso-Nerini (2019), for example, analyze the implementation of CE at the urban scale across the sectors of transportation, construction, food, water management, waste management, CE innovation, specific industries, education, digitalization, demography and policy, renewable energy, and local resources.

Paoli *et al.* (2022) also analyze urban CE across sectors, namely: waste, energy, water, the built environment, and mobility. The European Investment Bank – EIB (2024) organizes circular actions into eight sectors: the built environment; consumer goods; food; manufacturing; mobility and logistics; tourism and leisure; waste and materials management; and water and wastewater management.

In this exploratory study, the following key sectors for urban circularity are proposed: Waste, Agriculture and Food, Local Production and Industry, Energy, Mobility and Transportation, Water and Sanitation, and Space and the Built Environment. Figure 11 explains each of these sectors.

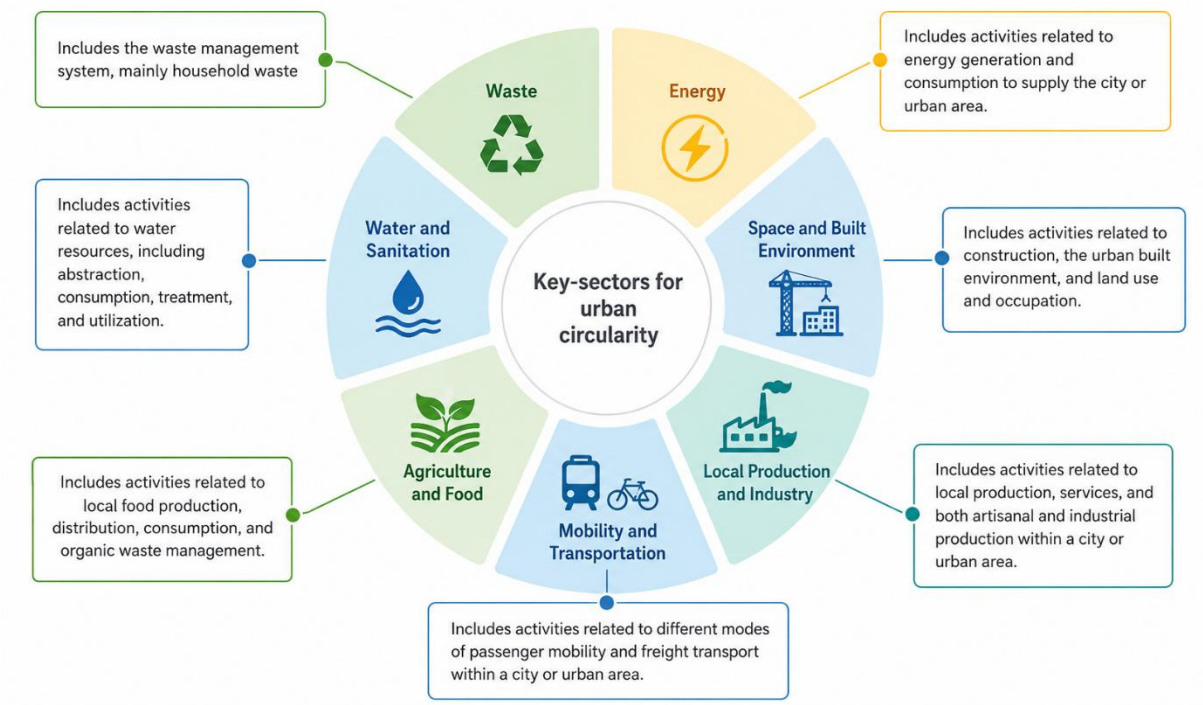


Figure 11 - Key sectors for urban circularity.

Source: Developed by the author, with the assistance of ChatGPT – OpenAI (2026).

The 2022 and 2024 reports of the *European Circular Cities Declaration* (a commitment signed by European local and regional governments to accelerate the transition to the circular economy) and the 2022 catalog of the *European Investment Bank's Circular City Center (A Catalogue of Circular City Actions and Solutions – The Circular City Centre)* list more than 200 circular actions implemented in European cities. The actions described in these documents were analyzed and grouped into the key sectors adopted in this study.

Table 3 presents the main objectives identified in the actions of each category, as well as examples of developed solutions. Additionally, it outlines the principles of urban circularity associated with these initiatives and the SDGs they address.

Table 3 - Analysis of Circularity Actions Implemented in European Cities.

Category	Objective of the actions	Circular actions	Principles	SDGs
Waste	Reduce waste and increase material recovery.	Selective collection of specific waste; promotion of reuse and repair of materials; exchange of materials; creation of recycling centers; awareness campaigns awareness and information campaigns.	Closing cycles, optimizing, and regenerating.	SDG 11 SDG 12 SDG 13 SDG 15
Water and Sanitation	Increase circularity and efficiency in water use.	Modernization of wastewater treatment, reuse systems, nutrient recovery, and water efficiency programs.	Close cycles, optimize, and regenerate.	SDG 2 SDG 13 SDG 15
Space and Built Environment	Reduce demand for virgin materials and extend the useful life of buildings.	Reuse of construction and demolition materials; material passports; adaptive reuse; building retrofitting; circular public procurement; remediation of contaminated sites.	Optimize, close cycles, regenerate, substitute, adapt, and localize.	SDG 11 SDG 12 SDG 13 SDG 15
Local Production and Industry	Encourage companies to develop circularity, industrial symbiosis, and circular business models.	Incubation of circular businesses; industrial symbiosis; financing; innovation programs.	Close cycles, replace, optimize, adapt, and localize.	SDG 8 SDG 9 SDG 12 SDG 17
Mobility and Transportation	Reduce transportation emissions and promote a shift in modes of transport.	Replacing the bus fleet with low-emission vehicles, installing bicycle infrastructure, planning for sustainable mobility, encouraging active mobility, and promoting car and bicycle sharing.	Optimize, share, replace, and virtualize.	SDG 3 SDG 7 SDG 10 SDG 11 SDG 12
Energy	Increase energy efficiency and reduce dependence on fossil fuels.	Biogas production; deployment of renewable energy; replacement of light bulbs.	Regenerate, optimize, and replace.	SDG 7 SDG 13 SDG 15
Agriculture and Food	Close nutrient cycles and prevent food waste.	Community composting; food redistribution; biomass recovery; home composting.	Regenerate, close cycles, adapt, localize, and share.	SDG 2 SDG 13 SDG 15

Urban circularity actions are diverse, spanning all key sectors proposed in this study, indicating that no single set of standard initiatives works for all cities. According to Petit-Boix and Leipold (2018), it is extremely complex for a city to define the combination of initiatives that will contribute to achieving sustainability.

A study of actions implemented in European cities showed that they focus on closing cycles (looping) and emphasize recycling, reuse, and recovery, with little attention given to adaptation and localization. A similar characteristic was identified by Marjanović *et al.* (2022) in their study of Canadian cities. Although these strategies are necessary, they may not be fully aligned with circular strategies of greater value or greater contribution to sustainability (Coussa, 2025).

In the reports analyzed in this study, European organizations identified the main challenges faced by the cities mentioned in the documents. Among these challenges, the following stand out: a lack of resources, a shortage of personnel and specific technical skills to operate within circular value chains, a management model characterized by institutional silos (fragmentation among different departments and levels of government), the persistence of the linear model, and the limited engagement of the actors involved, evidenced by the difficulty in mobilizing the private sector and citizens systemically, beyond isolated pilot projects (Circular Cities Declaration, 2024).

The documents also indicate that more ambitious goals are needed to achieve urban circularity. To date, the goals have focused primarily on recycling, reuse, and reducing the consumption of virgin materials. In this regard, it is necessary to expand objectives for the regeneration of nature through urban planning approaches that protect water bodies, green spaces, and the biodiversity of these ecosystems (Circular Cities Declaration, 2024; European Circular Cities Declaration, 2024).

Regarding the monitoring of results and the assessment of the impacts of circular actions, the reports highlight challenges, including a lack of local-level data, as much of the available data is only at the national scale and does not adequately reflect the impacts of municipal policies. Difficulties in measurement are also reported, including challenges in defining what should be measured and in prioritizing metrics, highlighting the need to move toward a consolidated set of indicators to support strategic decision-making (Circular Cities Declaration, 2024).

The analysis of European cities allowed for the identification of priority sectors, implementation patterns, and gaps in the operationalization of circular actions, which formed the basis for defining the key sectors and structuring the indicators proposed in this study.

Given the above, a fundamental characteristic of a tool designed to support the circular transition is a structured set of indicators that enables measurement of the results of implemented actions. These indicators must be strategic for tracking initiative performance, assessing their impacts over time, and supporting monitoring and decision-making processes.

4.3 The Paris-Saclay Urban Area and the Circular Economy

The *Communauté d'Agglomération Paris-Saclay* (CPS) is an intermunicipal administrative structure located in the department of Essonne, in Île-de-France (the Paris metropolitan area). The territory comprises 27 municipalities, covers approximately 190 km², and is home to approximately 316,000 inhabitants. In addition to performing functions related to territorial planning and the management of shared public services, the CPS is part of the Paris-Saclay science and technology hub, considered a major European cluster for higher education, research, innovation, and ecological transition.

The circular economy in the CPS is integrated into territorial strategies for ecological and climate transition, particularly through the *Climate, Air, and Energy Plan* (*Plan Climat Air Énergie Territorial 2025–2031—PCAET*). In this context, circularity emerges as a cross-cutting approach to reducing natural resource consumption and emissions and promoting more sustainable production and consumption models. In the PCAET action plan, the circular economy is primarily linked to policies related to waste management, responsible consumption, sustainable food systems, and the transition of economic activities.

In 2024, the CPS also published its *Feuille de Route Économie Circulaire 2024-2029* (*Circular Economy Roadmap*), structuring its territorial CE strategy in a more integrated manner. The document was developed with support from ADEME and organizes the circular transition into six strategic pillars: governance and strategy; food; territorial planning; economic development; reuse and repair; and waste. In addition, the strategy establishes objectives, operational actions, and governance mechanisms to mobilize territorial actors, integrate public policies, and monitor the implementation of actions (CPS, 2024).

Thus, the region seeks to encourage changes in production and consumption patterns by mobilizing local actors, including businesses, research institutions, associations, and citizens.

Furthermore, the regional strategy calls for initiatives focused on waste prevention, the recovery and valorization of natural resources, the promotion of local food chains, and the integration of sustainability principles into economic activities and vocational training.

During the visit to the urban area, the region's mobilization to promote circular initiatives was evident. Among the various initiatives observed, the collection and recovery of organic waste (*bio-déchets*) stand out, driven primarily by the *Anti-Waste Law* (*Loi Anti-Gaspillage pour une économie circulaire—AGEC*) passed by France in 2020. The AGEC's primary objective is to reduce resource waste, promote reuse and recycling, and transform production and consumption systems. Regarding organic waste, the law set ambitious targets. It mandated that, by 2024, all producers of organic waste in the country (households, restaurants, supermarkets, etc.) must have access to a solution for separating and recovering such waste.

The observation activities at CPS took place between 2022 and 2023, and it was evident that urban managers were concerned with creating solutions for organic waste and meeting the targets set by AGEC. SIOM (*Syndicat Intercommunal des Ordures Ménagères de la Vallée de Chevreuse)*, the union responsible for waste collection, sorting, public awareness, and energy, material, and organic recovery in 21 cities within the CPS, began implementing separate collection in volunteer households in April 2022. This initiative was accompanied by the distribution of kitchen caddies (*bio-seaux*) for collecting kitchen waste to volunteer households that registered on the SIOM website.

Since then, the organic waste collection initiative has been expanding across the region. According to *SIOM's Annual Report*, by 2024, 9% of the 95,000 households in the region had already adopted organic waste separation and collection. Of the organic waste collected, 90% is sent for methanization (a process that produces biogas and energy) and 10% for composting (allowing nutrients to return to the soil) (SIOM, 2024). However, even with the implementation of separate collection of household organic waste, the union states that collection is complementary to local composting; therefore, it encourages residents to continue practicing local composting.

At the same time that the territory was implementing a separate collection of household organic waste, a series of other initiatives were underway. Pamphlets guiding the collection of organic waste and other household waste were distributed throughout the territory. Events such as the *Recycling Festival* (*Fête de la Recup*), organized by SIOM to promote waste management

practices, include workshops on sorting and composting organic waste, tips for reducing food waste, visits to waste management facilities, and a local products fair. Events of this kind serve as tools for raising awareness, fostering understanding, and promoting social engagement.

A notable feature of CPS initiatives focused on organic waste is the close relationship between SIOM and the *Paris-Saclay University community*. Projects developed by students at *CentraleSupélec* sought solutions to reduce emissions associated with organic waste collection, while other students from the same university developed products and startups to facilitate local composting. In addition, an open innovation convention was held to increase the organic waste collection rate. With the participation of researchers, engineers, and representatives from companies operating in the sector, two days of co-creation were organized to develop solutions for the separate collection of organic waste for the benefit of the community.

Waste-to-energy conversion is also present in the region. Household waste that cannot be recycled is treated at the SIOM Energy Recovery Facility, located in *Villejust* (a city within the CPS). In this process, the waste is incinerated, and the heat generated by combustion is recovered to produce electricity and hot water. The energy produced is distributed to the power grid and the district heating system, supplying the city of *Les Ulis* and the *Courtaboeuf* business park (CPS industrial zone).

The circular economy in the region is also being implemented through strategies to reuse, exchange, and repair objects, thereby complementing waste collection and treatment policies. One of the key initiatives concerns the 2024 opening of a center for the recovery and reuse of objects (*Ressourcerie*) on the Saclay plateau. This facility enables the collection of objects with potential for reuse, sorting, repairing, and redistributing these materials through affordable sales or donations. SIOM maintains the center in partnership with the social integration company *ReSaclay* (a social and solidarity-based enterprise) and has approximately 900 m² dedicated to reuse (SIOM, 2026).

In this way, the initiative promotes extending products' useful lives and reducing waste generation, contributing to waste-prevention and resource-circularity strategies. In addition to environmental benefits, this type of initiative has a significant social dimension, as it fosters responsible consumption practices, raises public awareness of reuse, and, in some cases, supports social inclusion and job creation. This finding reinforces the solidarity-based nature of the French circular economy, as identified by Fratini *et al.* (2019).

The initiatives observed in Paris-Saclay are strongly aligned with some of the actions proposed by Williams (2019a) for implementing urban circularity, particularly regarding closing cycles (Looping), sharing (Sharing), optimizing resource use (Optimization), and valuing local solutions (Localization). Strategies focused on the collection and recovery of organic waste, reuse, composting, and territorial mobilization demonstrate significant progress in these areas.

However, as identified in other European cities analyzed in this study, there is still limited attention paid to actions related to urban adaptation (Adaptation) and territorial regeneration (Regeneration). This fact shows that expanding urban circularity beyond waste management and the efficiency of material flows remains a challenge in the Paris-Saclay Urban Area (CPS).

The observations made in the Paris-Saclay urban area reinforced the idea that the implementation of urban circularity depends on coordination among different territorial actors, the integration of public policies and local initiatives, and the combination of environmental, social, and economic strategies, aspects considered in structuring the tool proposed in this study.

4.4 Structuring the *CIRCCITY* Tool

Based on the exploratory study, the main challenges associated with the development of urban circularity include the need to promote a truly sustainable transition and to establish a set of effective indicators to evaluate the results and impacts of circularity initiatives. In the Brazilian context, there is also the challenge of assessing what has already been implemented in the region and understanding cities' capabilities and gaps so that, based on this, more consistent strategies for the circular transition can be developed.

To assist local governments and public managers in developing urban circularity, this study proposes a management tool to help them overcome these challenges. Furthermore, the tool aims to assist managers at different stages of the circular transition, from diagnosing the current situation to assessing impacts. Thus, the study presents a strategic tool for local governments.

According to Paiho *et al.* (2020), to implement the CE, local managers must: (1) define what circularity means for the urban area; (2) specify the paths they will follow for the circular transition; (3) indicate their circularity goals; (4) specify which indicators will show progress during the transition; (5) consider and decide on concrete means for circularization

(circularization strategy); (6) enable support services; (7) interact with and involve stakeholders throughout the process. The steps identified by Paiho *et al.* (2020) are used to construct the tool.

The proposed tool (*CIRCCITY*) consists of three components. The first component concerns the assessment and planning of urban circularity and aims to assist managers in organizing the factors that drive the circular transition, namely vision, governance, regulation, financial incentives, stakeholder engagement, and implementation strategy (EMF, 2019b; Vanhuyse *et al.*, 2023). The second component concerns monitoring key sectors for urban circularity, while the third assesses impacts on urban sustainability.

Figure 12 presents the conceptual model of the tool.

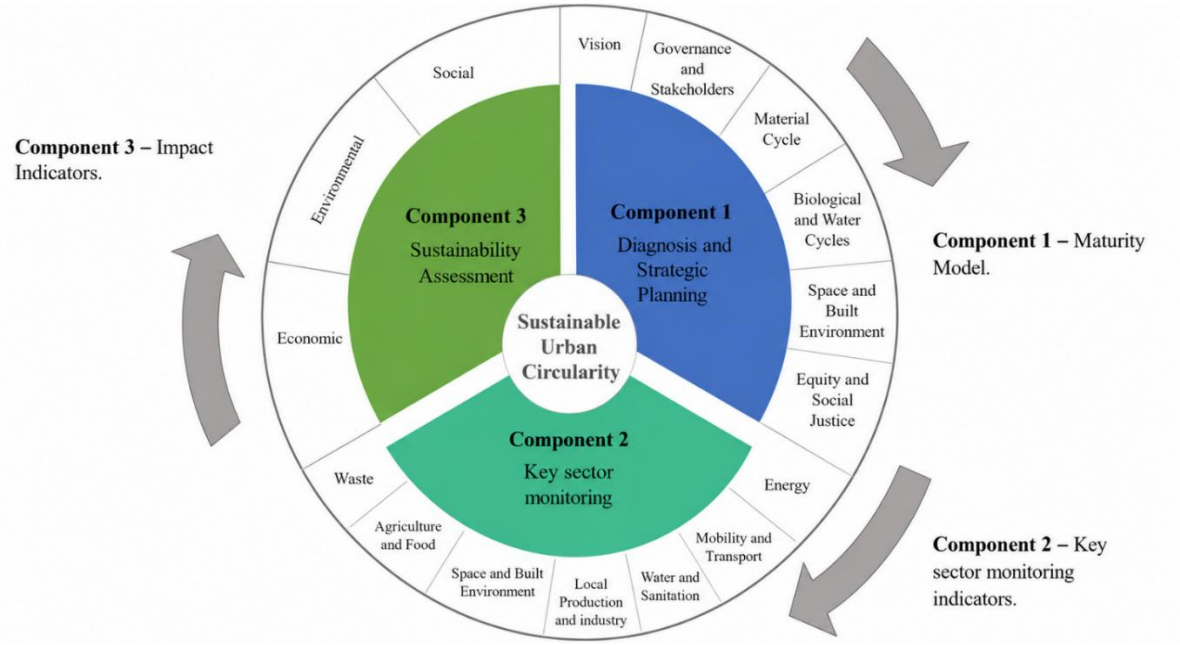


Figure 12 - Conceptual Framework of the *CIRCCITY* Tool.

It is worth noting that the structure of the proposed tool follows the DSR logic, in which the artifact is developed based on evidence from the exploratory study and refined according to the needs identified in the urban context. Furthermore, each component of the proposed tool relates to at least one of the steps for implementing UC at the urban scale identified by Paiho *et al.* (2020).

- **Component 1 - Diagnosis and planning of urban circularity:** Supports decision-makers in stages 1, 2, 3, 5, 6, and 7 of Paiho *et al.* (2020) .
- **Component 2 – Monitoring of key sectors:** assessed using the indicators proposed in this study and supports decision-makers in stages 3 and 4 of Paiho *et al.* (2020).

- **Component 3 – Assessment of impacts on urban sustainability**: Supports stage 4 as suggested by Paiho *et al.* (2020).

The use of the tool begins with identifying the current maturity stage, enabling a diagnosis of the urban area. To do this, managers must answer questions related to each category that assesses maturity. During this process, the manager can identify potential gaps in each category and thus plan for urban circularity more effectively. It is worth noting that maturity levels may vary across categories. By analyzing these levels, the urban manager gains an overview of the transition stage and can, in this way, plan and structure the circular transition more strategically.

In the Brazilian context, the maturity tool is particularly relevant, as the country is still in the early stages of the circular transition and few cities are discussing its implementation in a structured manner. In this scenario, the tool can help public managers structure the transition process gradually and strategically, supporting the setting of goals, monitoring of progress, and coordination among different sectors and stakeholders involved. For cities that already have defined circularity strategies, the maturity model can help assess how well these actions align with sustainability principles, identify gaps, and guide improvements to initiatives.

Regarding the set of indicators proposed in component 2, in cities that already have defined circularity strategies, these indicators enable the identification and monitoring of the results of implemented actions. In cities in the early stages of the circular transition, such as many Brazilian cities, this set of indicators enables the establishment of a baseline, facilitates the setting of goals, and monitors the progress of initiatives over time.

For the circular strategy at the urban scale to be truly sustainable, it is necessary to assess the social, environmental, and economic consequences of the transition to circularity. For this reason, the tool includes a third component that proposes a set of indicators to evaluate the long-term impacts of the implemented actions and the adopted strategy.

For the tool to ensure continuous improvement, its implementation must occur cyclically. In other words, whenever managers identify negative outcomes in the impact indicators (social, environmental, or economic), decision-makers should reassess the circular transition strategy or projects. Only by identifying and mitigating potential rebound effects will it be possible to move toward a truly sustainable urban circularity.

Figure 13 presents the visual identity of the *CIRCCITY* tool.



Figure 13 - Visual identity of the *CIRCCITY* Tool.

The proposed tool, developed based on the results obtained in this chapter, enabled the identification of key characteristics that should guide the development of a tool to support urban circular transition, underpinning the proposed maturity model and the set of indicators presented in the following chapters. These characteristics relate to the need to integrate different urban sectors, consider multiple dimensions of sustainability, and establish mechanisms that enable the diagnosis, planning, and monitoring of urban circularity.

The study conducted in this chapter showed that, although there has been progress in implementing urban circularity, initiatives still occur predominantly in a sectoral and fragmented manner, with a greater concentration in the waste sector, and with limitations in integrating sustainability dimensions and measuring results. These findings reinforce the need for systemic approaches and justify the development of tools to support urban managers in conducting the circular transition in a structured manner.

4.5 Reflections

An analysis of European cities has shown that the implementation of urban circularity varies across cities, reflecting different interpretations of the circular economy's role in the urban landscape. While some cities focus their strategies on waste management and the efficiency of material flows, others seek to incorporate aspects related to social inclusion, innovation, governance, and territorial planning. In this sense, urban circularity cannot be understood as a single, linear model of transition but rather as a complex territorial process

influenced by the economic, social, institutional, and environmental characteristics of each urban area.

The analysis also reveals that aspects related to urban adaptation, territorial regeneration, and the structural transformation of urban systems remain only marginally addressed in the experiences analyzed. This fact reinforces the discussions presented in Chapter 2 regarding the limitations of overly technocentric approaches to CE and highlights the need to expand urban circularity beyond resource efficiency.

These gaps underscore the importance of developing tools to support urban managers in systemically diagnosing, planning, and monitoring the urban circular transition, aligned with sustainability principles.

In this context, the tool proposed in this study was developed based on evidence from the exploratory study, particularly regarding the fragmentation of circular initiatives, the difficulty of monitoring, and the absence of integrated approaches to support urban-level decision-making.

The tool was developed to assist urban managers at different stages of the circular transition, from diagnosing the territory's capabilities and limitations to monitoring the results and impacts of the implemented actions. To this end, its structure was organized into three complementary components: diagnosis and planning for urban circularity, monitoring of key sectors, and assessment of sustainability impacts. Thus, the tool seeks to integrate aspects related to governance, strategic urban sectors, and the environmental, social, and economic dimensions of sustainability.

5. MATURITY MODEL

This chapter presents the development of the maturity model, which constitutes the first component of the CIRCCITY tool. It also introduces the proposed maturity matrix for assessing urban circularity.

5.1 Decision Parameters for the Maturity Model

To develop the proposed maturity model, an adaptation of the works by Mettler (2010) and De Bruin *et al.* (2005) was used. The steps for developing the maturity model are described below.

5.1.1 Step 1 – Contextualization

Activity 1: Identification of need or scenario

During the literature review, a need was identified for tools to support the development of circularity in urban areas. As previously explained, maturity models provide useful tools for analyzing the evolution from a linear city to a sustainable, circular city. This is because such models allow for structuring the different stages of development, identifying gaps and intervention priorities, supporting decision-making, and systematically monitoring progress over time.

However, no maturity models specifically focused on sustainable urban circularity were found, highlighting an opportunity to develop one. Thus, the following decision parameter was established:

- Innovation decision criterion: its purpose is to identify what the proposed maturity model brings that is new to studies in the field of research. According to Mettler (2010), the model can be new (entirely original), a variant (a variation of an existing model), or a version (an updated version of a specific maturity model). Since no maturity models focused on urban circularity were found in the analyzed literature, the model is classified as "new" under the innovation parameter.

Activity 2 – Defining the Scope

As proposed by Mettler (2010) and De Bruin *et al.* (2005), the scope definition identifies strategic parameters for developing a maturity model. At this stage, the model's focus and the

stakeholders relevant to its construction are determined. In the adaptation carried out in this study, the following parameters were defined: model objective (purpose of development), target audience (for whom the model is intended), focus (scope of the model, which may be general or specific), and stakeholders (actors who can contribute to the construction of the maturity model). Table 4 presents the parameters determined in Activity 2 of Stage 1.

Table 4 - Decision parameters: objective, target audience, focus, and stakeholders.

Decision parameter	Description
Objective	The objective of the maturity model is to assist in diagnosing and planning for a sustainable circular city.
Target Audience	The target audience for the maturity model is decision-makers, that is, urban managers involved in a municipality's sustainable circular transition.
Focus	The proposed model has a specific focus: analyzing the sustainable circular transition in urban contexts. Unlike general models, which are applicable across multiple domains, this model focuses on a specific thematic field.
Stakeholders	A combination of academics and professionals involved in urban circularity.

5.1.2 Step 2 – Design

Activity 1: Development of the maturity framework

In this step, adapted from Mettler (2010) and De Bruin *et al.* (2005), the number of maturity levels is defined, along with their descriptions. To determine these levels, evaluation categories are established. The description of the levels and categories is also completed at this stage. Table 5 presents the structure of the decision parameters adopted in this study. It should be noted that the maturity categories presented in the table are the final categories adopted in the model; that is, they already incorporate the suggestions of the experts consulted during the learning stage.

Table 5 - Decision parameters: maturity levels, maturity category, and model presentation.

Decision paramete	Description
Maturity levels	The model consists of four levels: Level 0 – Linear City; Level 1 – Waste Management; Level 2 – Circular Economy; Level 3 – Sustainable Circular City.
Maturity Categories	The assessment is structured into six categories: Vision; Governance and Stakeholders; Material Cycle; Biological and Water Cycle; Space and Built Environment; and Equity and Social Justice.
Presentation of the model	The model will be presented as a Maturity Matrix.

Activity 2: Defining the classification criteria

In this activity, adapted from Mettler (2010) and De Bruin *et al*. (2005), the evaluation criteria for the categories comprising the maturity levels are defined. The method used to measure maturity is also established, as well as those responsible for its application (respondents). Table 6 presents the decision parameters established in this study.

Table 6 - Decision parameters: classification criteria, maturity assessment method, and respondents.

Decision parameter	Description
Evaluation categories	The criteria adopted were: Vision; Governance and Stakeholders; Material, Biological, and Water Cycles; Space and the Built Environment; Equity and Social Justice.
Maturity assessment method	The assessment is conducted using a questionnaire linked to a scoring system (rubric questionnaire).
Respondents	Experts in urban circularity.

5.1.3 Step 3 – Learning and Application

Like the other steps, this one is also based on an adaptation of the work by Mettler (2010) and De Bruin *et al*. (2005). Its objective is to test the conceptual model developed in the previous stages and understand what needs to be modified so that the model can achieve its objectives.

Activity 1: Learning

In this step of the model-building process, learning occurs through applying the model or consulting experts, to identify the changes needed to make it more efficient. Learning can occur through consultation with experts and through questionnaires, interviews, the Delphi method, and other approaches.

It is worth noting that this step ensures the iterative nature of the DSR, as it involves consulting individuals with practical knowledge of the subject, enabling the generation of knowledge from these interactions and the incorporation of improvements into the artifact (maturity model). Table 7 describes the decision parameters adopted in this model.

Table 7 - Decision parameters: form of learning, timing of learning, and adjustment.

Decision Parameters	Description
Form of learning	Consultation with experts working directly with urban circularity via an online questionnaire.
Timing of learning	During the model's development, following the creation of the first conceptual model, enabling learning and co-creation.
Adjustment	Changes were made to the maturity matrix (alterations to descriptions), categories (additions and removals), and the questionnaire (questions were included or excluded).

The expert consultation process was conducted via an online questionnaire. As described in the methodology, a consultation cycle was conducted with the participation of 18 experts from 12 countries: Brazil (4 participants), the Netherlands (3), France (2), Italy, Latvia, Norway, Spain, Switzerland, Turkey, the United Kingdom, the United States, and Vietnam (1 participant each). Regarding academic qualifications, 33.3% of respondents reported holding a master's degree, 33.3% a postdoctoral degree, 27.8% a doctoral degree, and 5.6% indicated having another type of qualification. In addition, the experts demonstrated extensive experience in the subject under study, with 33.3% having worked in the field for 5 to 10 years, 27.8% for more than 10 years, 22.2% for 1 to 3 years, and 16.7% for 3 to 5 years.

Overall, the experts found the model useful: 61.1% rated it as very useful, while 38.9% rated it as moderately useful. There were no responses indicating that the model is not useful, which reinforces its relevance and its potential for application as a tool to support the diagnosis and planning of urban circularity.

As for the suggested modifications, they were mainly related to the inclusion of new categories in the maturity matrix, since some experts considered that aspects relevant to urban circularity were either not addressed or included only secondarily. The suggestions made by the experts were adopted, resulting in the categories used in this study, namely: Vision, Governance and Actors, Material Cycle, Biological and Water Cycle, Space and Built Environment, and Equity and Social Justice.

Activity 2 – Application (model testing)

This activity consists of applying the model to real-world cases. Applying the conceptual model to a real-world situation allows for the identification of various aspects that can be improved. Furthermore, applying the model also allowed for an assessment of its usefulness and suitability for the analyzed urban context. For this study, the decision parameters presented in Table 8 were defined.

Table 8 - Decision parameters: method of application (test), scope of application, and dissemination.

Parameter	Description
Form of application (test)	Test in a real municipality that already incorporates circularity principles into its planning. The application was carried out through the collection of municipal data, consultation of municipal information platforms, and study of municipal plans.
Application scope	Municipality of São Paulo.
Dissemination	Dissemination refers to how the model will be made available (published) for future use. In this study, the model will be disseminated openly via an online platform.

The definition of these parameters guided the artifact's implementation phase, in line with the DSR, which requires that the developed artifact be demonstrated and evaluated in a real-world context. In this sense, applying the model to the city of São Paulo enabled testing its conceptual and operational structure in a real-world setting, thereby verifying its usefulness, coherence, and suitability for the urban context under analysis. Furthermore, this stage contributed to the iterative cycle of the DSR by enabling the identification of limitations, adjustments, and future opportunities for refinement.

5.2 Presentation of the proposed maturity model

The proposed maturity model aims to assist managers in diagnosing and planning for urban circularity. It can be used for the self-assessment of urban areas and to guide decision-

makers toward building sustainable circular development. The application of the model also allows for the establishment of objectives and targets and enables benchmarking between cities.

In this model, four maturity levels are proposed, as shown in Figure 14. The progression from one level to another represents not only an increase in the number of circular practices implemented but also a qualitative shift in how the city understands, plans, and implements urban circularity.

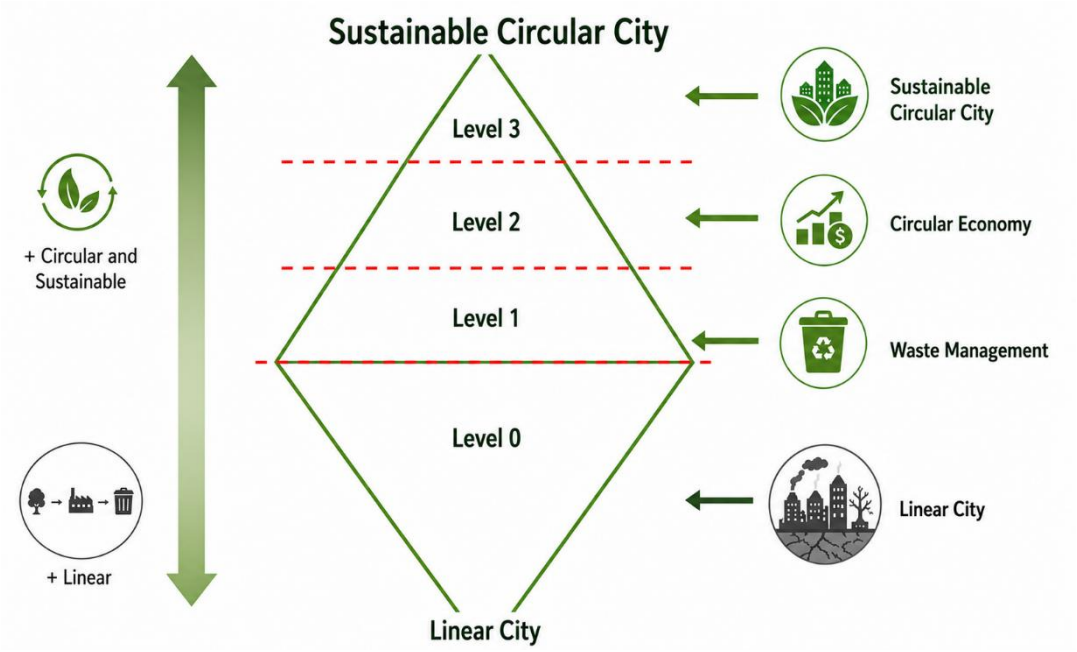


Figure 14 - Relationship of each level to the Sustainable Circular City.

The first stage corresponds to cities organized predominantly under a linear logic. Next, waste management emerges as an initial step in the transition, in which waste is understood as a resource and actions are structured to recover and reintegrate it into production cycles, as highlighted by UCCI (2022). The next level corresponds to the implementation of the Circular Economy at the urban scale, with greater emphasis on circular business models, innovation, technology, sharing, resource optimization, and closing cycles. However, it is still dominated by technocentric approaches, as discussed by Calisto Friant *et al*. (2023).

Finally, the most advanced level refers to the sustainable circular city, in which circularity is systematically incorporated into urban planning. At this stage, the circular transition is no longer restricted to economic efficiency or the closing of material cycles but also involves the adaptation of urban structures, the regeneration of natural systems, the localization of production and consumption, equity in access to urban resources, and the

continuous assessment of environmental, social, and economic impacts. This level aligns with the framework proposed by Williams (2019a), which conceptualizes urban circularity as a process that can generate positive impacts across the three pillars of sustainability.

Thus, the four proposed maturity levels are:

- **Level 0 – Linear City:** the city (or urban area) does not implement actions aimed at circularity, operating under a linear logic based on the extraction, production, consumption, and disposal of resources.
- **Level 1 – Waste Management:** the city begins to prioritize waste management, focusing on improving collection, treatment, and disposal systems. Actions aimed at recycling and energy recovery are implemented, promoting the partial reintegration of materials into the production chain, though with a predominant focus on post-consumption management.
- **Level 2 – Circular Economy:** the city expands its activities beyond waste management, incorporating CE practices across different urban sectors. There is an incentive to create circular business models, foster innovation, and promote more efficient use of resources, encouraging the reuse, repair, sharing, and optimization of material flows. Circularity is also increasingly viewed as an economic opportunity, with a predominance of technology-centric approaches.
- **Level 3 – Sustainable Circular City**: the city implements circularity in a systemic and integrated manner, promoting the reduction of resource consumption and the prevention of waste generation. There is a focus on the regeneration of natural systems, the adaptation of urban structures, and the localization of production and consumption. The circular transition incorporates continuous assessment of environmental, social, and economic impacts, avoids rebound effects, and promotes equitable access to urban systems through collaborative, long-term processes.

The levels represent the transition from linear logic to a systemic approach to urban circularity, with a progressive expansion of the scope of actions and the degree of integration among urban systems. This evolution involves not only changes in material and resource flows but also transformations in how circularity is understood, planned, and implemented, including strengthening governance, expanding stakeholder participation, adapting urban space, and incorporating social and territorial aspects. Thus, higher levels of maturity reflect greater

integration among environmental, social, economic, and institutional dimensions, thereby characterizing a more structured and sustainable approach to urban circularity.

Table 9 maps each proposed maturity level to actions based on the hierarchy of the 9 Rs (refuse, rethink, reduce, reuse, repair, recondition, remanufacture, repurpose, recycle, and recover), as outlined by Vanhuyse (2023) as a set of strategies for implementing urban circularity. Furthermore, it relates the levels to the circular city framework proposed by Williams (2019a).

Table 9 - Relationship between maturity level, 9Rs, and Williams' (2019a) circular city framework.

Maturity level	Actions based on the 9Rs hierarchy	Actions based on Williams' (2019) circular city framework.
Level 0 – Linear City	Not applicable.	Not applicable.
Level 1 – Waste Management	Recycle Recover (energy).	Closing the loop.
Level 2 – Circular Economy	Reuse Repair Recondition Remanufacture Recycle.	Closing cycles (looping) Optimization Sharing Replacement.
Level 3 – Sustainable Circular City	Integrated application of all 9 Rs, with an emphasis on: Refuse Rethink Reduce Regenerative actions.	Closing the loop Optimization Sharing Substitution Adaptation Localization Regeneration.

All maturity levels proposed in this study present specific management challenges for advancing to the next level. Table 10 summarizes the main challenges faced by urban management at each level, relating them to the prevailing logic, the focus, and the understanding of urban circularity.

Table 10 - Maturity Level: Dominant Logic, Focus, and Limitations.

Maturity Level	Dominant Logic	Main Focus	How "circularity" is understood	Limitations
Linear City	Extract, use, and discard.	Growth and consumption.	This concept does not exist.	High resource consumption, waste generation.
Waste Management	Mitigation of problems caused by waste.	Waste treatment.	Circularity = recycling, energy recovery, and proper disposal.	Does not alter production, consumption, or urban structure.
Circular Economy	Circularization of resources and economic benefits.	Efficiency, innovation, circular business models.	Circularity = closing cycles and creating economic opportunities.	Still centered on the economic system, it may overlook territory, governance, and social aspects.
Sustainable Circular City	Circularity and access to resources are the focus of urban planning.	Transformation of the urban system, sustainability	Circularity is a foundational principle of the city.	High complexity of implementation.

As previously mentioned, each maturity level comprises categories that help assess the city's evolution. The categories were defined based on gaps identified in the literature and on the analysis of practices observed in the cities studied in Chapter 4. The categories used to evaluate each level are presented below:

- **Vision**

According to Vanhuyse (2023), the vision refers to the city's ambition regarding CE, that is, how the urban area intends to implement it, what its objectives are, and where it intends to go. The vision must be clear, as it guides the definition of strategies for the circular transition and is directly related to how the concept of "circular" is understood in the urban context.

Vanhuyse (2023) also proposes guiding questions for his analysis, such as the degree of technology centrality, the integration of environmental, economic, and social dimensions, the scope of the initiative (whether comprehensive or sector-specific), and the actors involved in its development. Based on these elements, this study defines three criteria for evaluating the Vision category: meaning, objective, and technology. Their description by maturity level is presented in Table 11, which corresponds to the maturity matrix.

Table 11 - Criteria for the Vision category.

Category	Criterion	Description
Vision	Meaning	This criterion concerns how the city or urban area understands urban circularity, including the principles and approaches that guide that understanding.
	Objective	This criterion refers to the ultimate goal that the city or urban area seeks to achieve through the implementation of circularity, including the level of transformation intended for the territory.
	Technology	This criterion assesses how the city or urban area understands the role of technology in the circular transition, including the degree of reliance on technological solutions compared with systemic and social approaches.

- **Governance and Actors**

Campitelli *et al.* (2022) define governance as the set of measures necessary to manage, control, and regulate waste management at different levels, including laws, regulations, and political and financial instruments, an aspect also highlighted by EMF (2019b). In this sense, the Governance and Actors category refers to the existence and quality of governance, guidelines, institutional mechanisms, financing, and monitoring that enable the urban circular transition.

Furthermore, it incorporates the roles of actors (the various stakeholders involved in this process, such as government, the private sector, academia, and civil society) whose joint action is essential for the effective implementation of circularity, as noted by ICLEI (2020) and Vanhuyse (2023). Thus, this category assesses both the institutional structure and the degree of engagement, participation, and awareness of these actors, as detailed in Table 12.

Table 12 - Criteria for the Governance and Actors category.

Category	Criteria	Description
Governance and Actors	Laws and Guidelines	This criterion refers to the existence of public policies, laws, and regulations related to urban circularity.
	Financing	This criterion concerns the existence and diversity of financing mechanisms supporting the implementation of urban circularity initiatives.
	Monitoring	This criterion concerns how the circular transition is monitored, including the availability of data, indicators, and monitoring systems.
	Strategy	This criterion refers to the existence of a strategic vision for urban circularity, including defining objectives, prioritizing sectors, and integrating across areas and actions.
	Management structure	This criterion concerns the institutional organization and the definition of responsibilities among the actors involved in the governance of urban circularity.
	Stakeholder Engagement	This criterion refers to the degree of participation and the role of the different actors involved in the decision-making and implementation processes of circularity.
	Awareness and Capacity Building	This criterion refers to the level of knowledge, understanding, and skill development among the different actors regarding urban circularity, including education, training, and the promotion of behavioral changes.

- **Material cycle**

The experts suggested the material cycle category consulted during the model validation process. According to one expert, its inclusion helps align the proposed structure with widely used frameworks in the literature, such as the EMF framework (2012). This category seeks to analyze how material flows are managed in the urban environment, encompassing strategies such as reduction, reuse, repair, remanufacturing, recycling, and recovery. Thus, its incorporation strengthens the model's ability to assess the closure of technical cycles and the efficiency of resource use in cities.

The description of the criteria used to evaluate the category is presented in Table 13.

Table 13 - Criteria for the Material Cycle category.

Category	Criteria	Description
Material Cycle	Waste	This criterion addresses material cycle closure initiatives implemented in the key sector of Waste.
	Local Production and Industry	This criterion addresses material closed-loop initiatives implemented in the key sector of Local Production and Industry.
	Construction	This criterion addresses material closed-loop initiatives implemented in construction activities.
	Mobility and Transportation	This criterion addresses material cycle closure initiatives implemented in the key sector of Mobility and Transportation.
	Consumption and Behavior	This criterion addresses initiatives aimed at reducing resource consumption and changing consumption patterns and behaviors to help close the material cycle.

- **Biological and Water Cycle**

The inclusion of this category in the maturity model was also proposed by the experts consulted and, like the Material Cycle category, seeks to incorporate the conceptual approach of EMF (2012) into the model. Its inclusion is important for broadening the analysis of urban circularity, ensuring that the model is not limited to technical flows but also considers other dimensions essential to the functioning of the urban metabolism. Thus, the category contributes to a more comprehensive assessment, taking natural resources into account. The description of the criteria evaluating the category is presented in Table 14.

Table 14 - Decision criteria for the Biological and Water Cycle category.

Category	Criteria	Description
Biological and Water Cycle	Agriculture and Food	This criterion refers to initiatives related to closing the biological cycle in the agriculture and food sector, including nutrient recovery, the use of organic resources, and integration with regenerative agriculture.
	Water and Sanitation	This criterion refers to initiatives aimed at closing the water cycle, including the treatment, reuse, and management of water resources, as well as the adaptation of urban structures to preserve them.

- **Space and the Built Environment**

The experts suggested the inclusion of this category consulted to expand the analysis of urban circularity beyond material flows to incorporate spatial and territorial dimensions. Its

inclusion is essential, since the built environment directly influences resource consumption patterns, the efficiency of urban infrastructure, and the feasibility of implementing circular strategies, such as building adaptation, multifunctional space use, and reduced travel needs.

In this regard, Wandl *et al.* (2023) highlight that the transition to CE in cities and regions requires an integrated approach that considers land use, urban form, and infrastructure as central elements. Thus, incorporating this category strengthens the model by enabling a more systematic assessment of urban circularity. The description of the category's evaluation criteria is presented in Table 15.

Table 15 - Criteria for the Built Environment category.

Category	Criterion	Description
Space and Built Environment	Regeneration	This criterion refers to initiatives aimed at regenerating urban space, including expanding green areas and using nature-based solutions.
	Adaptation	This criterion refers to the adaptation of urban structures to integrate natural and urban systems, promoting better use of land and resources.
	Location and Spatial Organization	This criterion refers to the organization of urban space to bring services, production, and consumption closer together, reducing the need for travel and promoting greater efficiency in the use of infrastructure.

- **Equity and Social Justice**

The experts suggested this category consulted during the model validation process to incorporate a dimension often neglected in the circular economy literature. Although circularity has advanced in the analysis of material flows and resource efficiency, several studies still address social impacts implicitly or as a secondary concern (Calisto Friant *et al*., 2023; Vanhuyse *et al*., 2021).

In this sense, the inclusion of this category is important for assessing how the circular transition contributes to reducing inequalities, including those affecting vulnerable groups, and to promoting social well-being, as pointed out by Vanhuyse *et al.* (2021). The description of the criteria used to evaluate the category is presented in Table 16.

Table 16 - Framework - Criteria for the Equity and Social Justice Category.

Category	Criterion	Description
Equity and Social Justice	Access to Infrastructure and Services	This criterion refers to the distribution of and the population's access to urban infrastructure and basic services, with a focus on reducing inequalities within the region.
	Employment and Income	This criterion refers to the generation of jobs and income associated with circularity initiatives, including the quality of working conditions and the distribution of economic benefits.
	Inclusion of Vulnerable Groups	This criterion refers to the inclusion of vulnerable and marginalized groups in urban circularity initiatives to promote greater social equity.

5.2.1 Maturity matrix for classifying urban circularity

Based on the definition of levels, categories, and evaluation criteria, the Maturity Matrix for urban circularity was developed, as presented in Table 17. The matrix synthesizes the conceptual foundations discussed in the literature and operationalizes the evaluation of urban circularity, guiding managers in identifying gaps, progress, and priorities for action.

Table 17 - Maturity Matrix for Urban Circularity

	Level 0 - Linear City	Level 1 – Waste Management	Level 2 – Circular Economy	Level 3 – Sustainable Circular City
Vision	Lack of vision regarding urban circularity.	Circularity associated with waste management; focus on recycling and recovery.	Circularity in the urban Circular Economy, focusing on creating an environment for innovation and circular business models.	Systemic and long-term vision; integration of circular, regenerative, and adaptive actions; transformation of production, consumption, and location patterns; alignment with environmental, social, and economic sustainability.
Governance and Actors	No governance for urban circularity.	Governance focused on waste management; limited stakeholder participation. Funding for improvements in waste management and sector monitoring.	Partially integrated governance; participation of multiple stakeholders, with a focus on innovation and circular ecosystems, involving the private sector, research centers, and universities. Funding directed toward companies and monitoring of economic gains.	Collaborative and multilevel governance; strong coordination among stakeholders and active public participation; integration across sectors and institutional levels. Robust monitoring framework and established financing mechanisms.
Material Cycle	Linear flows (extraction, consumption, and disposal).	Focus on recycling and energy recovery; partial closing of cycles.	The expansion of circular practices (reuse, repair, remanufacturing, repurposing) is promoted by circular business models.	Integrated materials management; prioritization of refuse, rethink, and reduce; closing of cycles with high circular value. Change in consumption patterns.
Biological and Water Cycle	Linear flows (extraction, consumption, and disposal).	Initiatives for biogas production from organic waste and specific composting actions. Water and wastewater treatment.	Implementation of circular practices, such as water reuse, agriculture-linked composting, nutrient recovery from wastewater, and food waste reduction, is promoted through circular business models.	Integration of biological and water cycles; regenerative solutions focused on water resources and ecosystems; local agriculture utilizing urban space.
Space and Built Environment	Linear flows (extraction, consumption, and disposal).	Initial focus on construction and demolition waste; adoption of basic management practices and proper disposal. Infrastructure for waste management.	Planning the built environment for circular ecosystems; encouraging local production and industrial symbiosis; maximizing the use of material stock (reuse, selective demolition, repurposing, and modular construction).	Integrated planning of the built environment; regeneration of green spaces; integration of natural and urban systems; enhancement of the built stock (optimization and reduction of underutilization); infrastructure with equitable access and greater proximity to urban services.
Equity and Social Justice	Unequal distribution of resources, services, and infrastructure.	Greater equity in access to waste management services; initial inclusion of informal waste pickers.	Incorporation of solidarity-based practices, such as donation, redistribution, and access to low-cost products, circular business models promote job and income generation.	Social justice integrated into circularity; redistribution of access to resources, urban space, and services; reduction of consumption and socio-spatial inequalities; promotion of sufficiency, solidarity economy, and sharing.

This matrix constitutes the main artifact of the first component of *CIRCCITY*, as it organizes, within a single analytical framework, the elements necessary to diagnose the stage of urban circularity. In the context of DSR, this matrix represents the materialization of the design process, transforming theoretical and empirical findings into an operational framework to solve a practical urban management problem.

Thus, urban circularity can be assessed in a progressive and multidimensional manner. This characteristic distinguishes the model from other approaches that restrict circularity to waste management or the closing of material cycles. In this sense, the matrix's unique feature is that it incorporates the following categories: Vision, Governance and Actors, Material Cycle, Biological and Water Cycle, Space and Built Environment, and Equity and Social Justice, making it possible to identify not only the city's overall level of maturity but also the specific aspects that limit or drive its circular transition. Therefore, the matrix helps transform the concept of urban circularity into a practical tool for diagnosis, planning, and decision support.

The proposed maturity matrix helps us understand the urban circular transition as a gradual process in which different dimensions of the city can advance at varying paces. In this sense, the model seeks to identify the city's stage of maturity in urban circularity, considering its progress and limitations in each category analyzed. This approach enables recognition of different levels of development, identification of more fragile categories, and guidance on specific actions to advance the city's evolution toward sustainable urban circularity.

To assess the maturity of urban circularity, a rubric-based questionnaire is used, in which each response is assigned a predefined score. Based on these scores, it is possible to calculate a circularity index that represents the city's level of development in the circular transition. The circularity index is calculated by category and is obtained by the ratio of the city's total points to the maximum possible score in the respective category, as shown in the following formula:

$$\text{Circularity Index (\%)} = \frac{\Sigma\ \text{City's score}}{\text{Maximum possible score}}\ x\ 100$$

The city's overall Circularity Index is obtained by averaging the circularity indices of the evaluated categories. The simple average was used to avoid distortions associated with the number of criteria in each dimension and to ensure the comparability of results, as shown in the formula below:

Overall Circularity Index (%) = average of the circularity indices of the categories.

This index is then classified based on a maturity scale consisting of four levels: Level 0 – Linear City (0% ≤ Circularity Index ≤ 25%); Level 1 – Waste Management (25% < Circularity Index ≤ 50%); Level 2 – Circular Economy (50% < Circularity Index ≤ 75%); and Level 3 – Sustainable Circular City (75% < Circularity Index ≤ 100%). Thus, the adopted scoring method ensures transparency, replicability, and consistency in assessing maturity level.

The complete maturity model, including the rubric questionnaire, can be accessed via the following URL: https://goo.su/iPvJom. It is also available through the online platform (https://ccplatform.com.br/) developed to disseminate the model. It is worth noting that the model developed in this chapter constitutes the first component of this research's artifact, as proposed by the DSR approach.

The model was structured based on the literature review and the study of reference cities presented in Chapter 4. Thus, the model reflects both theoretical developments and the gaps observed in its practical implementation. It seeks to address the identified limitations, particularly the fragmentation of actions, the predominance of sectoral approaches, and the absence of structured monitoring mechanisms. Thus, the model advances beyond existing approaches by structuring urban circularity as a systemic, evolutionary process and integrating material, territorial, social, and institutional dimensions into a single decision-support tool.

6. URBAN CIRCULARITY INDICATORS

This chapter presents the results of the study on circularity indicators and describes the processes of selecting, systematizing, and validating the set of indicators that constitute the second and third components of CIRCCITY.

6.1 Urban Circularity Indicators

As mentioned earlier, the concept of urban circularity is still taking shape in the academic literature. In this context, assessing and measuring the progress and effects of circular initiatives in urban areas poses a complex challenge (Paoli *et al*., 2022). The definition of metrics capable of capturing direct outcomes and systemic impacts has emerged as a key focus of recent research, highlighting the need for robust methodological approaches integrated with sustainability (Falah *et al*., 2025).

Given these limitations, it is necessary to make progress in defining indicators that capture the complexity of urban circularity. In this study, such indicators are understood to capture not only the closure of resource cycles but also the systemic effects of circularity on urban functioning, including regeneration, adaptation, localization, and social, environmental, and economic impacts.

Thus, this study proposes a set of indicators to monitor outcomes and assess the impacts of circular initiatives on urban sustainability. These indicators are part of the developed tool and correspond to the second and third components, as described earlier.

To identify the indicators used in this study, a literature review was conducted in March 2023, as described in Chapter 3. The review covered publications from 2014 onward, with the first identified article dating from 2017. This fact underscores the topic's recent nature and reinforces the need for further research.

To complement the analysis, the following documents were included: *Circular City Indicators Set* (2020), by *the Nordland Research Institute* and ICLEI; *The Circular Economy in Cities and Regions* (2020), by the OECD; *Les indicateurs de l'économie circulaire* (2022), *by the Institut Paris Region*; and *A Guide to Circular Cities* (2020), by UNECE. Sector-specific guides were also considered, such as *Circular economy indicators for personal mobility and transport* (2020) and *Circular Economy Indicators for Buildings and Housing* (2021), from the

CE-Center *Circular Economy Policy Research Center* (Belgium), as they contribute to the understanding of key sectors.

Indicators present in CE plans of European cities were also identified but not included directly, as they had already been systematized in studies by Girard and Nocca (2019) and Paoli *et al*. (2022). Thus, these indicators were incorporated indirectly into the analysis.

Finally, to keep the survey up to date, publications on urban circularity indicators were monitored through January 2026. This monitoring enabled the inclusion of eight additional studies not covered in the SLR, either because of their publication dates or due to limitations of the adopted criteria. Thus, 63 documents comprise the set of references used to identify the indicators. Appendix B presents all the works used.

6.2 Survey and analysis of indicators

To map the indicators associated with urban circularity, a list was compiled of those found in the analyzed articles and documents. This step aimed to understand how circularity has been measured in the context of cities, as well as which aspects the literature and organizations consider relevant for its assessment.

Based on the selected studies, all identified indicators were entered into a spreadsheet. Identical indicators, in both the information provided and the wording, were recorded only once. Indicators that presented similar information but differed in measurement method, wording, or unit of analysis were also included in the list.

A total of 1,796 indicators were included. This number is justified by the fact that urban circularity is linked to resource use across key urban sectors, each of which is highly complex and involves distinct aspects to assess. In this regard, some studies provide in-depth analyses of specific sectors, such as Arora *et al*. (2022), which present indicators related to water circularity, and the CE-Center's document “Circular economy indicators for personal mobility and transport” (2020), which compiles indicators focused on transportation.

After listing, the indicators were classified into two categories: key sectors and sustainability dimensions. In the sustainability classification, indicators reflecting results across economic, social, and environmental aspects were considered.

In cases where indicators had characteristics that allowed them to be classified under more than one dimension, an analytical decision aligned with the research perspective was

adopted. For example, the indicator “material footprint per monetary unit spent” could be classified as economic or environmental. In this study, it was allocated to the environmental dimension.

In the categorization by key sectors, the following categories were defined: Waste; Water and Sanitation; Mobility and Transportation; Agriculture and Food; Local Production and Industry; Energy; and Space and the Built Environment. In addition to these, the categories Governance, Stakeholders, and Information (focused on management, engagement, and transparency) and Material Flows and Resource Consumption (related to the consumption and circulation of materials in the urban system) were included.

The indicators, classified by key sectors, represent both direct outcomes of circularity actions and medium- and long-term changes or systemic transformations associated with the sectors analyzed. Figure 15 presents the percentage of indicators by key sector.

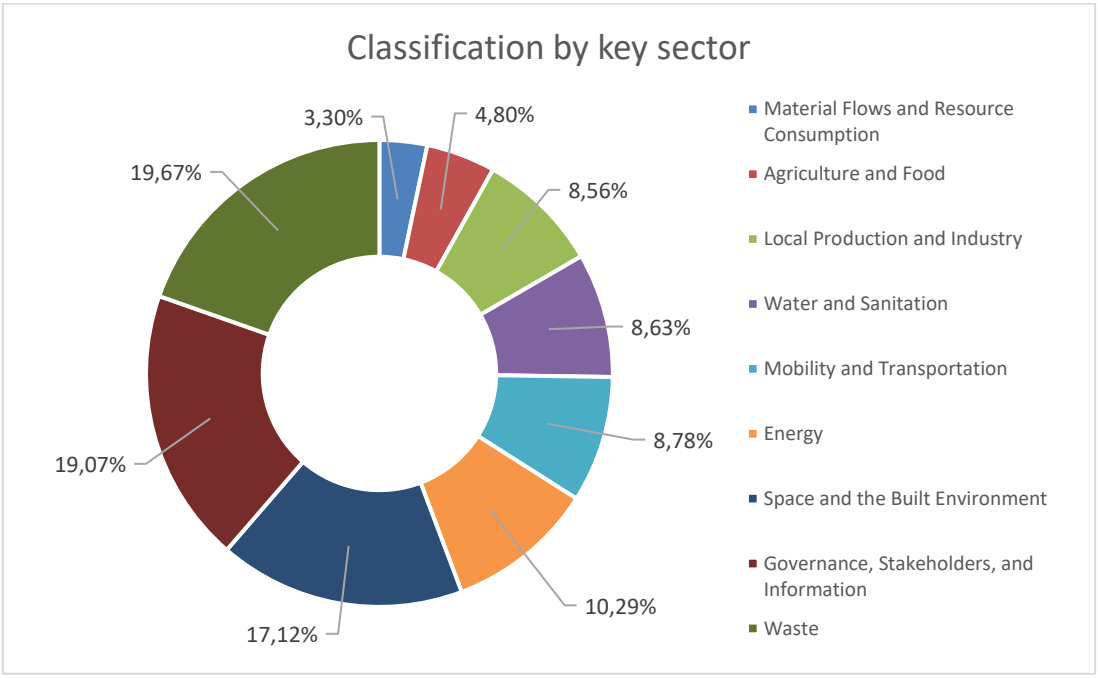


Figure 15 - Percentage of indicators by key sector.

Among the 1,796 listed indicators, 1,335 instances were identified as related to the key sectors of urban circularity, while 726 classifications were assigned to the dimensions of sustainability (Figure 16). Of this total, 264 received simultaneous classification in both categories.

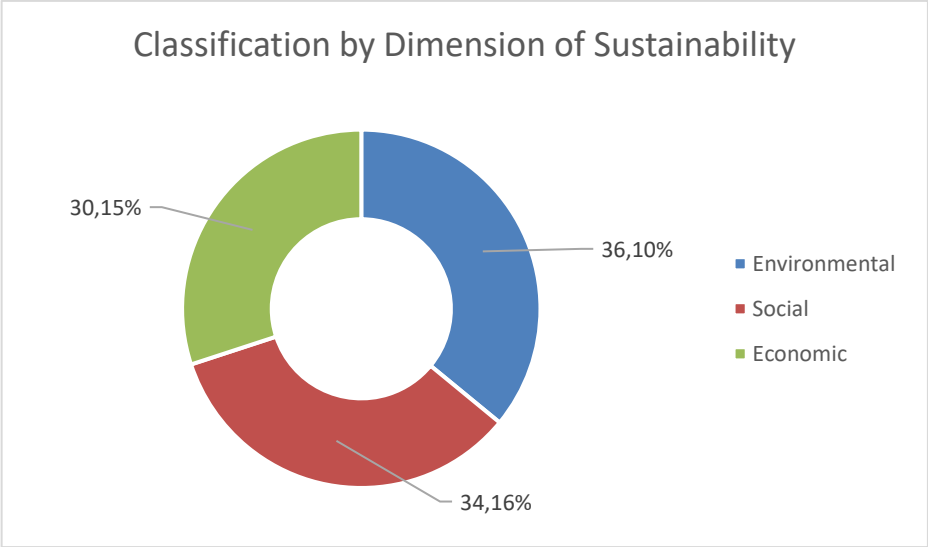


Figure 16 - Percentage of indicators by sustainability dimension.

The "Waste" category had the highest number of indicators (262), accounting for approximately 20% of the total classified in the key sectors. In general, the indicators in this sector cover information on waste generation, management, and treatment; recycling; reuse; material recovery; diversion from landfills; and management of specific waste streams (such as waste from electrical and electronic equipment and textiles).

Analysis of the indicators in the waste key sector reveals a predominance of "downstream" metrics, focused on the destination and treatment of waste after it is generated. Few indicators measure prevention and non-generation. This scenario indicates that urban circularity remains primarily associated with waste management, while broader approaches aimed at reducing material consumption and "upstream" initiatives receive less attention.

Regarding sustainability indicators for the key waste sector, the largest number falls under the economic dimension (28 indicators), highlighting concerns about costs, investments, and revenues from management and recycling. The environmental dimension appears in fewer indicators (9), covering aspects such as illegal dumping sites and emissions. The social dimension, however, is more limited (7 indicators), including job creation, the inclusion of the informal sector, universal waste collection, and access to management systems.

The "Governance, Stakeholders, and Information" indicators also numbered 254, underscoring the need to measure aspects of the management processes of the circular transition. In general, these indicators provide information on institutional structure and

capacity, training and education initiatives, information and transparency efforts, and economic instruments and public procurement related to CE.

In the "Governance, Stakeholders, and Information" category, the high prevalence of binary indicators stands out: while they facilitate measurement (especially in cities at an early stage), they do not allow for an assessment of the quality, effectiveness, or impact of initiatives. Regarding the dimensions of sustainability, there are social indicators (24) related to participation, engagement, education, and social perception; economic indicators (16) associated with financial capacity and investment instruments; and environmental indicators (5) focused on incorporating environmental issues into planning.

The key sector "Space and the Built Environment" comprises 228 indicators, primarily related to the circularity of construction materials, infrastructure modernization, land use and land cover, and green spaces. Although some indicators suggest a more holistic approach, most still focus on construction and demolition waste. In this regard, Dąbrowski and Wandl (2024) point out that the metrics neglect the stocks of materials incorporated into buildings and infrastructure.

Regarding sustainability indicators for the key sector "Space and the Built Environment," 21 are social indicators, related to access to public spaces, territorial equity, and housing, highlighting a socio-spatial concern. Four are economic indicators and refer to investments, particularly in green infrastructure. Finally, 27 indicators are environmental, related to emissions mitigation and green space coverage.

In the key sector of Energy (137 indicators), the indicators assess demand, the energy mix, renewable energy generation, energy efficiency, integration with waste management, and energy recovery. The economic indicators (5 indicators) measure efficiency, costs, and investments; the social indicators (5 indicators) address energy access and equity; and the environmental indicators (9 indicators) address the climate impacts of energy generation and consumption.

In the key sector "Mobility and Transportation" (117 indicators), the indicators assess the modal structure, accessibility, active mobility, operational efficiency, e- -sharing, urban logistics, and freight transport, highlighting a focus on reducing emissions and adapting infrastructure. In this sector, there are 7 social indicators related to access and walkability; 1

economic indicator related to cost reduction; and 4 environmental indicators measuring transportation emissions and the carbon footprint.

In the key sector “Water and Sanitation” (115 indicators), the indicators address availability, infrastructure, access, water quality, reuse, wastewater treatment, and resource recovery (nutrients). The social indicators (9 indicators) address access and equity; the economic indicators (7 indicators) address efficiency and investments; and the environmental indicators (25 indicators) address water quality and pressure on water resources.

In the key sector “Local Production and Industry” (114 indicators), the indicators address resource use, waste recovery, water reuse, energy efficiency, industrial symbiosis, and innovation. The social indicators (5 indicators) address job creation; the economic indicators (12 indicators) address competitiveness, investment, and productivity; and the environmental indicators (12 indicators) address emissions, pollution, and pressure on water resources.

With regard to the “Agriculture and Food” sector (64 indicators), the indicators focus on organic waste management, nutrient recovery, local production, and food security, with a predominance of waste-related metrics. The social indicators (2 indicators) address food security; the economic indicators (2 indicators) address investments; and the environmental indicators (5 indicators) address soil quality and cultivated areas, highlighting gaps in the social dimension.

In the “Material Flows and Resource Consumption” category (44 indicators), the indicators address material consumption, pressure on natural resources, material reintroduction, and external dependence, based on Material Flow Analysis (MFA) studies. There are only 1 social indicator, 2 economic indicators, and 10 environmental indicators, highlighting low coverage in social and economic areas.

In total, 247 social indicators were identified to assess job creation, inclusion, quality of life, education, and participation. However, there is a lack of indicators that capture behavioral changes, community initiatives, and the quality of jobs generated in circular initiatives. As highlighted by Girard and Nocca (2019), many social aspects are only partially measurable. This study confirms the authors’ assertion by showing that social indicators do not capture all aspects necessary for monitoring a just circular transition.

It is also worth noting that the set of indicators identified in the literature paid little attention to measuring gender-related aspects of equity. Only four indicators sought to provide

information on the inclusion of women in circular initiatives. This result shows that studies on urban circularity still address gender inequalities in cities and the impacts of the circular transition on different social groups only to a limited extent.

The 218 economic indicators primarily assess economic performance, investments, efficiency, and the generation of economic value. However, they do not capture the distribution of economic benefits. The 261 environmental indicators, on the other hand, measure resource consumption, emissions, land use, biodiversity, and water-related impacts.

However, regarding environmental indicators, little attention is paid to ecological regeneration and impacts that extend beyond the urban territory. In this regard, Kopp *et al.* (2024) highlight that environmental indicator systems remain limited, territorialized, and focused on waste flows, failing to capture systemic impacts and global externalities.

Figure 17 presents a synthesis of the indicator analysis, classified by key sectors of urban circularity and sustainability dimensions. It illustrates how the indicators are distributed across the analyzed sectors and among the social, economic, and environmental dimensions.

Key Sector	Occurrences by Key Sector	Social Indicators	Economic Indicators	Environmental Indicators
Waste	262	7	28	9
Governance, *Stakeholders* and Information	254	24	16	5
Space and Built Environment	228	21	4	27
Energy	137	5	5	9
Mobility and Transport	117	7	1	4
Water and Sanitation	115	9	7	25
Local Production and Industry	114	5	12	12
Agriculture and Food	64	2	2	5
Material Flows and Resource Consumption	44	1	2	10
Total occurrences by key sector	1,335	81	77	106
Indicators classified in only one dimension of sustainability	—	166	141	155
Total indicators per dimension	—	247	218	261

Figure 17 - Distribution of indicators by key sector of urban circularity and dimension of sustainability.

Source: Developed by the author, with the assistance of ChatGPT – OpenAI (2026).

The summary presented in Figure 17 reinforces that, although there is a diversity of indicators, their distribution across sectors and dimensions remains uneven. Recent studies also highlight that urban circularity involves institutional, sociocultural, technological, and territorial dimensions, reflecting the complexity and integration among different urban systems (Aina *et al*., 2026). In this sense, there is a need for more comprehensive monitoring approaches that capture the multiple dimensions of the circular transition.

In this context, Falah *et al.* (2026) point out that even when analytical frameworks incorporate different circularity strategies, significant conceptual gaps persist, particularly in early-stage transformative strategies and interventions aimed at extending the useful life of products and materials. This reinforces the point that the existence of different indicators does not necessarily mean that urban circularity is being assessed comprehensively or that it encompasses all aspects of a CC, as proposed by Williams (2019a).

Thus, the indicators currently used are not capable of capturing the full complexity of urban circularity. The analysis of the indicators shows that urban circularity is still predominantly interpreted through the lens of waste management, with a strong concentration of indicators focused on downstream solutions. Furthermore, there are significant limitations in measuring social dimensions and capturing systemic transformations, particularly those related to prevention, changes in consumption patterns, and the regeneration of urban systems.

6.3 Selection and validation of indicators

Based on the classification of indicators, the selection phase began using four criteria: consistency, applicability, redundancy, and utility. As explained in Chapter 3, the consistency criterion sought to verify whether the indicator was coherent with the tool's objectives and with the proposal to monitor key sectors or assess the impacts of urban circularity initiatives on sustainability.

The applicability criterion, on the other hand, assessed whether the indicator could be effectively measured at the urban scale, considering the existence, availability, or feasibility of collecting the necessary data. The redundancy criterion, in turn, sought to identify whether the information provided by a given indicator was already covered by another selected indicator, thereby avoiding the inclusion of repeated or highly similar indicators. Finally, the utility

criterion assessed whether the information provided by the indicator was effectively useful for supporting urban managers in diagnosis, monitoring, and decision-making.

It is worth noting that most indicators were excluded under the redundancy criterion, as many of them, although they had different names, measured similar phenomena or provided overlapping information. For example, indicators such as “Municipal Solid Waste Generated,” “Municipal Solid Waste Generation,” and “Amount of Waste Produced in the City” all measure the amount of waste generated. Thus, only the clearest, most comprehensive indicators applicable to the tool’s objectives were retained.

This preliminary selection sought to concisely represent the most relevant and measurable aspects of urban circularity, prioritizing indicators with greater practical applicability, data availability, and the ability to reflect systemic transformations. It should be noted that indicators related to the categories “Governance, Stakeholders, and Information” and “Material Flows and Resource Consumption” were not included.

The “Governance, Stakeholders, and Information” category was not included in the final set of indicators because its core elements are already covered by the maturity model proposed in this study. It involves elements such as institutional capacity, stakeholder participation, transparency, management tools, guidelines, and evaluation mechanisms, which are more appropriately assessed using qualitative and progressive criteria. Thus, its inclusion as sectoral indicators could lead to overlap among the tool’s components, since these aspects are analyzed in the component focused on urban maturity diagnosis.

The category “Material Flows and Resource Consumption,” however, was not included in the final set due to its high methodological and operational complexity. Although it is a central dimension for understanding urban metabolism, its measurement requires detailed data on the inflow, circulation, stock, transformation, and outflow of materials in the urban system, often dependent on specific studies, such as material flow analyses, territorial inventories, and databases that are not always available or comparable across municipalities, especially in the Brazilian context.

Furthermore, many indicators in the “Material Flows and Resource Consumption” category require a high level of sectoral and territorial disaggregation, which could limit the tool's practical applicability in municipalities with limited technical capacity or low data availability. Thus, their exclusion from the final set does not stem from their lesser relevance

to urban circularity, but from the need to ensure greater methodological and operational feasibility and comparability across different urban contexts.

The set of indicators selected in this study aims to provide key information that allows urban managers to measure the results of circular initiatives and their long-term impacts on sustainability. Thus, a set of indicators was defined for monitoring key sectors (component 2) and for impact assessment (component 3). When gaps were identified in the literature, new indicators were proposed, always based on the adopted selection criteria. Some indicators were also adapted to better align with the tool's objectives.

Following this stage, the indicators were submitted to experts in urban sustainability and CE for validation, as described in Chapter 3. In total, 22 experts participated in the process, which aimed not only to validate but also to refine the set of indicators based on professionals' opinions in the field. The experts received the validation form via email and evaluated the indicators using a Likert scale, as shown in Chapter 3.

In the context of the DSR, this process represents a refinement stage of the tool, in which the indicators initially identified in the literature were evaluated, adjusted, and supplemented based on consultation with experts. Thus, Components 2 and 3 of the tool are not merely a compilation of existing indicators, but the result of a co-creation process, focused on utility, applicability, and alignment with the context of sustainable urban circularity.

6.3.1 Indicators for the Key Sector: Waste (Component 2)

The indicators for the key waste sector that were selected and underwent the validation process with experts were:

1. Municipal solid waste generation: amount generated within the territory.
2. Landfill diversion rate: proportion of waste diverted through recycling, reuse, and recovery.
3. Waste-to-energy: energy recovery via biogas, waste-derived fuel, and thermal treatment.
4. Special materials collected: amount of waste with high circular potential, such as textiles, electronics, and furniture.

Figure 18 presents the results of the expert consultation on the proposed indicators for this sector.

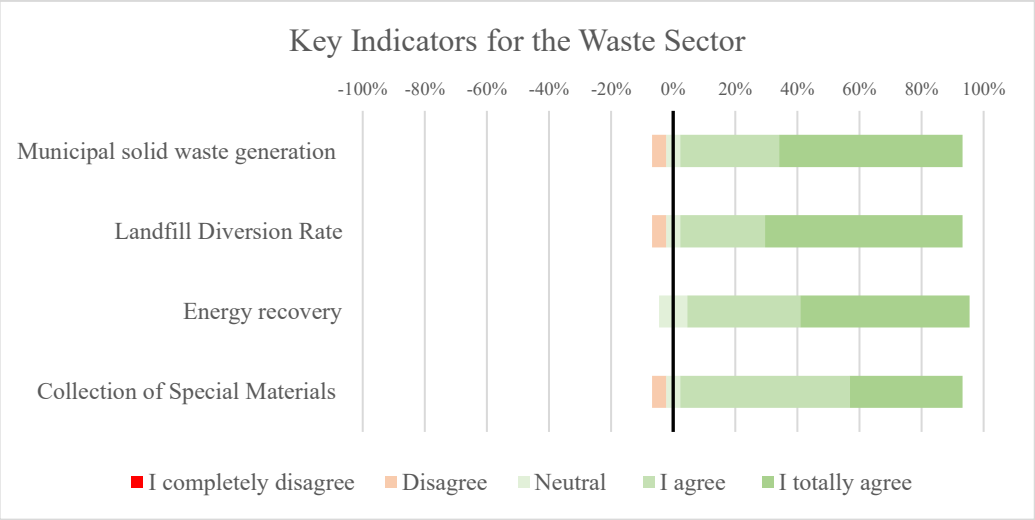


Figure 18 - Degree of agreement on indicators for the key Waste sector.

The indicators for this key sector showed a high level of agreement (the sum of "agree" and "strongly agree"), at around 91% across all indicators. Nevertheless, the experts made relevant comments. They suggested that the waste generation indicator be calculated per capita (per capita waste generation), an adjustment incorporated into the final set.

Another suggestion was to change the calculation method for the "landfill diversion rate" indicator and to include specific indicators for the total amount of materials repaired and reused. One of the experts also pointed out that energy recovery should not be considered a circular process, but rather a form of waste treatment. The criticism is valid, since studies on circular economies indicate that energy recovery is a lower-value action for circularity than waste-non-generation strategies (Dąbrowski *et al*., 2024).

However, the proposed indicator is not limited to thermal energy recovery (incineration) but also encompasses other forms of recovery. The production of biogas from organic waste, for example, can be considered a circular strategy, especially when the byproduct (fertilizer) returns to the soil. Although it should not be prioritized over alternatives such as composting, this practice helps close the biological cycle. Furthermore, biogas production in landfills can generate energy, reduce methane emissions, and decrease fossil fuel consumption.

Thus, monitoring the "Energy Recovery" indicator may be relevant for understanding the evolution of these initiatives. Since this indicator is directly related to energy generation, it was allocated to the Energy key sector, and this change was incorporated into the model.

Table 18 presents the final set of indicators for the Waste Key Sector.

Table 18 - Final set of indicators for the Waste key sector.

Indicator	How to measure	Description
Per capita generation of municipal solid waste	$\frac{\text{Total municipal solid waste generated}^*}{\text{Total population}}$ * Municipal solid waste is defined as waste generated by residential, commercial, and service activities in cities. Unit: kg/capita/day	Measures the amount of waste generated in an urban area. This information is strategic for evaluating the effectiveness of circular economy initiatives aimed at reducing waste generation.
Landfill diversion rate	$\frac{\text{Total waste generated} - \text{Waste sent to landfills}}{\text{Total waste generated}} \text{x } 100 \ [\%]$	This indicator allows for monitoring the proportion of materials not sent to landfills. This information is strategic for assessing the level of resource recovery from waste.
Special materials collected.	Total quantity of special materials* collected that were properly disposed of in accordance with environmental regulations. * The following materials are considered special: electrical and electronic equipment, textiles, batteries, furniture, etc. Unit: t.	Measures the quantity of special materials collected that were properly disposed of in accordance with environmental regulations.
Quantity of materials with extended life cycles.	Quantity of materials reused or repaired through circular economy initiatives. *Examples of circular initiatives include repair centers, repair cafés, Unit: units of materials.	Measures the amount of products or materials that remain in use through strategies such as repair, reuse, refurbishment, or remanufacturing.
Recycling rate	$\frac{\text{Waste sent for recycling}}{\text{Total waste generated}} \text{x} 100 \ [\%]$	Measures the amount of waste sent for recycling and reintroduced into the production cycle.
Number of repair or reuse centers	Number of centers for the reuse and repair of products and materials. Unit: number of centers	Measures the availability of spaces for repair and reuse (repair cafés, stores offering repair services, reuse and repair centers).

It is worth noting that the indicators selected for the key sector aim to go beyond traditional approaches, incorporating not only waste management metrics but also indicators related to prevention, reuse, and the extension of materials' life cycles. Thus, the set of indicators proposed for the Waste Key Sector allows not only monitoring waste management but also for evaluating the transition to more circular practices, including strategies for prevention, reuse, and the extension of material lifecycles.

6.3.2 Indicators for the Key Sector: Agriculture and Food (Component 2)

The indicators for the Agriculture and Food key sector that were selected and underwent the validation process with experts were:

1. Food waste: amount of food discarded (restaurants, supermarkets, markets, etc.).
2. Organic waste sent for composting: amount of organic waste sent for composting.
3. Consumption of locally produced food: amount of food produced and sold locally.
4. Areas designated for food production: total area designated for production (community gardens, green roofs, etc.).

All indicators achieved a concordance rate of over 70%. The "Food waste" indicator showed 81.82% agreement; "Organic waste destined for composting," 86.36%; "Consumption of locally produced food," 77.27%; and "Areas designated for food production," 81.82%. Figure 19 presents the results of the expert consultation for this sector.

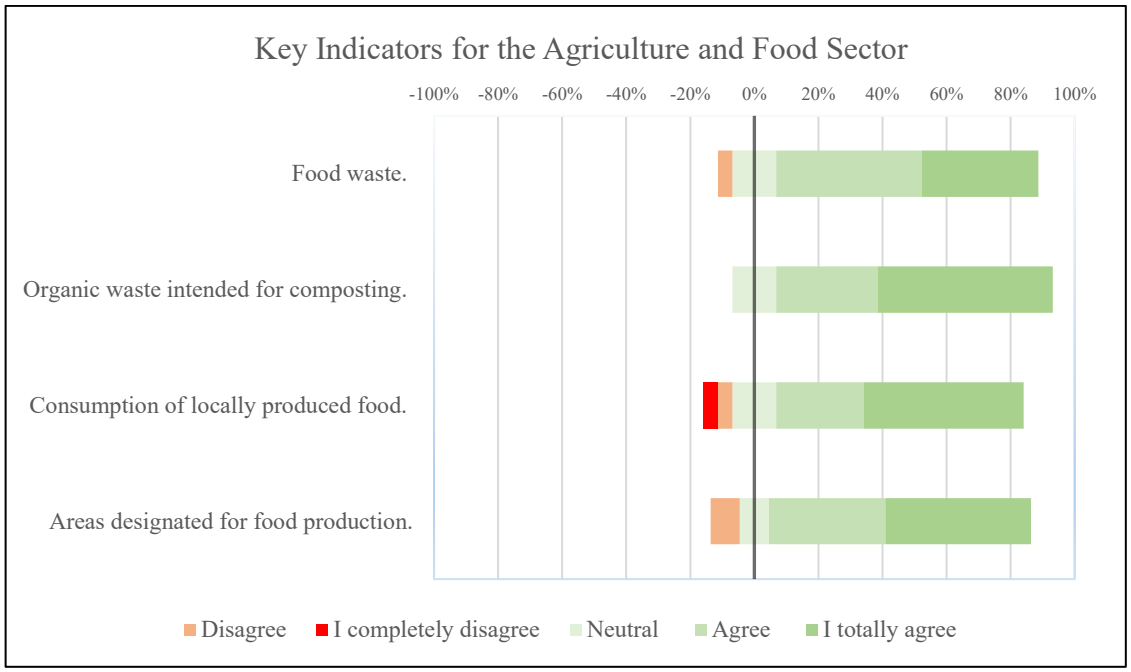


Figure 19 - Degree of agreement on indicators for the Agriculture and Food key sector

Regarding the "Food waste" indicator, experts pointed out the need to refine its definition, noting the potential for double counting with the organic waste indicator. In response, the indicator was adapted to focus on waste in retail and food services, considering only food fit for human consumption that was not sold. Thus, organic waste, such as peels and food scraps, was excluded.

The “Consumption of locally produced food” indicator, which had the lowest agreement rate, received suggestions for adjusting its measurement method. The evaluators pointed out the need for greater clarity regarding its relationship to circularity and the calculation method; these changes were incorporated. Additionally, the potential difficulty in obtaining data for this key sector was highlighted.

The set of indicators for the Agriculture and Food key sector is presented in Table 19. In general, the indicators for the Agriculture and Food key sector aim to incorporate territorial and regenerative aspects of urban circularity, enabling not only the monitoring of organic waste management but also the assessment of circular practices associated with food production and consumption at the local level.

Table 19- Final set of indicators for the Agriculture and Food Key Sector.

Indicator	How to measure	Description
Food waste	Amount of food discarded in commercial establishments. * Establishments: food retail (supermarkets, farmers’ markets, produce stores, etc.) and food service (cafés, restaurants, etc.). * Only food suitable for consumption is quantified Unit: t.	Measures the amount of food fit for human consumption that is unsold and discarded in supermarkets, restaurants, cafes, etc. This food waste can be reduced through circular economy initiatives.
Organic waste destined for composting.	Quantity of organic waste collected and sent for composting. Unit: t.	Measures the amount of waste destined for composting and is essential for cities promoting initiatives to close the nutrient cycle.
Consumption of locally produced food using circular practices	$\frac{\text{Local and circularly produced food}}{\text{Total amount of sold food}} \text{x}100\ [\%]$ * Circular production: uses organic compost or natural fertilizers (recovered nutrients)	Measures the proportion of food consumed in the urban area that is produced locally using circular practices (such as composting, organic inputs, or nutrient recycling).
Areas designated for food production.	$\frac{\text{Total food production area}}{\text{Total municipal area}} \text{x}100\ [\%]$ * Areas designated for food production include: urban and community gardens, productive green roofs, and small farms located within the municipal territory	Measures the availability of areas designated for food production within the municipal territory that can be transformed into circular food production systems.

6.3.3 Indicators for the Key Sector: Local Production and Industry (Component 2)

The indicators for the Local Production and Industry sector that were selected and underwent the validation process with experts are:

1. Energy savings: the amount of energy saved through circular initiatives.
2. Percentage of industries involved in industrial symbiosis: number of industries participating in symbiosis practices.
3. Industrial solid waste generation: the amount of waste generated by industries.
4. Industrial water reuse rate: amount of water reused.

The indicators "Percentage of industries involved in industrial symbiosis," "Industrial solid waste generation," and "Industrial water reuse rate" achieved high agreement rates, all above 80%. The "Energy savings" indicator, in turn, showed 72.73% agreement, which is not low enough to warrant its exclusion but does indicate the need for adjustments to its application.

Figure 20 presents the results of the validation of the indicators for this sector.

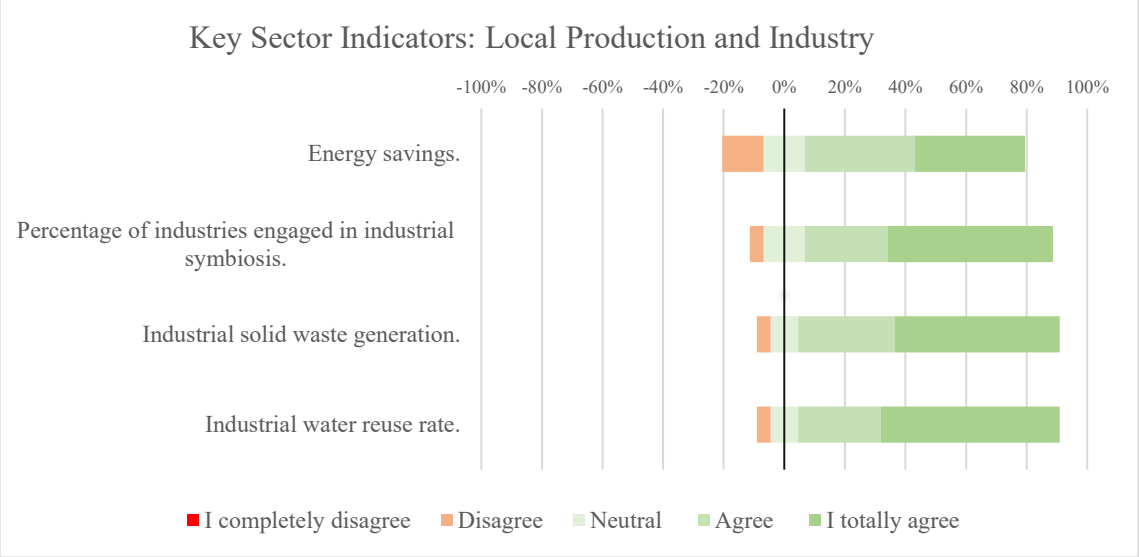


Figure 20 - Degree of agreement of the indicators - Local Production and Industry.

Regarding the "Percentage of industries involved in industrial symbiosis" indicator, one expert noted that it does not specify the intensity or effectiveness of the symbiosis. To address this gap, the "Total resources exchanged through industrial symbiosis" indicator was added and is also described in Table 20.

Table 20 - Final set of indicators for the Key Sector: Local Production and Industry.

Indicator	How to measure	Description
Energy savings.	Average energy consumption before the action − Average energy consumption after the action. Unit: MWh	Measures the energy saved in local industries, companies, or production systems resulting from implementing circular actions.
Percentage of industries involved in industrial symbiosis.	$\frac{\text{Industries in industrial symbiosis}}{\text{Total number of industries}} \text{x}100\ [\%]$	Measures the progress of industrial symbiosis initiatives and circular partnerships in the analyzed territory.
Generation of industrial solid waste.	Total amount of solid waste generated by industrial activities in the territory. Unit: t.	Measures the amount of waste generated by industrial activities, enabling assessment of resource efficiency and monitoring the adoption of circular practices for reducing, reusing, and recovering materials.
Total resources exchanged through industrial symbiosis	Total quantity of materials transferred between industries through industrial symbiosis initiatives in the municipality.	Measures the amount of resources exchanged between industries through industrial symbiosis.
Industrial water reuse rate.	$\frac{\text{Amount of reused water}}{\text{Total water demand}} \text{x}100\ [\%]$	Measures the proportion of water used in local industrial and production processes that is reused in productive activities.

Regarding the “Energy savings” indicator, the experts highlighted the difficulty of obtaining reliable data from local industries and companies, as well as the need to better define its measurement method and specify what would be considered a circular initiative. Thus, the indicator was adapted based on the experts’ suggestions, with its final version presented in Table 20.

In general, the indicators for the Local Production and Industry key sector enable assessment of the incorporation of circular practices into local production systems, considering not only resource efficiency but also inter-industry cooperation, the closing of material cycles, and energy recovery.

6.3.4 Indicators of the Key Sector Energy (component 2)

The indicators for the “Energy” Key Sector that were selected and underwent the validation process with experts were:

1. Total energy demand: total amount of energy consumed in the territory.
2. Share of renewable energy in total consumption: proportion of renewable energy relative to total consumption.
3. Renewable energy generation potential: capacity for renewable energy generation within the territory.

The indicators for the "Energy" key sector showed agreement levels ranging from 81.82% to 95.45%, as shown in Figure 21.

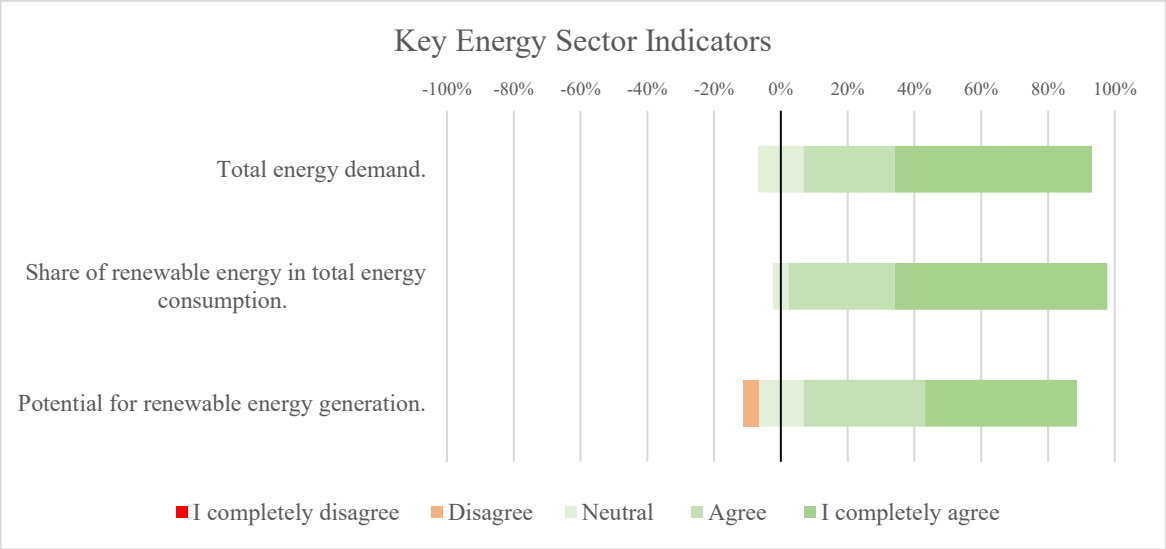


Figure 21 - Degree of agreement for the indicators of the Key Sector: Energy.

Regarding the "Total Energy Demand" indicator, experts cautioned against using values already accounted for in the "Local Production and Industry" sector. Thus, it was decided that energy demand would be calculated by considering consumption in the residential, commercial, street lighting, and public sectors. Although this indicator, on its own, does not provide direct information on the results of these actions, it was retained as it represents a baseline metric, useful for future analyses. It is worth noting that the indicator initially named "Total Energy Demand" was renamed "Total Energy Consumption" to ensure greater conceptual clarity and alignment with the measurement method adopted.

Regarding the indicators related to renewable energy ("Renewable Energy Generation Potential" and "Share of Renewable Energy in Total Energy Consumption"), the experts highlighted the difficulty of obtaining data for their measurement, especially in the Brazilian context. Nevertheless, the indicators were retained, as they are relevant for understanding the transition toward a more sustainable and locally sourced energy mix.

In addition, the inclusion of the "Public lighting" indicator was suggested, which aims to assess the replacement of light bulbs with more efficient and sustainable technologies, a circular action identified in the cities analyzed. As mentioned earlier, the indicator for energy generation from solid waste was transferred to this key sector.

The final indicators for evaluating the sector are presented in Table 21. Overall, the indicators for the Energy key sector allow for the assessment of the transition to more sustainable energy systems, considering not only consumption and the diversification of the energy mix, but also the adaptation of urban structures to reduce consumption and the use of renewable sources within the territory.

Table 21 - Final set of indicators for the Energy Key Sector.

Indicator	How to measure	Description
Total energy consumption	Sum of energy consumed by the residential, commercial, and public sectors, and by street lighting. Unit: MWh	Measures the total amount of energy consumed in the municipality's urban area, including the residential, commercial, street lighting, and public sectors.
Share of renewable energy in total energy consumption	$\frac{\text{Renewable energy consumed}}{\text{Total energy consumed}} \text{x} 100 \ [\%]$ * Renewable energy: solar, wind, and energy from waste-to-energy.	Measures the share of renewable energy sources relative to total energy consumed in the urban area.
Renewable energy generation potential	Amount of MWh that can be generated from renewable sources* *Potential for solar energy + potential for wind energy + potential for energy generation from waste) Unit: MWh	Measures the potential for renewable energy generation in the territory.
Street lighting	$\frac{\text{Number of lamps changed}}{\text{Total number of lamps}} \text{x} 100 \ [\%]$	Measures the proportion of streetlights in the public lighting network that have been replaced with more efficient and sustainable technologies.
Energy recovery from waste	(Energy generated from waste recovery)/(Total energy generation capacity from waste) x 100 [%]	Measures the amount of energy generated from the utilization of municipal solid waste (incineration, landfill gas, anaerobic digestion, and pyrolysis).

6.3.5 Indicators for the Key Sector Mobility and Transportation (Component 2)

The indicators for the "Mobility and Transportation" Key Sector that were selected and underwent the validation process with experts were:

1. Fuel type of the fleet: proportion of each fuel source in the fleet.
2. Mode of transport: proportion of each mode in total trips (car, motorcycle, bus, subway, bicycle, walking, etc.).
3. Public transportation use: number of residents who use public transportation daily.
4. GHG emissions in the mobility and transportation sector: total amount of emissions associated with urban mobility.

The indicators for this sector showed a concordance index ranging from 81.82% to 95.45%, as shown in Figure 22.

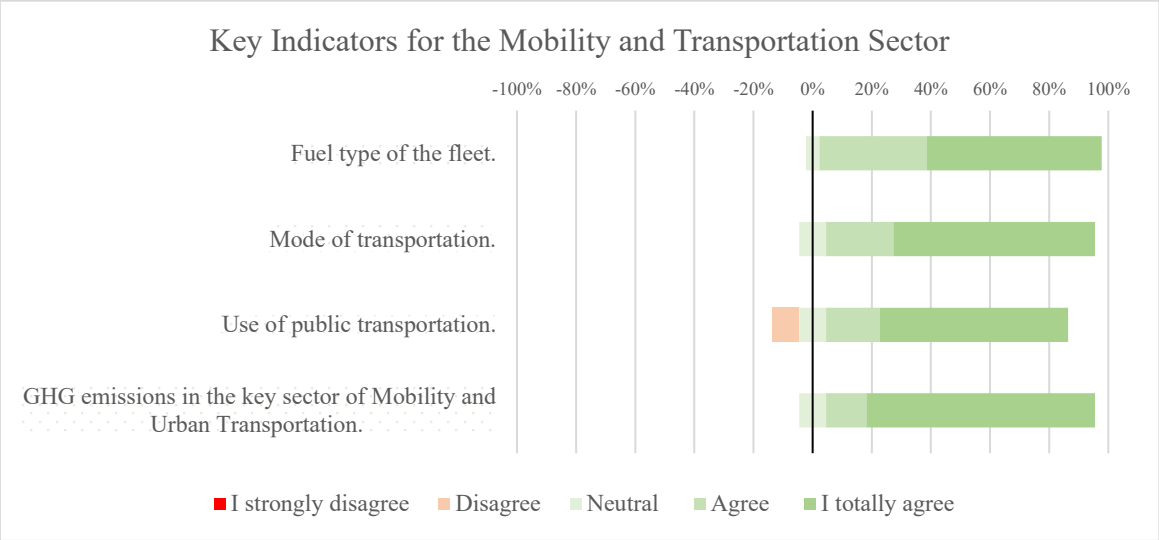


Figure 22 - Degree of agreement among indicators in the Mobility and Transportation Key Sector.

Regarding the "Fleet fuel type" indicator, experts expressed concern about the availability of urban-level data and noted that it would be useful to include bicycle use in the transportation assessment. Consequently, the "Mode of transportation" and "Public transportation use" indicators were consolidated into the "Sustainable modes of transportation" indicator, described in Table 22.

Table 22 - Final set of indicators for the Mobility and Transportation Key Sector.

Indicator	How to measure	Description
Fuel type of the fleet	Percentage of each fuel source relative to the total fleet [%]	Allows monitoring of whether the urban area is transitioning to lower-impact fuels for its fleet.
Sustainable modes of transportation	$\frac{\text{Number of sustainable trips}}{\text{Total number of trips}} \text{ x } 100$ [%] *Modes with lower environmental impact, such as low-emission public transit, bicycles, and shared mobility options	Measures trips made using sustainable modes of transport, such as public transit, bicycles, and shared mobility.
Particulate matter emissions in the Mobility and Transportation key sector.	Number of buses × distance traveled × particulate matter emission factor. *Focused on buses due to data availability. Unit: t/year	Measures the amount of particulate matter emitted by urban mobility and transportation activities.
GHG emissions in the Urban Mobility and Transportation key sector.	Total GHG emissions in the sector. Unit: tons of CO2 equivalent.	Measures GHG emissions from the key sector of Mobility and Transportation and allows for an analysis of whether circular initiatives are reducing such emissions.

The experts also suggested including indicators related to particulate matter emissions in the mobility and transportation sector. This indicator was adapted for public transportation vehicles (buses) and included in the sector's final set of indicators, as presented in Table 22.

In general, the indicators for the key sector of Mobility and Transportation enable an assessment of the transition to more sustainable mobility systems, including emissions reductions, the adoption of lower-impact transportation modes, and improvements in environmental quality within the urban area.

6.3.6 Key Sector "Water and Sanitation" Indicators (Component 2)

The indicators for the "Water and Sanitation" key sector that were selected and underwent the validation process with experts were:

1. Water consumption: total volume consumed in the territory.
2. Percentage of treated wastewater: proportion of treated wastewater relative to the volume consumed.
3. Water losses: amount lost due to urban leaks.
4. Water reuse: total volume reused within the territory.

Regarding the experts' opinions on the indicators selected for the sector, the degree of agreement ranged from 86.36% to 100%. Figure 23 presents the results of the expert consultation for the Key Sector Water and Sanitation.

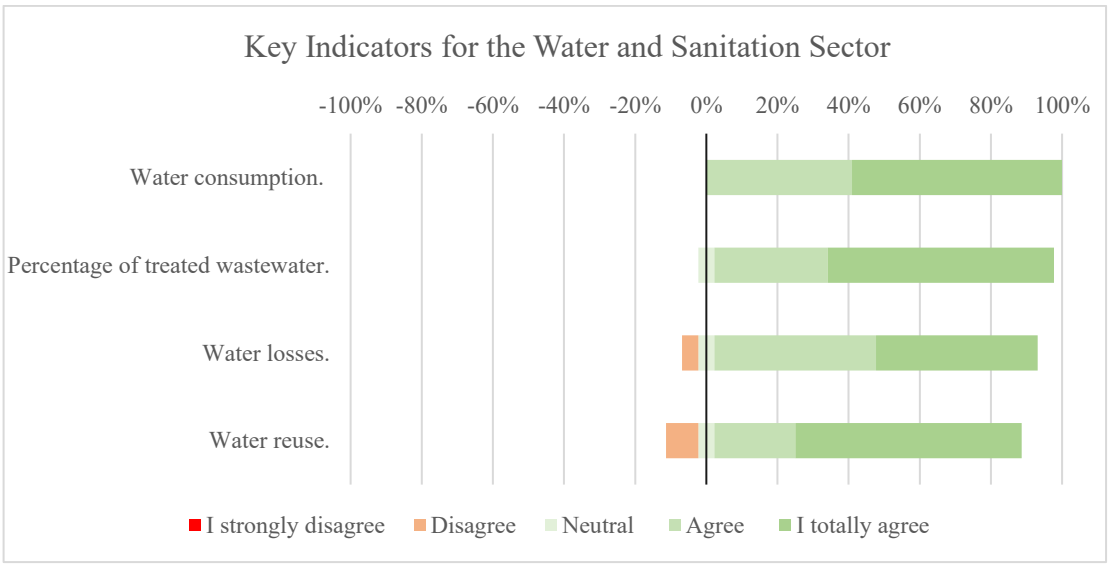


Figure 23 - Degree of agreement on indicators for the Water and Sanitation Key Sector.

The indicator that achieved 100% agreement was "water consumption," highlighting its relevance for understanding water resource usage patterns in the territory. In the context of urban circularity, this indicator is fundamental, as it allows for the assessment of pressure on the water cycle and the identification of opportunities to implement circular strategies in the sector. Despite this, it was suggested that per capita water consumption be considered.

Regarding the indicator "Percentage of treated wastewater," experts noted that it did not reflect circularity, as it assessed only water treated and returned to the environment. Consequently, it was adapted to "Reuse rate of treated wastewater."

The "Water Losses" indicator, it was suggested to specify the type of loss, which was incorporated as an adjustment. Additionally, it was suggested to include the "Water Quality Index" indicator in the environmental dimension and the "Nutrient recovery rate from sludge" in this key sector, as shown in Table 23.

Table 23 - Final set of indicators for the Water and Sanitation Key Sector.

Indicator	How to measure	Description
Annual per capita water consumption	$\frac{\text{Total annual water consumption}}{\text{Total population}}$	Measures the average annual water volume consumed per resident in the municipality's urban area.
Treated wastewater reuse rate	$\frac{\text{Treated and reused wastewater}}{\text{Total treated wastewater}} \text{x100 [\%]}$	Measures the proportion of treated wastewater reused within the urban area, such as for irrigation, industrial uses, street cleaning, or other non-potable purposes, thereby contributing to the circularity of water use.
Water losses in the distribution network	$\frac{\text{Water lost in the distribution network}}{\text{Total distributed wastewater}} \text{x100 [\%]}$ * Water losses may include leaks in pipes and reservoirs.	Measures the proportion of water lost in the urban water supply system due to leaks in the distribution network, unauthorized connections, or metering failures.
Rainwater reuse rate	$\frac{\text{Rainwater collected and reused}}{\text{Total water consumption}} \text{x100 [\%]}$	Measures the proportion of municipal water use that comes from rainwater harvesting and reuse systems.
Nutrient recovery rate from sludge	$\frac{\text{Amount of sludge with nutrient recovery}}{\text{Total amount of sludge}} \text{x100 [\%]}$	Measures the proportion of sludge generated at wastewater treatment plants that undergoes nutrient recovery processes.

In general, the indicators for the key sector Water and Sanitation allow for the assessment of the transition to more circular sanitation systems, considering not only water consumption and efficiency but also reuse, loss reduction, and the recovery of resources, such as nutrients, throughout the urban system, thereby contributing to ensuring the sustainable use of water resources.

6.3.7 Indicators for the Key Sector Space and Built Environment (component 2)

The indicators for the key sector Space and the Built Environment that were selected and have undergone the validation process are:

1. Buildings designed for disassembly: number of modular buildings that can be disassembled.
2. Waste generated: amount of construction and demolition waste.

3. Recycling and reuse of construction waste: amount of waste reused or recycled.
4. Vacancy rate: number of vacant properties.
5. Sustainable buildings: number of buildings with sustainable initiatives.
6. Green spaces: proportion of urban area occupied by green spaces.
7. Urban extent: total area of the urban territory.

The indicators for the key sector Space and Built Environment showed a degree of agreement ranging from 72.73% to 90.91%, with the lower values indicating the need to reassess some indicators. Figure 24 presents the results of the expert consultation.

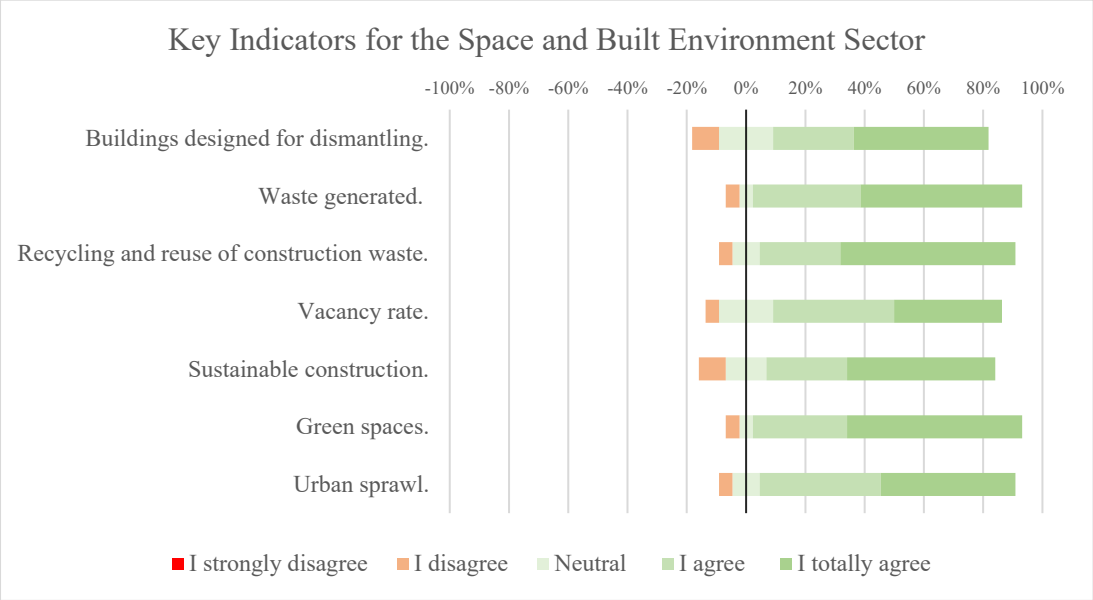


Figure 24 - Degree of agreement for the indicators of the Space and Built Environment key sector.

The variation in the degree of agreement is related to the sector's complexity, given that circularity involves both material aspects (generated waste) and spatial aspects, such as land use, infrastructure location, and resource stocks in the built environment. Thus, the divergence among experts may reflect different interpretations regarding the role of the key sector and which circular practices can be effectively implemented.

Regarding the indicator "Buildings designed for disassembly," experts noted that, in addition to design, it would be necessary to measure material reuse. To address this suggestion, the indicator "Reuse of materials from modular buildings" was added, as described in Table 24.

Table 24 - Final set of indicators for the Space and the Built Environment key sector.

Indicator	How to measure	Description
Buildings designed for dismantling	Total number of buildings designed for dismantling. Unit: number	Measures the number of modular buildings designed for disassembly, which enable the recovery of components and materials at the end of the building's useful life.
Reuse of materials from modular buildings	$\frac{\text{Reused materials from modular buildings}}{\text{Materials from modular buildings}} \text{x100 } [\%]$	Measures the proportion of materials recovered during the dismantling of modular buildings that are reused or recycled.
Waste generated	Total solid waste generated during construction and demolition processes. Unit: t.	Measures the amount of waste generated and is essential for assessing the impact of circularity initiatives in reducing it.
Recycling and Reuse of Construction Waste	$\frac{\text{Reused construction waste}}{\text{Total construction waste}} \text{x100 } [\%]$ *Reused waste: recycling, reuse, repair.	Measures the percentage of construction and demolition waste reused through repair, recycling, and other means.
Vacancy rate of residential properties	$\frac{\text{Number of vacant residential properties}}{\text{Number of residential properties}} \text{x100 } [\%]$	Measures the percentage of vacant residential properties relative to the total number of residential properties in the municipality, indicating the level of utilization of the urban housing stock.
Adaptive reuse	Number of buildings that have undergone adaptive reuse in the municipality.	Measures the number of buildings whose original function has been altered through adaptive reuse, repurposing the existing built stock for new uses.
Buildings with sustainable construction certifications	$\frac{\text{Buildings with sustainability certifications}}{\text{Total number of buildings in the territory}} \text{x100 } [\%]$	Measures the percentage of buildings that hold recognized sustainability certifications.
Green spaces	$\frac{\text{Total of green areas}}{\text{Total area of the territory}} \text{x100 } [\%]$ *Green spaces: squares, parks, conservation areas, etc.	Measures the percentage of green spaces in the urban area (squares, parks, conservation areas).

Regarding the “Waste generated” indicator, particularly in the Brazilian context, the difficulty of obtaining reliable data was noted, as it depends largely on self-reporting by construction companies. The same applies to the “Recycling and reuse of construction waste” indicator. For the “Vacancy rate” indicator, it was suggested to specify that it refers to residential properties.

The “Adaptive reuse” indicator was included to assess properties adapted for new functions, reflecting strategies that extend the useful life of buildings, reduce new construction, and avoid additional consumption of materials and urban land. Regarding the “Sustainable Buildings” indicator, experts suggested using data on certified buildings. Thus, it was adapted to “Buildings with sustainable practices certification.”

It was also suggested that the “Green Areas” indicator be transferred to the environmental dimension. However, it was retained in this key sector because it enables monitoring of nature regeneration practices in urban spaces. Finally, the “Urban Extension” indicator was excluded because its information is already captured indirectly by other indicators.

Despite the set of indicators proposed for this key sector, measuring all aspects of circularity in the built environment remains challenging. The literature does not yet offer indicators that can comprehensively capture the stocks of resources available in cities, especially those incorporated into buildings, infrastructure, and other elements of the built environment.

These materials remain incorporated into the urban structure and can represent important sources of secondary resources for future use. However, existing approaches and indicators focus on analyzing material flows, neglecting those that remain “stockpiled” in the built environment (Wandl *et al*., 2023). This limitation is also present in the proposed set of indicators.

In general, the indicators for the Space and the Built Environment key sector enable assessment of the incorporation of circular practices into the built environment, including waste reduction, material reuse, optimization of the use of the built stock, and the regeneration of urban spaces.

6.3.8 Environmental Dimension Indicators (component 3)

The selected Environmental Dimension indicators that have undergone the validation process are:

1. GHG emissions: total amount emitted in the urban area.
2. Air quality: annual average concentration of particulate matter.
3. Water quality: proportion of samples compliant with national standards.
4. Biodiversity: number of species identified in the territory.

The degree of agreement ranged from 86.4% to 90.9%, as shown in Figure 25.

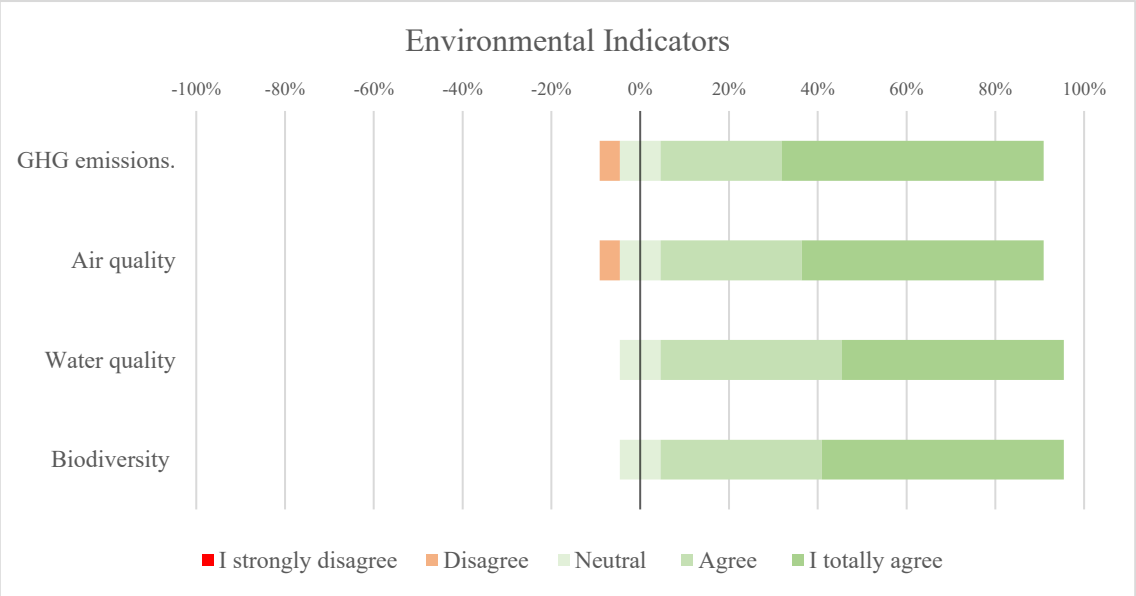


Figure 25 - Degree of agreement for the Environmental Dimension indicators.

Experts suggested including the "Material Footprint," "Land Footprint," and "Water Footprint" indicators in the environmental dimension, given their ability to broaden the assessment of urban metabolism impacts and pressure on natural resources across production and consumption chains. These indicators contribute to a more comprehensive understanding of resource use and the impacts associated with urban supply. However, the difficulty of measurement at the local level, especially in Brazilian municipalities, is noteworthy.

The indicators were included and are described in Table 25.

Table 25 - Final set of indicators for the Environmental Dimension.

Indicator	How to measure	Description
GHG Emissions	Total amount of greenhouse gas emissions generated within the territory. Unit: tons of CO_2 equivalent (tCO_2e).	Measures the volume of greenhouse gases emitted by activities within the territory.
Material Footprint	Total amount of primary materials required to meet the city's final consumption, including biomass, fossil fuels, metallic ores, and non-metallic minerals. Unit: tons per capita per year.	Measures the total amount of material resources mobilized across production chains to sustain consumption patterns within the territory.
Land Footprint	Total land area required to sustain the city's consumption activities, including food production, raw materials, and infrastructure. Unit: hectares per capita per year	Measures the pressure that urban activities exert on land use, considering the area required to produce the goods and services consumed by the urban population.
Water Footprint	Total volume of freshwater used directly and indirectly to sustain the city's consumption. Unit: m^3 per capita per year	Measures the total volume of freshwater used throughout the production chains associated with urban consumption, accounting for both direct and indirect uses incorporated into the production of goods and services consumed by the population.
Air Quality	Annual average concentrations of particulate matter. Unit: $\mu g/m^3$	Measures the amount of particulate matter (PM2.5 and PM10) in the air of the study area.
Water Quality Index (WQI)	An index calculated from a weighted geometric mean of nine water quality parameters (dissolved oxygen, thermotolerant coliforms, pH, BOD, temperature, total nitrogen, total phosphorus, turbidity, and total solids).	Measures the water quality of water bodies in the urban area using a composite index that integrates physical, chemical, and biological parameters.
Biodiversity	Number of native and non-native species identified in the urban area. Unit: Number of species	Measures the diversity of species present in the urban area, distinguishing between native and non-native species.
Soil quality	The soil quality index is calculated based on physical, chemical, and biological soil parameters. * It is recommended to use the soil quality index adopted by the competent local authority, depending on the availability of data and methodologies applicable to the analyzed territory.	Measures soil conditions in urban areas using physical, chemical, and biological parameters, such as pH and organic matter content.

The “Water Quality” indicator was replaced by the “Water Quality Index” in accordance with recommendations from the assessment of the Water and Sanitation key sector. Regarding the “Biodiversity” indicator, experts suggested distinguishing between native and non-native species. The inclusion of an indicator to measure soil quality was also recommended.

Although this study recommends monitoring the set of environmental indicators presented in Table 25, it is important to note that, taken in isolation, they do not comprehensively capture (beyond the municipal territory) all the environmental impacts of circular initiatives. Indicators calculated from municipal data are not always the most appropriate for this assessment. In this regard, Kopp *et al*. (2024) highlight the difficulty of measuring impacts that occur outside the municipal territory, especially those related to the resource footprint and global production and consumption chains.

In general, indicators of the environmental dimension seek to assess the impacts of urban circularity initiatives on natural ecosystems, considering not only emissions and the quality of natural resources but also the pressure on natural systems.

6.3.9 Social Dimension Indicators (Component 3)

The selected Social Dimension indicators that have undergone the validation process are:

1. Jobs: jobs created or lost due to circular initiatives.
2. Job quality: jobs are of high quality and ensure decent social conditions.
3. Inclusion of informal workers: rate of formalization of workers from the informal sector.
4. Resident satisfaction: percentage of the population that considers they have a good quality of life in the urban area.
5. Access to urban infrastructure: percentage of the population without access to urban services
6. Access to housing: proportion of the population with access to quality housing
7. Population and urban density: number of inhabitants per urban area
8. Public participation: percentage of the population that participated in circular economy initiatives

9. Public awareness: proportion of the population reached by educational campaigns on urban circularity.

The social indicators showed agreement ranging from 72.73% to 90.91%. This variation can be explained by the difficulty of measuring the social impacts of circularity, as discussed in Chapter 2 and Section 6.2. Furthermore, studies indicate that many urban circularity strategies do not yet adequately incorporate social issues, a finding also reflected in the academic literature (Vanhuyse *et al*., 2021).

The results of the expert consultation are presented in Figure 26.

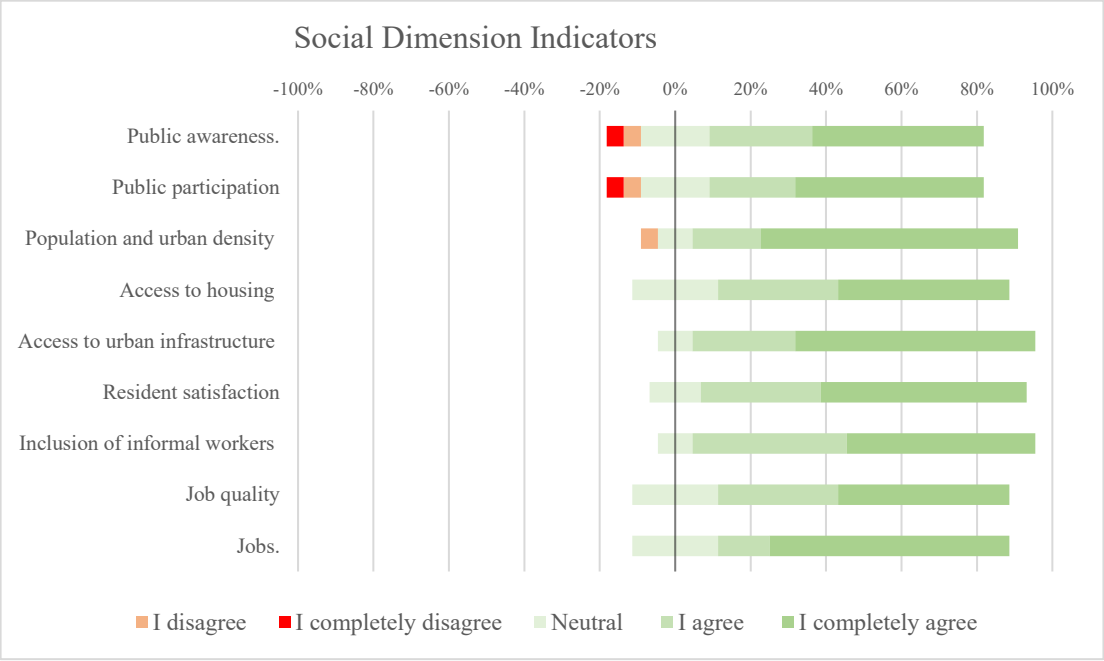


Figure 26 - Degree of Agreement on Social Dimension Indicators.

Regarding the "Jobs" indicator, experts suggested emphasizing that these are jobs generated by circular initiatives, an adjustment that was incorporated. Additionally, the importance of considering negative impacts was highlighted, leading to the inclusion of the "Job Loss" indicator, as presented in Table 26.

Regarding the "Job Quality" indicator, experts highlighted the difficulty of defining what constitutes a "quality job." Thus, the measurement was adapted to "formal employment," considering that many jobs associated with circular initiatives are informal, low-paying, and, in some cases, voluntary (Vanhuyse *et al*., 2021).

Table 26 - Final set of indicators for the Social Dimension.

Indicator	How to measure	Description
Jobs	Number of jobs created by circular initiatives. Unit: number.	Measures the impact of circular actions on job creation in the region.
Job Loss	Number of formal jobs lost due to circular initiatives.	Measures the reduction in job numbers resulting from the implementation of circular initiatives.
Formal employment in circular initiatives	$\frac{\text{Formal jobs in circular initiatives}}{\text{Jobs in circular initatives}} \text{x}100 \ [\%]$	Measures the number of formal jobs created relative to the total number of jobs created by circular initiatives.
Inclusion of waste pickers in the formal recycling sector	$\frac{\text{Waste pickers in the formal recycling sector}}{\text{Total number of waste pickers}} \text{x}100 \ [\%]$	Measures the proportion of recyclable material waste pickers who previously worked informally and have transitioned to formal employment through circular economy initiatives, such as cooperatives, associations, contracts with government agencies, or recycling companies.
Resident satisfaction	Percentage of the population satisfied with the results of the circular strategy's implementation [%].	Measures the population's level of satisfaction with the implementation of the circular strategy.
Public participation in developing the circular strategy	Percentage of the population that participated in developing the circular strategy through workshops, public consultations, hearings, and similar activities.	Measures the population's participation in developing the urban area's circular strategy.
Public engagement	$\frac{\text{Annual number of people in circular actions}}{\text{Total population}} \text{x}100 \ [\%]$	Measures the percentage of the population that participated in circular initiatives within the territory.
Urban density	$\frac{\text{Number of inhabitants}}{\text{Total urban area}}$ Unit: inhabitants/km²	Measures urban density; the information this indicator provides is essential for urban planning.

Regarding the “Inclusion of informal workers” indicator, the superficiality of the term “inclusion” was questioned. Despite its relevance, particularly for waste pickers in Brazil, the indicator was adapted to focus on waste-collection workers.

For the “Resident satisfaction” indicator, it was suggested to consider satisfaction following the implementation of the circular strategy; this adjustment was incorporated. The “Access to infrastructure” indicator, however, was excluded due to the difficulty of capturing the population’s access to all of the urban infrastructure.

Regarding the “Access to Housing” indicator, experts noted the difficulty of simultaneously measuring the housing shortage, housing quality, and access to public services, which led to its exclusion. The difficulty of measuring “Public Awareness” was also highlighted, and the indicator was adapted to “Public Engagement in Circular Initiatives.” It should be noted that this indicator alone does not capture the public’s level of knowledge, necessitating the development of new indicators.

Finally, the “Public Participation” indicator was adapted to “Public Participation in the Development of the Circular Strategy” because it better reflects the information considered relevant. Effective public participation is strategic, as it aligns the strategy with the public’s aspirations and fosters future buy-in.

In general, the indicators of the Social Dimension enable assessment of the impacts of urban circularity initiatives on society, including job creation, social inclusion, public participation, and engagement in circular actions. These aspects are fundamental for building a just and inclusive circular transition in the region.

6.3.10 Economic Dimension Indicators (Component 3)

The Economic Dimension indicators selected and validated are:

1. Investment in circular initiatives: total monetary value invested in circular actions
2. Capital generated through circular initiatives: financial return from urban circularity actions
3. Average per capita income: impact of circular actions on the population’s average per capita income.

Consultation with experts revealed that the indicators showed agreement ranging from 86.36% to 90.91%, as shown in Figure 27.

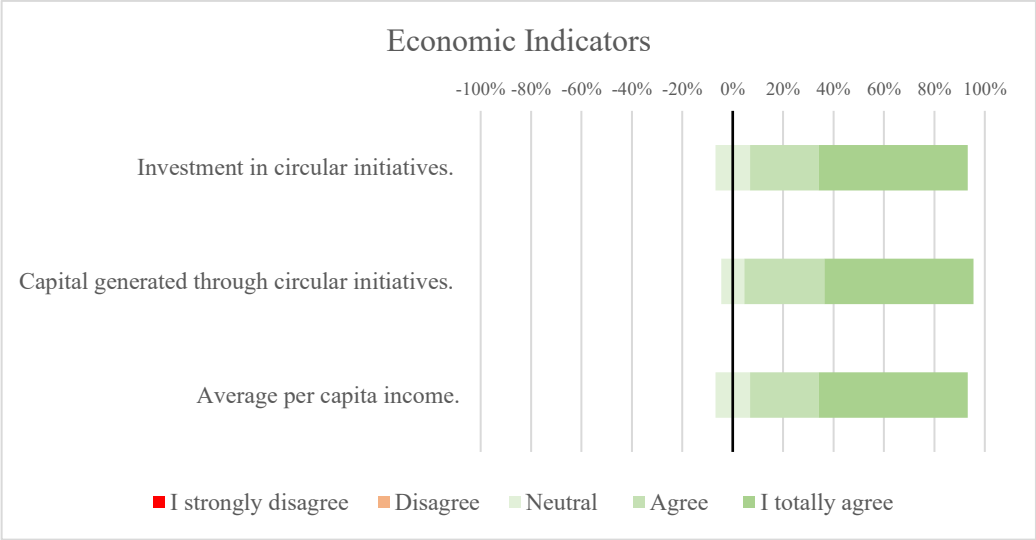


Figure 27 - Degree of agreement among the indicators of the Economic Dimension.

The experts pointed out the need to adjust the "Investment in circular initiatives" indicator by specifying the source of funds, a change that was incorporated. Regarding the "Average per capita income" indicator, they highlighted the difficulty of attributing direct impacts of circularity on the population's income. Thus, the indicator was adapted to focus on people employed in circular initiatives, comparing income before and after entering this type of activity.

Finally, it was suggested that the indicator "Share of the circular economy in the local economy" be included to assess the impact of these initiatives on the local economy. The set of indicators for the economic dimension is presented in Table 27.

Table 27 - Final set of indicators for the Economic Dimension.

Indicator	How to measure	Description
Investment in circular initiatives	Total public and private investments allocated to implementing or expanding circular initiatives in the municipality. Unit: local currency	Measures investment in circular initiatives, which is crucial for managers to develop circular transition projects based on available resources.
Capital generated through circular initiatives	Economic value (revenue) generated by local circular initiatives. Unit: local currency.	Measures the financial impacts of circular initiatives.
Average income of people employed in circular initiatives	Average income after entering circular employment − average income before entering circular employment.	Measures the difference between the average income of people before and after their placement in jobs associated with circular initiatives.
Share of the circular economy in the local economy	$\frac{\text{Circular economy product}}{\text{Municipal GDP}} \text{x100 [\%]}$	Measures the percentage of the city's GDP generated by circular-economy-related activities.

In general, the indicators of the Economic Dimension allow for the assessment of the impacts of urban circularity initiatives on the local economy, considering the volume of investments, the generation of economic value, the income associated with circular activities, and the circular economy's share of the local economy, thereby contributing to an understanding of the role of circularity in urban economic development.

Thus, the final set of indicators was obtained. It should be noted that the selection was not based solely on frequency of occurrence in the literature, but on their alignment with the objectives of the proposed tool, while also considering the limitations identified in studies on urban circularity indicators. Expert validation enabled refinement of the set, resulting in consistent, applicable indicators aligned with the study's proposal.

The results obtained in this chapter are summarized in Figure 28. The figure presents the number of indicators proposed for Components 2 and 3 of the *CIRCCITY* artifact. It also shows that the final set comprises 57 indicators: 37 associated with monitoring the key sectors of urban circularity (Component 2) and 20 intended to assess environmental, social, and economic impacts (Component 3).

Key Sector / Dimension	Indicators identified in the literature	Proposed indicators before validation	Proposed indicators after validation
Waste	262	4	6
Agriculture and Food	64	4	4
Local Production and Industry	114	4	5
Energy	137	3	5
Mobility and Transport	117	4	4
Water and Sanitation	115	4	5
Space and Built Environment	228	7	8
Environmental Dimension	261	4	8
Social Dimension	247	9	8
Economic Dimension	218	3	4
Total proposed	—	46	57

Figure 28 - Summary of the Results of Indicator Selection and Validation.

Source: Developed by the author, with the assistance of ChatGPT – OpenAI (2026).

Despite the robustness of the selected set, significant limitations remain, particularly regarding data availability and quality, the measurement of indirect impacts, and the ability to capture systemic dynamics of urban circularity. This limitation is particularly relevant in Brazilian cities, as noted by Moraes *et al*. (2022) in their analysis of waste management indicators in CCs.

Nevertheless, the study makes progress by structuring the indicators into an integrated decision-support system, linking the monitoring of actions in key sectors to the assessment of their impacts on urban sustainability. In this way, it seeks to overcome the fragmented approaches found in the literature and contribute to a more systemic analysis of the circular transition in urban areas, even in the face of recognized limitations.

7. APPLICATION IN SÃO PAULO

This chapter presents the results of applying the CIRCCITY artifact in the city of São Paulo. It also analyzes and discusses the potential for implementing urban circularity across the key sectors.

7.1 The Municipality of São Paulo

São Paulo is a major global metropolis and the fifth-largest city on the planet. In 2022, the city had a population of 11,451,999 and a population density of 7,528.26 inhabitants per square kilometer (IBGE, 2024). The municipality is located in the Southeast region of Brazil and is part of the São Paulo Metropolitan Region, comprising 39 municipalities with which it maintains strong economic and social interdependence. Figure 29 shows the location of the municipality of São Paulo.

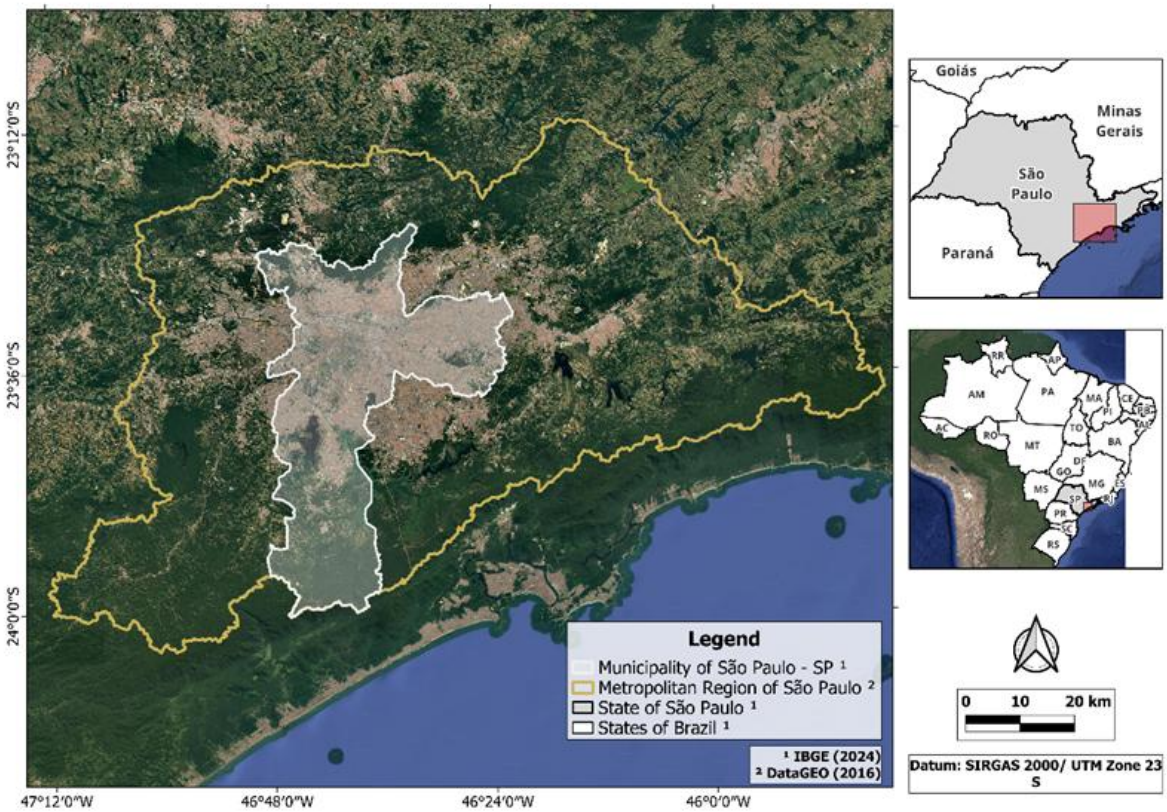


Figure 29 - Location of the municipality of São Paulo.

In social terms, the municipality is marked by socioeconomic inequalities. According to the PMDE - 2022, monthly household income highlights these territorial disparities. While the Alto de Pinheiros district, located in the western zone, is generally considered a higher-income

area, the average monthly income is R$ 9,591.93. In the district of Lajeado, situated in the eastern zone and characterized by greater socioeconomic vulnerabilities, the average household income is R$ 2,016.55. Other indicators, such as life expectancy and access to public services, also show significant variations across the territory (São Paulo, 2022a).

These socioeconomic characteristics of the municipality must be taken into account, as they reflect the environment in which a circular strategy will be implemented and the potential benefits it offers. Given this context, it is evident that São Paulo's circular transition presents challenges different from those observed in the European cities analyzed in this study. This scenario requires the municipality to adapt its approach to urban circularity to its local reality, taking into account its specific socioeconomic and territorial characteristics.

Given the significant socioeconomic disparities faced by São Paulo's population, the social dimension of circularity takes center stage. In this context, the *Guide to Circular and Inclusive Cities*, published by the *Ministry of the Environment* (MMA) in 2025, reinforces the idea that the incorporation of CE principles in Brazil has a social character. The guide also states that, although environmental and economic performance are fundamental to most CE approaches, the social dimensions of circularity are not always explicitly emphasized but must be considered when addressing Brazilian municipalities (MMA, 2025).

Despite its territorial and socioeconomic complexity, São Paulo is considered a pioneer in developing policies focused on urban issues, a trend also evident in circularity initiatives. In 2021, for example, the municipality entered into a strategic partnership with the EMF to develop the *Sampa Circular* project, marking the foundation's first global partnership with a city (EMF, 2021a).

In addition to the *Sampa Circular* project, the City of São Paulo has already received technical support from EMF to develop the food circular economy (EMF, 2021b). These factors reinforce the need to study the development of urban circularity in the municipality, making it an ideal case study for applying the maturity model.

7.2 Maturity Level of the Municipality of São Paulo

The maturity model was applied to the municipality of São Paulo, with the rubric questionnaire answered by the author of this study based on the analysis of plans, data, and information collected from the City Hall's official platforms. The results indicate that the municipality is, for the most part, at Maturity Level 1 (Waste Management), with an average

circularity index of 48,85% across categories. Figure 30 presents the spider chart, created based on the responses to the rubric questionnaire. The rubric questionnaire completed for São Paulo can be accessed at the web address provided in this URL: https://goo.su/9sEDV.

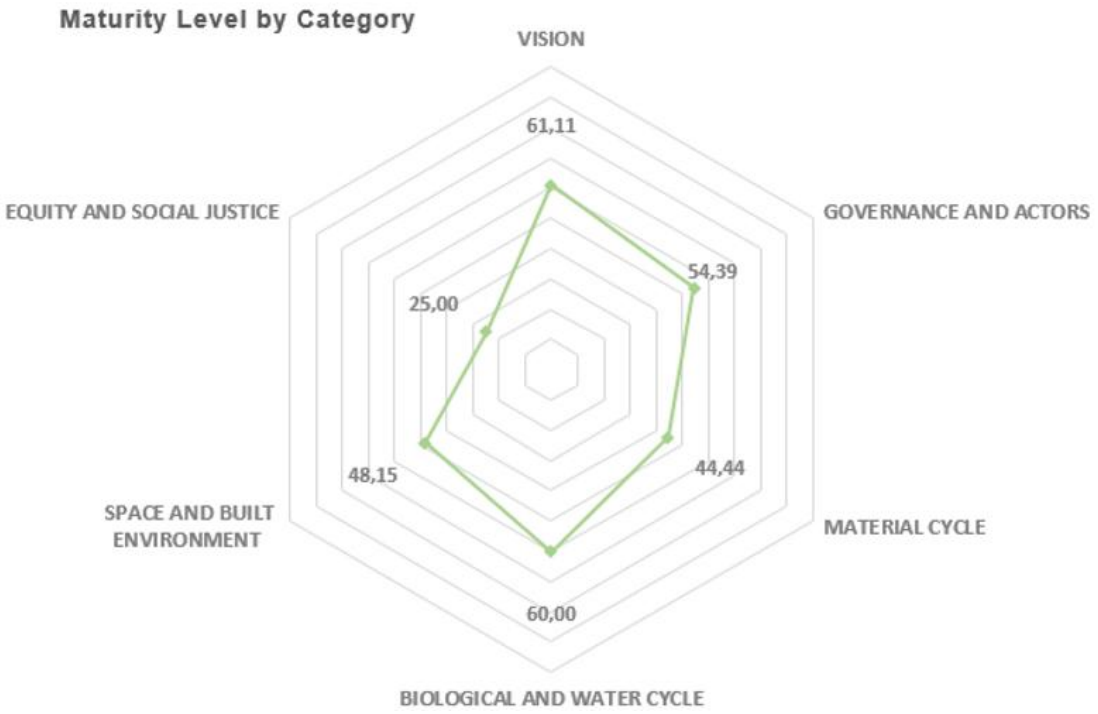


Figure 30 - São Paulo's maturity levels by category.

Upon examining the chart, the highest circularity index was observed in the Vision category, at 61.1%, classified at Level 2 (Circular Economy). This result is mainly because the municipality recognizes that the CE can generate economic benefits and create jobs. The 2022 PMDE highlights this trend by setting the goal of "by 2025, promoting the circular economy in the Municipality of São Paulo, reducing the generation and disposal of municipal solid waste in landfills." According to the document, this goal aims to "create new jobs in the green economy and generate opportunities for entrepreneurship" (São Paulo, 2022a).

São Paulo's PMDE and its goal related to the CE demonstrate a technocentric character, as presented by Calisto Friant *et al*. (2020), since the plan suggests that developing new business models can help reduce the environmental impacts associated with waste. However, this vision, while representing progress compared to an approach focused solely on waste management, still lacks a systemic view of the territory that considers all dimensions of urban sustainability.

In this sense, the municipality should consider creating circular strategies in which urban infrastructure is regenerated, as well as how the territory can be adapted to favor the localization

of production and consumption, aiming for a more efficient and equitable use of resources and the adoption of a more comprehensive approach, aligned with the CC framework proposed by Williams (2019a). Thinking about circularity beyond entrepreneurship and economic development would enable São Paulo to advance to the highest level of maturity within the Vision category.

About the Governance and Actors category, the municipality achieved a circularity index of 54.4%, placing it at Level 2 (Circular Economy). Although the municipality already recognizes that circularity can generate economic gains beyond the Waste key sector, in practice, it still lacks a robust institutional framework to achieve higher levels of maturity. The main challenges encountered in this category are related to the following criteria: monitoring, financing, stakeholder engagement, awareness-raising, and capacity building. Furthermore, there are no published plans specifically for the municipality's circular transition.

Regarding the identification of stakeholders involved in the circular transition, the municipality has sought to create spaces that foster dialogue and the joint development of strategies. An example of this effort is the *First São Paulo Circular Economy Week*, organized by the City Hall in 2022 (São Paulo, 2022b). This initiative represents an initial effort to coordinate across sectors and disseminate the concept of the circular economy within the region. However, given the size and complexity of São Paulo, such actions remain sporadic and limited in scope.

In addition, the municipality established a strategic partnership with EMF (EMF, 2021a). However, no information was found regarding the continuity or the results of this partnership. In this context, consolidating a circular transition requires more robust, continuous, and institutionalized strategies that promote effective integration among government, the private sector, academia, and civil society. This includes the creation of internal, permanent governance structures and formal coordination mechanisms, which were not identified within the municipality.

It is worth noting that, according to Bourdin and Torre (2024), the implementation of urban circularity depends on governance that can coordinate actors, align policies, and promote collaboration across institutional levels. The authors assert that the absence of these mechanisms undermines the consolidation of circular strategies in the region. In this regard, São Paulo must structure its institutional mechanisms and processes and engage stakeholders toward sustainable urban circularity.

Monitoring structures remain fragile when analyzing the circular transition in the municipality. In addition to the absence of robust indicators, as noted in Chapters 2 and 6, and the limited identification of stakeholder engagement, there is a lack of tracking of basic information, even at lower levels of maturity. As an example, the lack of traceability for waste destined for selective collection stands out, since, although recyclable waste is sent to the recycling industry, the municipality lacks precise information on the amount actually recycled or on the portion that becomes waste during the industrial process (São Paulo, 2025a).

Still within the scope of monitoring and governance of the circular transition, it is worth noting that none of the economic indicators and only one social indicator (population density) associated with the municipality's circular transition could be calculated. This fact reinforces the need for more robust monitoring structures, so that progress toward a sustainable circular economy can be properly tracked and evaluated. It is also necessary to make progress in calculating environmental indicators, as only information on GHG Emissions, Air Quality Index, and Water Quality Index was available.

Regarding the financing of the circular transition, it also remained unclear how the municipality intends to achieve the ambition of "positioning the City of São Paulo as a global benchmark for sustainable economic development," as mentioned in the PMDE (São Paulo, 2022a). In this regard, the municipality needs to identify funding sources and coordinate with other levels of government (federal and state) and the private sector to attract capital to create new circular business models and drive technological innovation.

About the "Capacity Building" criterion within the Governance and Actors category, significant gaps are evident, including the absence of initiatives focused on training in equipment repair (appliances, furniture, and clothing). Regarding public awareness, the scenario is even more critical. Even within the realm of waste management, São Paulo faces significant challenges related to environmental education. Notable issues include high rates of sorting errors and illegal waste disposal on public streets, often linked to low public awareness. (São Paulo, 2025a).

This context limits the progress of more mature initiatives, especially those aimed at changing production and consumption patterns, which are fundamental to the consolidation of a sustainable CC. Furthermore, the challenge of raising public awareness about consumption hinders the closure of the material cycle, which was classified as Level 1 (Waste Management) and achieved a circularity index of 44.4%. This is because, in the municipality, material flows

are still treated predominantly as waste, with efforts focused on proper disposal rather than prevention.

However, the understanding of waste as a resource with economic and social value remains limited. Most of the waste generated is sent to landfills, recycling rates are low, and the municipality plans to advance in energy recovery. However, little effort is directed toward higher-value strategies for closing material cycles. Initiatives aimed at waste prevention and upstream solutions, which are more aligned with urban circularity, are practically nonexistent.

This finding reinforces the understanding that urban solid waste management is an important yet still early stage of the urban circular transition. As discussed by Moraes *et al*. (2022), sustainable CC requires a broader approach than merely improving waste systems; it incorporates changes in consumption patterns that are only possible through the engagement of the population and other actors involved in the circular transition. Therefore, São Paulo must advance public policies to change the population's behavior.

In this scenario, advancing the Material Cycle category to higher levels of maturity depends on shifting the focus of closing the cycle away from post-consumption actions and toward incorporating, within the municipality, strategies for the initial stages of the product life cycle. Thus, actions aimed at waste prevention, reducing material consumption, eco-design, reuse, repair, and remanufacturing take center stage. Furthermore, it is strategic for São Paulo to promote integration among different key sectors and production chains, encouraging the reintegration of materials as inputs and the development of circular business models.

The Biological and Water Cycle, in turn, achieved a circularity index of 60%, classified as Level 2 (Circular Economy). This result is mainly due to the promotion of local regenerative agriculture (EMF, 2021b) and the use of organic compost generated from waste from open-air markets, as part of the Markets and Gardens project (presented in section 7.3.2), thereby closing the biological cycle.

Although the project has raised the category's maturity level, it is important to note that most of the organic waste generated is currently sent to landfills, which constitutes a linear practice that should not occur in a sustainable CC. Furthermore, the composting initiatives led by the City Hall are not distributed equitably across the municipal territory (São Paulo, 2025a).

Regarding water circularity, it was possible to infer that the municipality has made progress in water flow management, particularly in sewage treatment and water supply,

although inequalities in access persist (São Paulo, 2025b). These actions are fundamental for maintaining urban services, but they are still guided by a linear logic. The circular approach presupposes the valorization of water as a resource, with practices such as reuse, nutrient recovery, and integration with urban agriculture. In this sense, the municipality still has incipient initiatives, which limit progress toward higher levels of maturity in the Biological and Water Cycle category.

As for the Built Environment and Space category, the municipality achieved a circularity index of 48.15%, ranking at Level 1 (Waste Management). Although regenerative actions have been identified in the territory, such as the opening of parks, spatial planning initiatives, including the establishment of predominantly industrial zones (ZPIs) as outlined in the PDE (São Paulo, 2014b), and infrastructure adaptation practices, these initiatives remain fragmented and isolated.

According to Wandl *et al*. (2025), the transition to a circular built environment requires integrating multiple scales, from materials to territory, as well as coordinating multiple aspects, such as resource flows, land use, and governance. In this sense, fragmented approaches focused on isolated initiatives are insufficient to establish systemic circularity.

The establishment of dedicated technological development areas is still limited, which hampers the development of an innovation environment for circular business models and causes bottlenecks even within a technocentric view of circular development. The potential for industrial symbiosis and circular ecosystems in the municipality remains largely unexplored. Additionally, the City Government should conduct studies to identify priority material flows.

In this context, advancing this category to higher levels of maturity depends on consolidating an integrated approach that views the built environment as a stock of materials and promotes strategies such as redesigning buildings, reusing construction components, and adapting existing structures for new uses. Such actions are fundamental to reducing pressure on natural resources and aligning urban development with the principles of circularity.

Furthermore, the promotion of equity in access to urban infrastructure must be incorporated into the circular transition strategy, avoiding the bottlenecks identified by Calisto Friant *et al*. (2023) and Vanhuyse *et al*. (2022), which show that social justice has been neglected in European cities. Given this, the Equity and Social Justice category achieved a circularity index of 25%, being classified as a Linear City.

The identified social initiatives that link circularity to this dimension focus primarily on the inclusion of waste pickers in the municipal waste management system. However, most waste pickers lack a formal partnership with the City Government, working under precarious conditions and living on the margins of society. Even the number of informal waste pickers working in the municipality is unknown (São Paulo, 2025a).

Regarding social equity, some circular business models were identified, supported by municipal public policies that promote entrepreneurship and have a social and inclusive character. However, these initiatives remain few compared with the size of the municipality. In this regard, it is necessary to promote social entrepreneurship across the territory, especially in the most disadvantaged regions, by expanding access to economic opportunities, training, and institutional support, to foster a more inclusive and equitable circular transition that also ensures decent working conditions and fair compensation for those involved.

Finally, regarding equitable access to urban infrastructure, the municipality exhibits significant inequalities in the distribution and quality of services. Although there have been advances in some key sectors, such as water and sanitation and waste management, access remains limited in peripheral and socially vulnerable regions (São Paulo, 2025a; São Paulo, 2025b). This inequality undermines the effectiveness of the sustainable circular transition. In this regard, promoting equitable access to infrastructure must be incorporated as a central element of circularity strategies, ensuring that the benefits of the transition are distributed fairly across the territory.

Despite the challenges, investing in the circular transition can generate benefits for the municipality, contributing to improvements in its environmental, social, and economic performance. For example, initiatives aimed at reducing resource consumption and waste generation can help lower GHG emissions, which totaled 11.44 million tCO_2e in 2022 (the most recent year reported by the municipality). Thus, it is important that São Paulo not only develop and publish circular transition plans but also incorporate a circular resource-use perspective into all municipal plans and decisions (São Paulo, 2026a).

7.3 Key Sectors: Actions and Potential for Sustainable Urban Circularity

This section aims to analyze the development of circularity in São Paulo's key sectors and, where possible, based on available information, present the results of the indicators

proposed in Chapter 6. Additionally, throughout the text, suggestions are presented, and the potential for the city's circular transition is analyzed.

7.3.1 Key Sector: Waste

The Waste key sector primarily refers to the management of household and urban (non-organic) waste. In São Paulo, the management of this waste is the responsibility of the City Government, through an inter-departmental arrangement and in collaboration with the private sector. Concessionaires provide collection, transportation, and final disposal services, while contractors are responsible for urban cleaning services, which include the removal of waste from public areas and the management of special waste, such as bulky waste (São Paulo, 2025a).

The diagnostic report for the 2025 revision of the PGIRS indicates that, in 2024 alone, 3.5 million tons of household waste were generated, representing a per capita generation of 0.826 kg/person/day (Indicator: Per capita generation of municipal solid waste). Apart from household waste, other types of waste tracked by the City, including street sweepings, debris from cleaning streams, culverts, storm drains, and healthcare waste, bring the total annual waste generated in the municipality to about 5.6 million tons, highlighting the significant waste management challenge (São Paulo, 2025a).

Currently, most of this waste is sent to landfills, which poses one of the main challenges for municipal waste management. This is because the landfills serving the city of São Paulo are nearing the end of their useful life. The diversion of materials from landfills remains low, and circular economy solutions are sporadic and limited. The 2026 revision of PlanClima highlights the need to reduce the amount of materials sent to landfills, as emissions from these facilities are rising (São Paulo, 2026a). In this context, developing a circularity strategy for São Paulo is essential for addressing climate change in the municipality.

With regard to household waste, selective collection (to be universalized by 2024) amounts to 103,842.47 tons, resulting in a Landfill Diversion Rate of 2.87%, which indicates low utilization of potentially recyclable materials. This indicator was calculated based on the total amount of household waste collected without sorting (approximately 3.5 million tons) and the volume destined for selective collection (103,842.47 tons) (São Paulo, 2025a).

It is important to note, however, that the calculation has limitations due to a lack of detailed information on the fraction of waste in selective collection, which may imply an even

lower landfill diversion rate. Furthermore, the Diagnostic Report of the 2025 PGIRS revision highlights the lack of information on recyclable materials collected by thousands of informal waste pickers in the municipality and the lack of traceability for materials destined for recycling through the formal system, thus making it impossible to calculate the actual value of the Recycling Rate indicator (São Paulo, 2025a).

The integration of recycling cooperatives into the formal management system represents an important inclusive circular initiative for the municipality. These cooperatives receive selectively collected waste, sort it, and enable the return of materials to the production cycle. Support for the cooperatives is provided primarily through the SP Coopera Program, which assists the cooperatives with rent subsidies, legal matters, and technical support. In 2024, the program supported 59 cooperatives, which sent a total of 35,000 tons of waste for recycling, generating income for approximately 1,500 cooperative members (São Paulo, 2024c).

It is worth noting, however, that the cooperatives participating in SP Coopera and authorized by the City to operate within the formal waste management system are unable to meet the municipality's need to sort all the material selectively collected within the municipality. Part of the material is sent to two mechanized sorting centers located in the municipality. In addition, informal waste pickers collect an unmeasured portion of the recyclable materials generated in São Paulo (São Paulo, 2025a).

The *Guide for Inclusive Circular Cities*, published by the MMA, recognizes that recyclable material collectors play a strategic role in the recycling chain, being responsible for a significant portion of material recovery and the reintegration of these resources into production cycles. The document also highlights that the transition to a circular economy in cities must go beyond strategies focused exclusively on resource efficiency and incorporate principles of social justice as well (MMA, 2025). Thus, it reinforces the need for recognition, appreciation, and adequate remuneration of waste pickers, as well as their inclusion in public waste management policies and urban circularity strategies.

In this context, the presence of thousands of informal waste pickers poses a challenge to the transition to a circular and sustainable city. Currently, not only is the exact number of informal waste pickers unknown, but most of these workers also face extreme social vulnerability. In general, they work under inadequate conditions, are exposed to various health risks, and often engage in unequal commercial relationships with their buyers (usually

intermediaries or scrap dealers), which can lead to economic exploitation and social exclusion (São Paulo, 2025a).

Regarding the collection of special materials, the selective collection of glass stands out. In 2023, São Paulo launched a selective glass collection project in partnership with a recycling company. Voluntary Glass Drop-off Points (PEVs) were distributed throughout the capital to collect glass bottles and containers. The expanding project has been well received, and the total amount of glass collected jumped from 15 tons per month in 2024 to approximately 93,590 tons per month in 2025 (São Paulo, 2025a).

Special waste collection can also take place at São Paulo's Ecopontos. Currently, the city has 129 Ecopontos, which accept small-scale construction waste generated by residents, as well as bulky items such as furniture, mattresses, and tree trimmings. In addition, in 2025, the City opened a dedicated Ecoponto for textile waste collection in the Brás neighborhood. In 2024, the Bresser Ecoponto, located in the same area, was also adapted to accept this type of material. In its first three months of operation, the Bresser Ecoponto received an average of 26.48 tons of textile waste per month (São Paulo, 2025a). However, these specialized collection facilities for special waste are not evenly distributed across the city.

Other special materials, such as waste from electrical and electronic equipment, tires, and batteries, must be collected through reverse logistics, which operates under the principle of shared responsibility established by the PNRS (Law No. 12,305 of 2010) (Brazil, 2010). Little data is available on the specific collection of these materials, and there is a lack of integration between the municipality and the private sector. However, the public can consult logistics entities to identify drop-off points distributed throughout the municipal territory. In this context, it is not possible to accurately calculate the indicator (Special materials collected).

Given this scenario, it is evident that circularity in the sector is still predominantly focused on sending materials for recycling, with low rates of waste diversion from landfills. At the landfills serving the municipality, methane is being utilized, and São Paulo plans to implement energy recovery from waste. Energy recovery will be discussed in greater detail within the Energy key sector. Furthermore, there are no adequate mechanisms for waste traceability nor precise data on the quantity of materials that are, in fact, recycled and reintroduced into the production cycle.

Thus, it can be inferred that the municipality lacks initiatives of greater value for the circular economy, such as those focused on the exchange, reuse, and repair of products and materials. For example, no recovery, repair, or reuse center under municipal management was identified (indicator: Number of repair or reuse centers). The municipality of São Paulo has the potential to create and maintain similar structures in different parts of the city, which could help divert more materials away from landfills, extend the useful life of products, and promote social inclusion.

Such solutions are of greater value for material circularity, as they prioritize strategies at higher levels of the waste management hierarchy and help reduce the environmental impacts associated with production and disposal. In addition, repair and reuse initiatives can generate significant socioeconomic benefits, such as creating local jobs, strengthening community initiatives, and promoting more sustainable consumption models.

Finally, it is worth noting that a central problem in waste management in São Paulo is the lack of awareness and environmental education among the city's residents. The document highlights errors in source separation, poor-quality materials intended for selective collection, and a lack of knowledge about recycling drop-off points and the public's role in waste management. Thus, it can be inferred that any action aimed at implementing reuse, repair, or exchange initiatives must be accompanied by a specific environmental education strategy (São Paulo, 2025a).

Figure 31 presents an interpretive summary of the analysis conducted for the waste sector, highlighting the main advances identified, the remaining challenges, and the strategic opportunities to strengthen circularity in the sector.

Key Sector	Proposed Indicators	Measured Indicators	Positive Aspect	Negative Aspect	Suggestions
Waste	6 proposed indicators	4 measured indicators	• Initiatives for the collection of special waste; • Programs for the inclusion of waste pickers; • Expansion of selective collection.	• High dependence on landfills; • Lack of environmental awareness and education; • Illegal disposal; • Informal waste pickers in precarious conditions; • Low traceability; • Recycling mostly limited and lack of upstream initiatives.	• Greater inclusion of informal waste pickers in the municipal system; • Implementation of solutions; • Implementation of exchange initiatives, reuse and repair of products and materials; • Reduce waste generation; • Extend the life cycle of products and materials; • Awareness-raising and environmental education campaigns.

Figure 31 - Summary of the analysis of the Waste key sector.

Source: Developed by the author, with the assistance of ChatGPT – OpenAI (2026).

7.3.2 Key Sector: Agriculture and Food

The Agriculture and Food key sector is one of the most relevant for closing the biological cycle using nutrients in agriculture. Although widely recognized as one of the world's largest urban centers, São Paulo has strong agricultural potential. This is because approximately one-third of its territory is classified as rural, particularly the Parelheiros region in the southernmost part of the municipality.

This potential has already been recognized by the municipal administration through the "*Ligue os Pontos*" Project. The project consists of a circular initiative that promotes local and sustainable food production. The food is produced through regenerative agriculture and sold locally. To facilitate this sales process, the project relies on a digital platform that connects producers with end consumers. To close the food cycle, the collected organic waste is sent for composting at City Hall facilities, and the resulting compost is then returned to rural producers (São Paulo, 2022b; EMF, 2021b).

This initiative, in addition to contributing to the closing of resource cycles, generates positive impacts in the social, economic, and environmental dimensions. The project enables income generation for various farmers in the municipality and provides high-quality food, while also encouraging regenerative agriculture practices that reduce the environmental impacts associated with agricultural production. The use of digital platforms to support this structure

also stands out as a successful application of technology that supports urban circularity. Furthermore, the initiative broadens understanding of the CE beyond strategies focused exclusively on recycling, promoting a systemic approach to the transition toward more sustainable urban models.

The "*Ligue os Pontos*" Project was renamed by City Hall and is currently known as "*Sampa Mais Rural*". The platform compiles data on agriculture in the municipality, not only in rural areas but throughout the entire territory. According to the available information, São Paulo has 848 Agricultural Production Units (UPAs), 225 urban gardens, 1,671 gardens on public grounds, and 17 Guarani Indigenous village. Among the UPAs, 71% of the properties exhibit characteristics of family farming. The municipality produces vegetables, greens, root vegetables, fruits, and other agricultural products (São Paulo, 2026f).

Figure 32 shows the location of agricultural units and composting plants in the municipality of São Paulo.

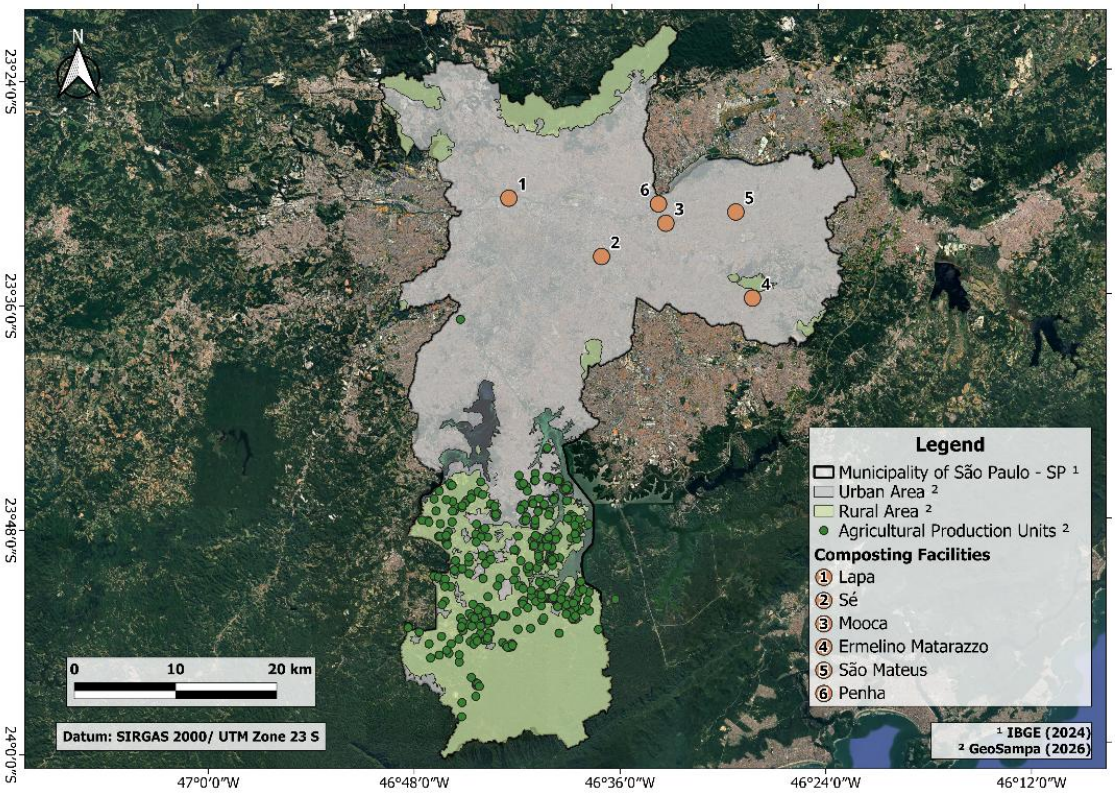


Figure 32 - Agricultural Units and Composting Plants.

However, it was not possible to directly calculate the indicator "Areas Dedicated to Food Production." Even though the "*Sampa Mais Rural*" initiative promotes the sale of

products within the municipality, it is also not possible to estimate the impact of these foods' consumption relative to total consumption (indicator “Consumption of Locally Produced Foods Using Circular Practices”). This scenario suggests the need to strengthen agricultural data collection in the municipality.

Regarding urban agriculture, the *Municipal Agroecology Plan* (2022–2030) notes that it takes place in schools, health facilities, parks and squares, leased public areas, condominiums, and residential backyards. According to the Plan, urban agriculture is driven by social, economic, political, and educational factors and contributes to food security. However, the document notes that measuring and analyzing these initiatives is difficult due to their decentralized nature (São Paulo, 2023a).

It is worth noting that Municipal Law No. 13,727, dated January 12, 2004, which establishes the *Urban and Peri-Urban Agriculture Program* (PROAURP), not only encourages local food production but also promotes the creation of solidarity-based forms of production and marketing, as well as the use of public facilities for agricultural production. Given this regulatory framework, the *Municipal Agroecology Plan* also provides for the use of idle public and private areas for food production to strengthen food sovereignty. In this sense, at least at the planning level, the municipality of São Paulo demonstrates alignment with more advanced principles of urban circularity by proposing actions to adapt urban structures and localize food production.

In practice, circularity in this key sector is based on closing the nutrient cycle, which is closely linked to the recovery of organic waste and its use in local agriculture. However, these actions are limited. About 46% of household waste generated in São Paulo homes is organic and, therefore, suitable for composting or biodigestion. In addition to household waste, major generators such as farmers’ markets, supermarkets, wholesale markets, produce markets, and hospitals, among others, also generate this category of waste, indicating great potential for the implementation of circular solutions, which do not yet cover the entire municipality (São Paulo, 2025a).

As in European cities and other urban areas, São Paulo demonstrates, at least at the level of urban planning, a concern for these materials. The 2014 *Integrated Solid Waste Management Plan* (PGIRS), for example, indicated the need for selective collection of organic waste (São Paulo, 2014a). Meanwhile, the *Diagnostic Report* for the 2025 PGIRS revision highlights the

need to modernize the system for treating this waste and to implement biodigesters and new composting facilities (São Paulo, 2025a).

Nevertheless, in practice, municipal initiatives for organic waste management are focused on the "*Feiras e Jardins*" Project, launched in 2015. As part of this project, composting sites were established in São Paulo (there are currently six sites in operation), where organic waste collected through separate collection at open-air markets is sent for composting.

The resulting compost is donated to the community (including the aforementioned farmers), who use this material, thereby closing the nutrient cycle. In 2024, through this project, 4,922 tons of organic waste were sent for composting (Organic Waste Sent for Composting indicator). However, the diagnostic report also indicates the need for further action to treat this waste, given that the amount sent for composting is very small relative to the total generated (São Paulo, 2025a).

Regarding the "Food Waste" indicator, no data were found to measure it. However, within the São Paulo City Government, the *Municipal Program to Combat Food Waste and Loss* stands out as an initiative that seeks to reduce waste while helping address food insecurity. The program collects fruits and vegetables sourced primarily from open-air and municipal markets that, although no longer commercially viable, are still suitable for consumption. After sorting, these foods are distributed to charitable organizations, which then distribute them to families in socially vulnerable situations (São Paulo, 2022c).

In addition, the municipality has a *Municipal Policy on Sustainable Food and Nutritional Security* that encourages initiatives to reduce food waste and strengthen food security. Among these initiatives, the Food Bank stands out for collecting surplus products from companies, supply centers, and open-air markets, sorting and distributing food fit for consumption to social assistance institutions and families in socially vulnerable situations (São Paulo, 2025a). Thus, the initiative contributes to reducing waste, making efficient use of resources, and strengthening social assistance efforts in the municipality.

This scenario highlights that, although relevant initiatives exist, circularity in the sector remains fragmented and limited in scale, which is insufficient to effectively close biological cycles in the municipality.

Figure 33 presents an interpretive summary of the analysis conducted for the Agriculture and Food key sector, highlighting the main advances identified, the remaining challenges, and the strategic opportunities to strengthen circularity in the sector.

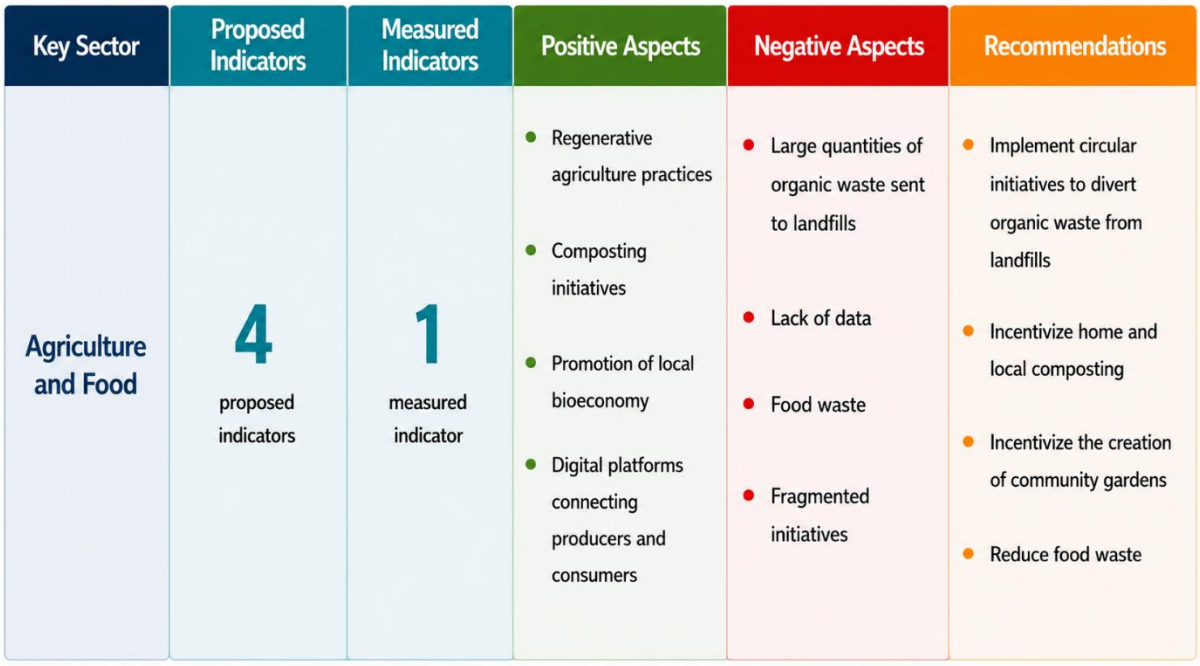


Figure 33 - Summary of the analysis of the Agriculture and Food key sector.

Source: Developed by the author, with the assistance of ChatGPT – OpenAI (2026).

7.3.3 Key Sector: Local Production and Industry

Historically, São Paulo has been an important industrial hub, considered one of the most industrialized cities in Brazil and having undergone various transformations over the years (São Paulo, 2022a). The municipality's industry is characterized by high sectoral diversity, with activities including the food, chemical, metallurgical, pharmaceutical, and textile industries, among others (São Paulo, 2024e).

Regarding the potential for CE, the textile sector stands out in the municipality, as São Paulo is a major national hub for textile production and consumption. Textile materials have high potential for the CE and are recognized as a priority stream by the European Union (EU, 2022).

Figure 34 shows the concentration of textile industries licensed by the City Hall, highlighting a higher concentration of these activities in the central and eastern regions of the municipality, although there is also production in the western and southern zones.

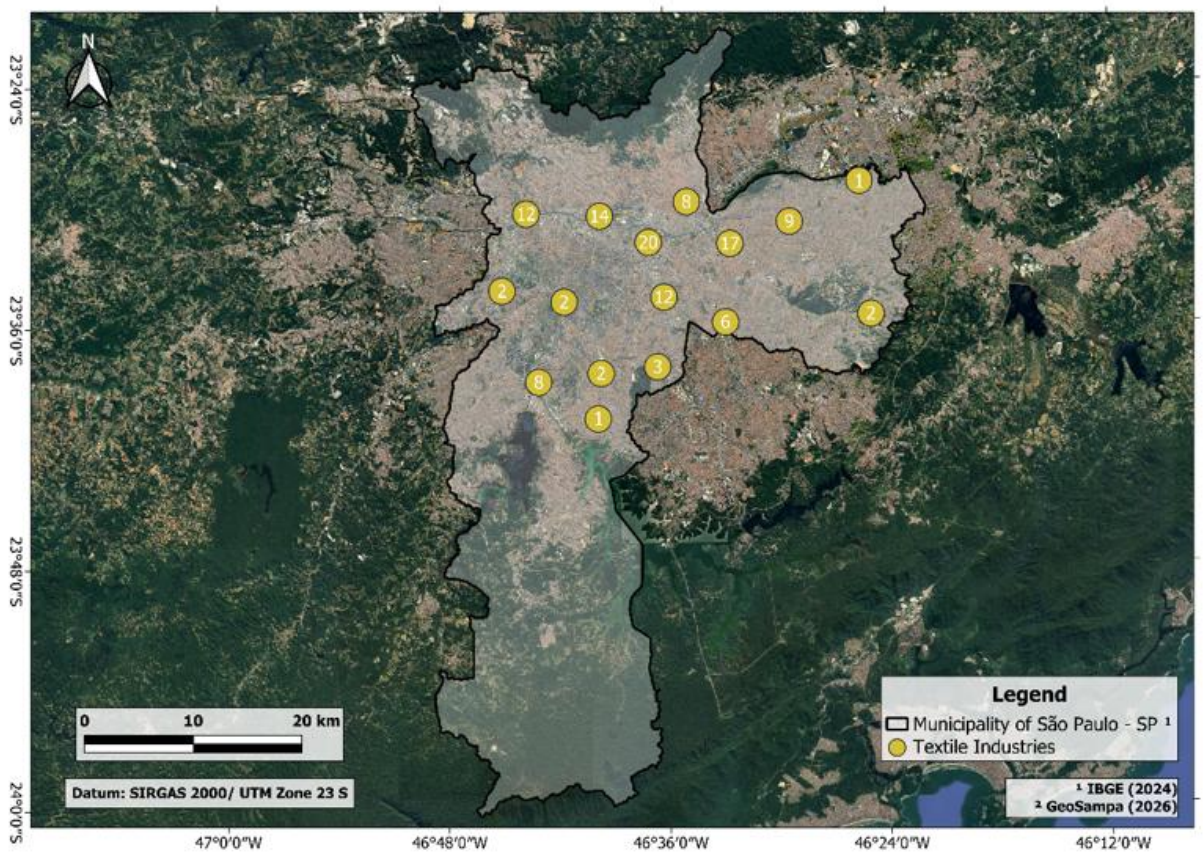


Figure 34 - Concentration of textile industries in the municipality of São Paulo.

This spatial distribution indicates the sector's relevance to local economic dynamics and reveals opportunities to implement circular strategies, such as upcycling textile waste, industrial symbiosis, and strengthening local production chains. It is worth noting that the municipality has several unlicensed garment factories and industries that are not licensed by the City Hall and, therefore, do not appear on the map.

Currently, waste from the textile industry poses a problem for the city's public sanitation services. This is because the companies responsible for waste collection remove approximately 50 tons of textile waste per day in São Paulo. The illegal disposal of waste from garment factories occurs on public roads in the municipality, mainly in the Brás, Bom Retiro, Mooca, Arthur Alvim, and Itaquera regions, which have the highest concentration of these businesses (São Paulo, 2025a).

Given this situation, the municipality of São Paulo has already recognized the potential for circularity in textile materials. During the *First Circular Economy Week*, organized by the City Government and the UCCI in 2022, discussions focused on the circular economy within

this production chain. Additionally, several private initiatives are seeking to develop circular solutions for the sector (São Paulo, 2022b).

The Bom Retiro Recicla Program, for example, is an initiative of the Brazilian Apparel Industry Association (ABIV) that seeks to reduce waste discarded in the region by diverting part of these materials to recycling, transforming them into blankets, and distributing them to people in socially vulnerable situations. Since the program's inception, over 500 tons of waste have been diverted from landfills (São Paulo, 2025a).

At the municipal level, in addition to the installation of textile recycling bins mentioned in the Waste key sector section, the *Municipal Fashion Sampa Program* was created to strengthen and promote the fashion sector in São Paulo, encouraging circular business models. Within the program, companies engaged in local production based on sustainable fashion and upcycling have already been supported. The projects supported by Fashion Sampa often promote social inclusion (São Paulo, 2026b).

Fashion Sampa is part of the São Paulo *Development Agency* (*Ad Sampa*), the municipal body responsible for promoting entrepreneurship, innovation, and economic development. It plays a central role in supporting sustainable businesses. *Ad Sampa* maintains an acceleration program for sustainable businesses and a hub (the *Green Sampa Hub*) that serves as an innovation center. *Green Sampa* has already accelerated several companies with circular business models that address different aspects of urban circularity, such as water and sanitation, energy, waste, and urban mobility and transportation (São Paulo, 2025d).

This scenario indicates that the municipality of São Paulo tends to encourage business models that develop sustainable solutions to urban problems locally. This fact demonstrates that, currently, the promotion of urban circularity occurs predominantly through a technocentric approach, although, in some cases, the supported companies also present initiatives focused on social inclusion.

Regarding the indicators proposed in this study, no data were found to measure any of them. This is mainly because the collection of information for this key sector relies on private companies, which hinders public access to the data, as noted by the experts who participated in the validation of the indicators. This scenario reinforces the need for engagement by all actors involved in urban circularity, including the private sector, which is responsible for local production and industry.

This scenario highlights that, although relevant initiatives exist, circularity in the sector remains fragmented and relies on ad hoc measures, which are insufficient to promote structural transformations in the municipality's production chains. In addition, the municipality should assess the potential to apply the CE to other industrial sectors, considering São Paulo's productive diversity and opportunities to close cycles across different chains.

Figure 35 presents an interpretive summary of the analysis conducted for the Local Production and Industry key sector, highlighting the main advances identified, the remaining challenges, and the strategic opportunities to strengthen circularity in the sector.

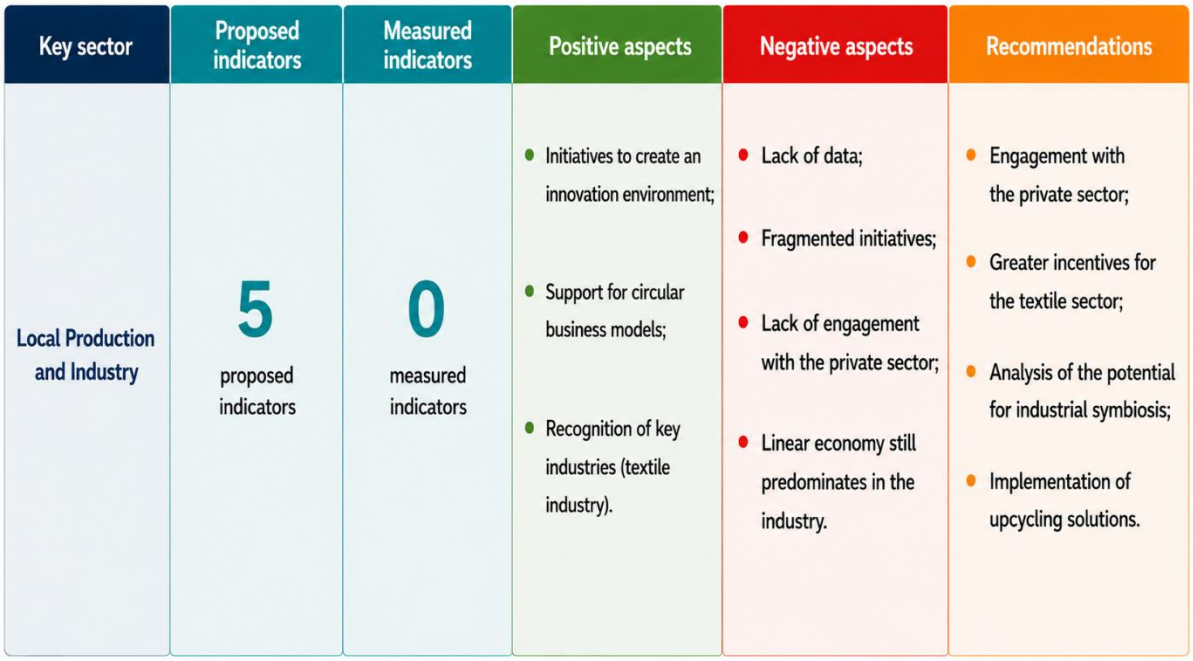


Figure 35 - Summary of the analysis of the Local Production and Industry key sector.

Source: Developed by the author, with the assistance of ChatGPT – OpenAI (2026).

7.3.4 Key Sector: Energy

According to the *Annual Energy Report* by Municipality in the State of São Paulo, the municipality recorded a total electricity consumption of 26.9 TWh (Energy Consumption Indicator) in 2023 (São Paulo, 2024d). Among the categories of energy consumption (residential, commercial, rural, public sector, among others), residential energy consumption stands out, representing approximately 44.8% of the total consumed in the municipality.

Seeking an energy mix with lower environmental impact, the *2030 Agenda* proposes expanding the use of renewable energy in the municipality and achieving the goals of SDG 7 (affordable and clean energy). In the document, São Paulo acknowledges that it does not have

full authority over the energy mix, as it depends on decisions at the national and state levels. Nevertheless, the municipality presents solutions for local energy generation within its sphere of influence. In this regard, it plans to incentivize the generation of photovoltaic energy, which can be produced in a decentralized manner in public and private buildings. This guideline relates to circular actions aimed at replacing the energy mix (São Paulo, 2020a).

Following the publication of the *2030 Agenda*, the municipality of São Paulo began releasing data on the indicator "Total installed photovoltaic power (kW)." Analysis of this data indicates that installed capacity increased from 150.20 kW in 2015 to 6,898.22 kW in 2020 (the most recent year available) (São Paulo, 2026e). In addition, the revision of PlanClima sets a target that, by 2050, 13% of the city's residential buildings will be equipped with distributed photovoltaic generation systems (São Paulo, 2026a). This scenario indicates a trend toward expanding the city's energy matrix, aligning with the principles of urban circularity.

The municipality of São Paulo has been investing in energy recovery from solid waste. Currently, the landfills that receive the municipality's waste already generate energy and use methane as fuel. At the *East Waste Treatment Plant*, a sanitary landfill in São Paulo's East Zone, for example, biomethane is utilized. The biomethane produced fuels the fleet of waste collection trucks, significantly reducing diesel consumption (São Paulo, 2025a).

At the Caieiras Landfill, located in the municipality of Caieiras in the Metropolitan Region, which receives waste from São Paulo, there is a thermal power plant considered the largest in Brazil, powered by landfill biogas and one of the largest in the world. At this plant, methane is used as fuel to generate electricity via motor-generators. In addition, the landfill also produces biomethane to fuel the waste collection fleet (São Paulo, 2025a).

The *Diagnosis of the PGIRS revision* indicated that, in addition to these waste-to-energy initiatives, the City plans to build three Ecoparks with waste-to-energy recovery facilities. Among these facilities are biological waste treatment units and the creation of three Energy Recovery Units (ERUs). ERUs are facilities that convert waste into energy through thermal treatment (controlled incineration) (waste-to-energy) (São Paulo, 2025a). The City argues that this initiative, in addition to providing energy for the municipality, will reduce the amount of materials sent to landfills.

Although energy recovery does indeed reduce the amount of waste sent to landfills and is widely used by European cities, it is important that, for a circular and sustainable transition,

São Paulo not neglect more rigorous strategies for extending the life cycle of products. Waste reduction through reuse and repair practices also helps divert materials from landfills and generates greater value for urban circularity, as noted by Dąbrowski *et al.* (2024). Furthermore, the municipality should consider the potential negative rebound effects of thermal waste treatment, considering the environmental risks associated with waste-to-energy plants.

Even though these initiatives are significant for the municipality's energy transition, it was not possible to accurately calculate the indicator "Share of renewable energy in total energy consumption." This is because the available data on installed photovoltaic capacity in the municipality is outdated (the most recent data refer to 2020). In addition, no data were found to address the indicators "Renewable energy generation potential" and "Energy recovery from waste."

Regarding street lighting, the *2030 Agenda* calls for replacing incandescent bulbs with LED bulbs, which consume about 50% less energy than sodium lamps (São Paulo, 2020a). According to data from Observa Sampa, the percentage of LED bulbs in public lighting jumped from 75.51% in 2020 to 99.85% in 2024 (São Paulo, 2026e). Given these data, the "Public Lighting" indicator proposed in this study performs well.

This scenario shows that although there have been advances in the adoption of renewable energy sources and the recovery of energy from waste, the energy transition in the municipality is still only partially underway, with limited data availability and integration across different urban systems, which restricts progress toward higher levels of circularity.

Figure 36 presents an interpretive summary of the analysis conducted for the Energy key sector, highlighting the main advances identified, the remaining challenges, and the strategic opportunities to strengthen circularity in the sector.

Key sector	Proposed indicators	Measured indicators	Positive aspects	Negative aspects	Recommendations
Energy	5 proposed indicators	2 measured indicators	• Incentive for the energy transition; • Growth of solar energy deployment; • Energy recovery from biogas generated at landfills; • Replacement of lighting equipment.	• The energy transition is still slow; • Lack of data; • Possible rebound effects and environmental impacts associated with WtE plants.	• Data collection; • Greater engagement with the private sector; • In-depth studies on the potential for local energy production; • Studies to prevent that energy recovery initiatives (waste to energy) do not hinder the adoption of higher-value circular solutions.

Figure 36 - Summary of the analysis of the Energy key sector.

Source: Developed by the author, with the assistance of ChatGPT – OpenAI (2026).

7.3.5 Key Sector: Mobility and Transportation

The Mobility and Transportation key sector, in which the principles of urban circularity focused on sharing (vehicles, bicycles), switching (fuel type), and adaptation (road infrastructure) can be used to contribute to the construction of an efficient and sustainable transportation system, stands as a strategic element in the urban transition. Despite its importance, the *São Paulo Mobility Plan* (PlanMob), the municipality's primary planning instrument, was published in 2015 and had not been revised as of the time of this study's preparation. Consequently, information on this key sector is outdated.

This plan establishes guidelines, objectives, and targets to reorganize the city's mobility system and guide public policies. Among its guidelines are prioritizing sustainable modes, integrating transportation and urban planning, and coordinating different transportation modes. The plan also sets objectives to improve the efficiency and attractiveness of public transit, increase the use of active modes, reduce dependence on private motorized transport, and promote greater equity in access to the city. In addition, it seeks to reduce the environmental impacts of the mobility system by decreasing pollutant emissions and optimizing the use of urban road space (São Paulo, 2015). These guidelines are consistent with circular initiatives in European cities for this key sector.

In practice, however, urban mobility and transportation seem far from what the municipality has planned. Even the 2015 plan acknowledges the city's bottlenecks and cites the main challenges: severe traffic congestion, excessive numbers of vehicles on the streets, and issues related to public transit, such as long travel times and inequalities in access (São Paulo, 2015). Although no more recent systematized data on transportation at the municipal level were found, which represents yet another bottleneck for the circularity of this key sector, some relevant information on changes in transportation modes has been published.

A study released by *Informes Urbanos of the Municipal Secretariat of Urban Planning and Licensing* indicated a significant increase in bicycle use in the municipality, with a 48% rise in the number of trips in 2017 compared to 2007. According to the study, one of the main reasons for this growth is investment in bicycle infrastructure, indicating a significant effort toward circularity by adapting urban structures to more sustainable modes of mobility (São Paulo, 2020b). In this regard, in 2008 there were 3.6 km of bike lanes, while in 2022 this figure reached 155.90 km (3.50% of the municipality's total road network) (São Paulo, 2026e).

Given the strong connection between São Paulo's transportation system and the *Metropolitan Region, the Origin-Destination Survey* published by the São Paulo Metro (2024) for the Metropolitan Region (RMSP) can serve as an indirect proxy for the "Sustainable modes of transportation" indicator. According to the study, in 2023, 35.6 million daily trips were made in the RMSP. About 70.5% of these trips were made by motorized modes (public and private), while the remaining 29.5% were made by non-motorized modes (bicycle and walking).

Among non-motorized modes, bicycle trips increased by 25%, while foot trips decreased by 24.7%. Despite this growth, bicycle trips still account for only 1.3% of the total. The study also noted a decrease in the total number of motorized trips in the metropolitan region (São Paulo Metro, 2024). Thus, the scenario indicates that although public transit plays a significant role, individual motorized modes, especially cars, remain prevalent, while bicycles still account for a very small share of urban mobility, despite growing encouragement.

Regarding the fuel used in vehicle fleets, the city of São Paulo is undergoing significant changes. Although it is not possible, with the data available on the City Hall's platforms, to measure the "Fleet Fuel Type" indicator for all vehicles in the city, the 2021 PlanClima and the *2030 Agenda* acknowledge that the municipal fleet's fuel mix is predominantly based on fossil fuels, mainly gasoline and diesel. This scenario has significant impacts on greenhouse gas emissions and air quality, and both documents set targets to make this mix more sustainable,

including actions to change the fuel used in the public transportation fleet (São Paulo, 2020a; São Paulo, 2021).

In this regard, São Paulo's public transportation system has been undergoing an energy transition in recent years, in line with the principle of exchange and substitution within the urban circular economy. This transition includes the electrification of the bus fleet, which, according to City Hall, reached 1,259 electric vehicles by 2026 (São Paulo, 2026c). This number represents a significant increase compared to the 217 electric vehicles operating in the city in 2018 (São Paulo, 2020a). However, it is worth noting that the bus fleet operating in the city comprises more than 12,000 vehicles; therefore, there is still room to expand the number of electric vehicles in the fleet circulating throughout the city.

Despite these limitations, data from *Observa Sampa* indicate a decline in emissions related to the bus fleet. In 2015, emissions from São Paulo's municipal bus fleet totaled approximately 1,170 tons of CO_2, while by 2025 this figure had fallen to about 920 tons (São Paulo, 2026e). This suggests progress in the transition to a more sustainable mobility system, associated with the adoption of technologies and fuels with lower environmental impact. This movement aligns with the "substitute" principle of the circular economy, indicating the gradual replacement of fossil fuels with cleaner alternatives in the public transportation system.

Complementing its fleet electrification efforts, the city of São Paulo has sought to incorporate renewable fuels into the public transportation system, including biomethane. In this regard, City Hall announced plans to publish a call for bids in 2025 to facilitate the inclusion of this fuel in the city's bus system. In this way, the municipality aims to reduce dependence on diesel and lower emissions of pollutants and greenhouse gases (São Paulo, 2025c). To date, the use of biogas from landfills is already a reality in waste management services; currently, 200 trucks used for waste collection run on biomethane (São Paulo, 2025e).

Regarding transportation-related emissions, the 2026 PlanClima review indicates that they account for 60% of total emissions in the municipality of São Paulo, reaching 7,288,188 tCO_2e in 2022 (GHG Emissions Indicator in the Mobility and Transportation key sector) (São Paulo, 2026a). In this regard, circular solutions, such as using biomethane as fuel, can have positive impacts. According to the São Paulo City Government (2025e), replacing diesel with biomethane in waste collection prevents the emission of 17,400 tons of CO_2 per year and reduces fossil fuel consumption by approximately 7 million liters.

Regarding the indicator "Particulate matter emissions in the Mobility and Transportation key sector" proposed in this study, data were available on particulate matter reductions by the bus fleet but not for the entire municipal transportation system. Regarding the indicator "Particulate Matter (PM) Emissions by the Bus Fleet," monitored by the Observa Sampa platform (São Paulo, 2026e), a cumulative reduction in these emissions is observed. In 2015, 93.91 tons of PM were emitted, while in 2025 this figure dropped to 18.74 tons.

Although it is possible to observe the municipality's movement toward more sustainable mobility, with the implementation of measures focused on substitution (shifting modes and fuels in the fleet), optimization (guidelines aimed at improving public transportation), and sharing (such as bike-sharing systems available at various points throughout the city), no initiatives were identified aimed at adapting the urban structure and the location of services to reduce dependence on transportation.

Similarly, there is no evidence that urban growth is being systematically directed toward areas near public transportation systems. Furthermore, bicycle-sharing initiatives still face territorial limitations, as they are not available throughout the entire municipality.

Figure 37 presents an interpretive summary of the analysis conducted for the Mobility and Transportation key sector, highlighting the main advances identified, the remaining challenges, and the strategic opportunities to strengthen circularity in the sector.

Key sector	Proposed indicators	Measured indicators	Positive aspects	Negative aspects	Recommendations
Mobility and Transport	4 proposed indicators	3 measured indicators	• Incentive for public transport; • Incentive for active mobility (bicycles); • Improvements to infrastructure; • Reduction of particulate emissions; • Expansion of the fleet of electric vehicles.	• Public data is not up to date; • Lack of information on the private fleet; • Inequality of access; • High dependence on fossil fuels; • Lack of urban adaptation initiatives to reduce transport dependence.	• Update data; expand the use of biomethane and other sustainable fuels; • Reduce dependence on individual motor transport; • Promote access to the public transport system; • Prioritize low-emission active modes and public transport; • Promote shared transport.

Figure 37 - Summary of the analysis of the Mobility and Transportation key sector.

Source: Developed by the author, with the assistance of ChatGPT – OpenAI (2026).

7.3.6 Key Sector: Water and Sanitation

The Water and Sanitation key sector analyzes one of the most important resources for sustaining urban metabolism: water. According to the Diagnosis of the 2025 Municipal Integrated Environmental Sanitation Plan, most of the municipality lies within the Alto Tietê River Basin (more than 90% of its territory), while a small portion belongs to the Baixada Santista River Basin. The territory has more than 200 watercourses, among which the Tietê, Pinheiros, and Tamanduateí rivers, as well as the Billings and Guarapiranga reservoirs, stand out (São Paulo, 2019; São Paulo, 2025b).

São Paulo's water bodies have suffered from urbanization, particularly those in the Alto Tietê Watershed. Two main processes have altered the basin's natural condition: the covering of surfaces with impermeable layers (concrete and asphalt) and the confinement of water bodies in enclosed channels (forming so-called underground rivers). As a result, the region now suffers from drainage and flooding problems, and the basin's water availability is among the lowest in the state, forcing the municipality to source water from cities far from the state capital (São Paulo, 2025b).

In this context, the municipality has great potential to implement measures to adapt and regenerate natural resources. Williams (2021a) states that regenerative actions in circular cities include the "renaturalization" of drainage systems and rivers within the territory. In this regard, it is suggested that São Paulo implement circular actions related to the de-paving of riverbanks (removal of impermeable surfaces to allow water infiltration into the soil and the recovery of natural processes), the restoration of vegetation along the banks of water bodies, and the implementation of nature-based solutions (rain gardens, linear parks, etc.).

The average per capita water consumption in the municipality was 205.51 L/person/day in 2024 (Annual per capita water consumption). This consumption has increased in recent years; in 2022, for example, it was 164.22 L per person per day. The increase is multifactorial and may be related to changes in consumption patterns or an increase in the loss rate. The loss rate recorded in 2024 was 29.5% (Water loss indicator in the distribution network) (São Paulo, 2025b). In this context, circular initiatives for water reuse and rainwater harvesting can reduce water demand.

The quality of water in the São Paulo region is also heavily affected by non-point-source pollution and the illegal disposal of waste into water bodies. According to the *Alto Tietê River*

Basin Agency Foundation (FABHAT) (2025), the Alto Tietê Basin alone receives approximately 21,000 tons of solid waste annually. Circular initiatives for waste reduction, particularly in the solid waste sector, can also help reduce the amount of waste entering São Paulo's water bodies.

Regarding water and wastewater treatment, the PMSAI Diagnosis recognizes the potential for implementing circular economy principles and presents existing initiatives in the municipality. According to the document, the recovery of waste (sludge) generated at treatment plants is an example of a circular practice (São Paulo, 2025b). However, it does not provide sufficient data to calculate the "Nutrient recovery rate from sludge" indicator.

Given this scenario, it is suggested that the municipality implement measures to recover sludge produced at treatment plants, as treated sludge can help close material and nutrient cycles in urban systems. In the case of sewage sludge, the recovery of nutrients such as phosphorus and nitrogen enables its use in agriculture. Additionally, anaerobic digestion processes generate biogas, thereby contributing to the production of renewable energy. Sludge from water treatment, on the other hand, can also be used to produce construction materials.

Regarding the indicators "Sewage Reuse Rate" and "Rainwater Reuse Rate," it was not possible to calculate their actual values because this would require information unavailable at the municipal level. It is worth noting that although there are legal incentives to promote water reuse, the municipality has recorded a decline in public-purpose reuse in recent years. This situation is because, during periods of water crisis (2014 and 2015), water reuse was widely utilized, but lost momentum in years of greater water availability (São Paulo, 2025b).

The "Treated Sewage Reuse Rate" indicator also has limitations regarding its calculation at the municipal level. However, the PMSAI Diagnosis indicates that São Paulo has a deficit in sanitary sewage treatment corresponding to approximately 16.6% of all properties connected to the sanitation system (São Paulo, 2025b). In this context, there is clear potential to advance circular initiatives in the sector by expanding treatment systems (including sludge recovery) and using treated sewage, suitable for industrial use, for public cleaning and garden irrigation.

Initiatives of this nature are already underway at *Aquapolo* (the largest industrial water reuse project in South America), located in the municipality, which implements circular actions in sewage treatment. The system uses treated wastewater for industrial purposes, supplying the

petrochemical hub of the ABC region in São Paulo. In 2023, the project produced and distributed over 10 million m³. In the same year, *Aquapolo* also obtained a license to expand the use of reclaimed water for non-potable urban purposes, such as street cleaning and construction, broadening its potential for integration with the urban ecosystem and reinforcing its contribution to the circularity of water resources in the São Paulo Metropolitan Region (Aquapolo, 2023).

These results indicate that, despite the high potential for implementing circular practices in the water sector, the municipality still exhibits a predominantly linear approach, marked by dependence on external supply sources, low incorporation of reuse strategies, and limited recovery of resources from sanitation systems. The initiatives identified are isolated and, to date, do not constitute a systemic strategy for closing water cycles in the territory.

Figure 38 presents an interpretive summary of the analysis conducted for the water and sanitation key sector, highlighting the main advances identified, the remaining challenges, and the strategic opportunities to strengthen circularity in the sector.

Key sector	Proposed indicators	Measured indicators	Positive aspects	Negative aspects	Recommendations
Water and Sanitation	5 proposed indicators	2 measured indicators	• Water reuse initiatives; • Projects in partnership with the industrial sector; • Recognition of the CE's potential.	• Waterbody channelization; • Few reuse initiatives; • Need for sludge valorization; • Limited adaptive and restorative actions.	• Implement actions to restore water bodies and their margins; • Adapt urban infrastructure to allow greater water infiltration; • Expand rainwater harvesting actions; • Implement sludge valorization strategies; • Reduce the amount of waste in water bodies.

Figure 38 - Summary of the analysis of the Water and Sanitation key sector.

Source: Developed by the author, with the assistance of ChatGPT – OpenAI (2026).

7.3.7 Key Sector: Space and Built Environment

The Space and Built Environment key sector is the most complex to analyze in a municipality such as São Paulo, as the territory contains regions of modern urbanization

alongside areas with socially vulnerable populations and precarious urban settlements, classified by the *Municipal Housing Secretariat* (SEHAB) as favelas, housing clusters, irregular subdivisions, tenements, and collective housing (São Paulo, 2024a). The *2022 Census* identified 1,359 favelas or urban communities, with a total of 1,738,235 people living in these areas (IBGE, 2022).

According to the 2024 Municipal Risk Reduction Plan, these areas have poor infrastructure, and limited access to urban services. They are more susceptible to extreme events caused by climate change, such as floods and landslides (São Paulo, 2024b). This fact highlights the lack of equity in access to the city's infrastructure and resources. In this context, the presence of informal and vulnerable territories reveals structural limitations to the transition to urban circularity, as it hinders the integrated implementation of strategies to close cycles in the built environment. Nevertheless, the transition to urban circularity can help reverse this situation by promoting an integrated and regenerative approach to the built environment and providing the ecological benefits described by Williams (2021b).

One of the central issues in the vision of a CC is optimizing urban resource use, which entails not only reducing material waste but also maximizing the use of existing structures within the territory. In this sense, the existence of vacant properties represents an inefficiency in resource use. Data from IBGE (2022) indicate that there are 588,978 vacant permanent dwellings, representing 11.8% of the total number of dwellings (Indicator: Vacancy rate of residential properties).

This scenario may be related to the existence of new real estate products and housing units geared toward investment and temporary rental. However, the dynamics of property use are strongly linked to the real estate market, and its consumption model runs counter to urban circularity (São Paulo, 2023b).

Furthermore, regarding urban space, the regeneration of green areas is an important circular initiative for cities. Data from *Observa Sampa* (São Paulo, 2026e) show that vegetation cover (trees and ground cover) accounted for 40.82% of the municipal territory, and by 2022, this percentage had reached 48.18%. In 2023, the City Government announced that vegetation cover had reached 54.13% of the municipal territory (Indicator: Green Areas) and that this increase is a result of investments in creating parks, planting trees, and combating deforestation (São Paulo, 2023c).

However, it is worth noting that vegetation in São Paulo is not distributed equitably, with the highest concentration in the southern region and the city's more affluent areas, which have greater vegetation coverage than the outskirts. In this context, circular and regenerative initiatives, such as creating parks, removing paving in impervious areas, and planting trees, can help make São Paulo a greener, more resilient, and more environmentally sustainable city.

No data were found on the number of buildings designed for dismantling (the "Buildings designed for dismantling" indicator) or on the reuse of materials from modular buildings (another indicator proposed in this study). This is due, in part, to the fact that modular construction is not yet a common practice in the city. Furthermore, information on the construction characteristics of buildings largely depends on the private sector, which limits its availability at City Hall. This limitation also prevented the measurement of the "Adaptive Reuse" and "Buildings with Sustainable Practices Certification" indicators.

Regarding the generation of construction and demolition waste, data from the 2025 PGIRS Diagnosis indicate that, in 2024, 121,653,942 m³ of such waste was generated (São Paulo, 2025a). Although it was not possible to measure the "Recycling and reuse of construction waste" indicator, the built environment scenario shows strong potential for implementing circular solutions. In this context, strategies such as the recycling of construction aggregates and the reuse and adoption of modular construction systems, which reduce material losses and facilitate dismantling and reuse, stand out, as does the implementation of monitoring systems for these actions.

Figure 39 presents an interpretive summary of the analysis conducted for the Space and Built Environment key sector, highlighting the main advances identified, the remaining challenges, and the strategic opportunities to strengthen circularity in the sector.

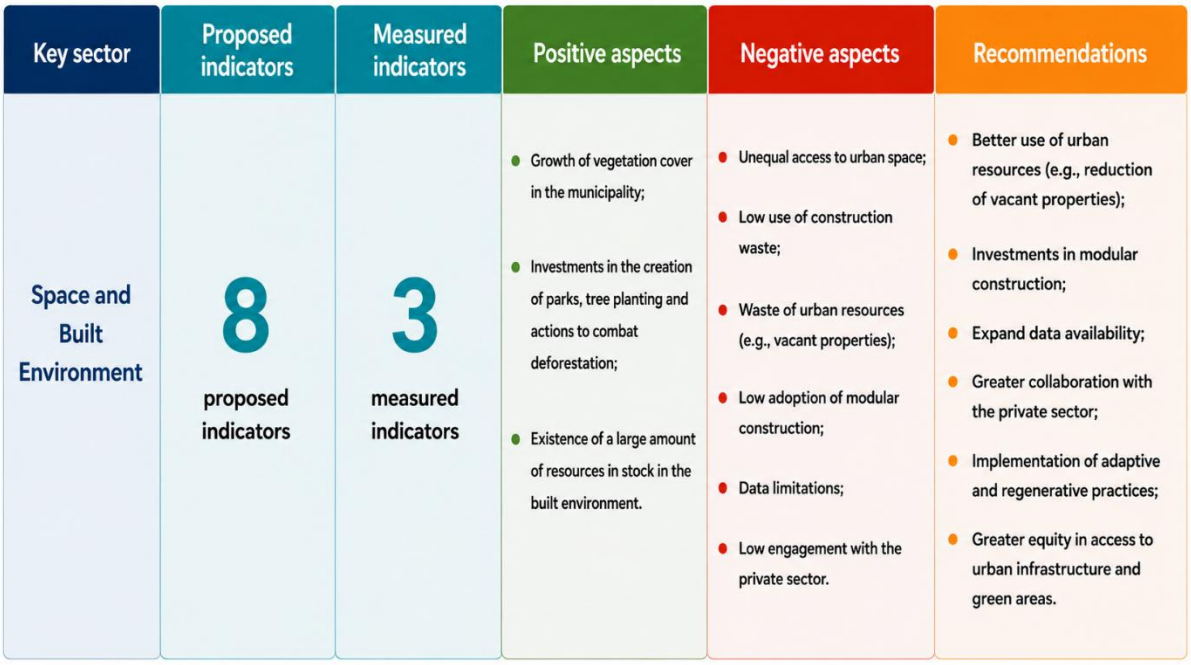


Figure 39 - Summary of the analysis of the Space and the Built Environment key sector.

Source: Developed by the author, with the assistance of ChatGPT – OpenAI (2026).

The analysis of the key sectors demonstrated that the municipality has relevant initiatives and significant potential to advance toward sustainable urban circularity in all sectors studied. Among these initiatives, composting, urban agriculture, energy recovery from landfills, incentives for sustainable mobility, the expansion of green spaces, and support for circular business models stand out.

Regarding the key sectors, Agriculture and Food, Energy, and Mobility and Transportation stood out for having more established circularity initiatives. In contrast, the sectors of Local Production and Industry, and Space and the Built Environment, presented greater limitations in implementing structured actions for the circular transition.

However, these actions still occur on an ad hoc basis, with limited coordination among key sectors, limited integration with the private sector, and difficulties implementing them at the territorial level. Thus, greater integration is needed among public policies, adaptation of urban structures, environmental regeneration, strengthening of local production, and expansion of solutions to close material, water, and nutrient cycles, in addition to initiatives focused on reducing waste generation, changing consumption patterns, and implementing upstream actions.

It is also worth noting that applying the indicators enabled an assessment of the potential and limitations of the set proposed in the tool. Overall, the indicators proved capable of identifying existing circular initiatives and gaps in action implementation, enabling opportunities for improvement across the key sectors.

This study also revealed limitations in the availability and quality of data, particularly in the Local Production and Industry and the Built Environment sectors. In several cases, the lack of systematized information made it impossible to calculate important indicators. Thus, it is recommended that information be collected to measure important aspects of the circular transition and that this data be made available.

A sustainable circular transition depends on a series of factors that can either facilitate or hinder circularity. Thus, the analysis of such factors becomes relevant. The following section presents an analysis of the main influencing factors using PESTLE analysis.

7.4 PESTLE analysis

The implementation of urban circularity in São Paulo is influenced by structural factors that can either drive or hinder its development. The PESTLE analysis was used to identify and organize the main challenges associated with implementing urban circularity in São Paulo. The results of this analysis are presented in Table 28.

Table 28 - Factors influencing the circular development of São Paulo.

P (political)	E (economic)	S (social)	T (technological)	L (legal)	E (environmental)
Policy change to promote CE.	An economic system that reinforces linear practices.	Persistence of current consumption patterns.	Technological development	Legislation aligned with a circular economy.	Climate change and extreme weather events.
Persistence of a technocentric view.	Economic transformation toward a “green” and sustainable model.	The population’s current relationship with the urban environment.	Preference for lower-value technologies for a circular economy.	Promotion of social equity, inclusion, and justice.	Increased demand for the natural resources that supply the city.
Coordination among different levels of government.	Financing of circular solutions.	Social inequalities and low pay for activities related to the circular economy.	Development of technologies for monitoring data and information.	Non-compliance (or partial compliance) with laws related to urban circularity	Pressure on protected areas.
Institutional capacity to implement urban circularity.	Incentives for circular business models.	Public engagement in circular solutions.	Partnerships with universities and research centers.	Specific laws focused on urban circularity.	Resilience of the systems that supply the municipality.
Influence of actors who prioritize linear practices.	Investment in solutions to adapt and regenerate the urban environment.	Sociodemographic.	Skilled technical workforce.	Enactment of national laws to promote the circular economy.	Negative spillover effects of technological solutions.
Resistance to systemic transformation in urban planning.	Ensuring the economic viability of circular solutions.	Creation of decent and fair job opportunities.	A dynamic business environment.	A legal framework covering all key sectors.	Scarcity of natural resources.
Continuity of public policies focused on the circular transition.	Creation of a local market for the consumption of local products, reused materials, repaired items, etc.	Social awareness and environmental education practices.	Innovation and circular development hubs.	Monitoring and enforcement of compliance with laws and guidelines.	Preservation of ecosystems.
International collaboration and partnerships in the development of public policies.	Potential for a circular bioeconomy (local agriculture).		Potential for creating technology parks with industrial symbiosis.		Land use and land cover.
Long-term systemic transformation policies.					

The PESTLE analysis was developed by applying the maturity model and analyzing the key sectors and their indicators. The factors presented in Table 28 must be considered when developing a strategy for sustainable urban circularity.

Political factors, such as the vision for urban circularity, institutional capacity, and the continuity of circular initiatives, are strategic for integrating circularity into São Paulo's planning. Currently, these factors do not drive sustainable urban circularity but rather the creation of ad hoc circularity initiatives that often focus on lower-value circular practices (recycling and energy recovery). Furthermore, the municipality faces difficulties maintaining long-term partnerships to promote sustainable urban circularity, as no recent information was found on its partnership with EMF.

Economic factors represent significant barriers to a sustainable circular transition. Adapting urban structures, regenerating nature, and relocating production may require significant investments, which are often scarce in municipalities. Furthermore, the current economic system, based on stimulating consumption, contradicts circular practices such as reducing consumption, extending the useful life of products, and repairing.

While an economic and technological perspective on circularity prevails in São Paulo, there are also signs of efforts toward social integration, particularly regarding the inclusion of waste pickers. However, most of these workers are not integrated into the formal system, remaining in precarious working conditions, thereby undermining sustainability and the achievement of SDG 8 (which calls for decent work and decent working conditions). Therefore, inequality and social disparities influence the development of a sustainable circular city.

The sociodemographic transformations a municipality undergoes directly influence circularity and constitute a relevant factor in the formulation of long-term circular strategies. This is because population changes affect the pressure the municipality exerts on natural resources, such as demand for water. These dynamics also influence the flows of materials and energy that traverse the urban system.

Regarding technological factors, they can facilitate the circularity of materials, enable sharing and exchange (through digital platforms), and create products with circular design that allow, for example, repair. However, strategies based predominantly on technological innovation tend to focus on resource efficiency, without necessarily promoting bigger changes in the production and consumption patterns that underpin urban systems.

In this regard, Calisto Friant *et al.* (2023) warn that many European cities have developed urban circularity strategies that are strongly driven by economic and technological factors, potentially limiting the promotion of broader sustainability goals. Therefore, structural transformations in production and consumption patterns and in dimensions of social justice remain limited, which reduces the potential of these strategies to promote truly sustainable urban circularity.

Beyond technological capabilities, institutional and regulatory arrangements also shape the implementation of urban circularity. Legal factors aim, among other objectives, to create an enabling environment for the development of circular strategies and actions. The municipality has a complex legal framework comprising sectoral plans (formalized by laws or decrees) that guide key sectors. Although these instruments do not always explicitly use the "lens" of urban circularity, many of them encourage the adoption of practices aligned with its principles. However, the effective implementation and enforcement of these regulations still pose challenges for São Paulo. The need to intensify oversight and expand the scope of established goals is frequently highlighted in various municipal plans.

Furthermore, the municipality currently lacks specific laws focused on the circular transition, particularly those related to urban specificities and key sectors. The legal framework includes the recently published Decree No. 64,915, dated January 26, 2026, which establishes the Municipal Impact Economy Strategy, considered by the municipality to be an economic model characterized by a balance between the pursuit of financial results and the promotion of solutions to social and environmental problems (São Paulo, 2026d). In this decree, the circular economy appears as one of the strategy's priority axes.

This framework reinforces the predominantly technocentric nature of circularity and indicates that legal mechanisms tend to support circular initiatives that promote innovation and economic gains. No laws or decrees were found linking urban circularity to an adaptive and regenerative vision for the municipality.

Environmental factors also are important drivers of urban circularity. This is evident in the way various cities around the world develop circular strategies to address climate change and reduce pressure on natural resources. However, ensuring that circularity actually results in positive environmental impacts remains a challenge, even for cities at more advanced stages of implementing these strategies.

Based on the PESTLE analysis, it can be inferred that political, economic, social, technological, legal, and environmental factors do not act in isolation but in an interdependent manner. This scenario helps maintain an approach that remains predominantly focused on waste and aligned with Level 1 of maturity in São Paulo. Institutional fragmentation (political factor), coupled with funding constraints (economic factor) and low integration among public policies, restricts the implementation of more systemic, higher-maturity strategies.

At the same time, social factors, such as inequalities in access to infrastructure and services, coupled with technological and monitoring limitations, hinder the expansion of circular practices beyond isolated initiatives. In this context, the importance of structured tools, such as the proposed maturity model, which can help managers identify these barriers and define more integrated strategies for the circular transition, is reinforced. Thus, these factors help explain why the municipality remains at Maturity Level 1 and faces difficulties advancing toward a more integrated and systemic approach to sustainable urban circularity.

The factors presented in Table 28 do not act in isolation but interact with one another, potentially both reinforcing São Paulo's persistence at Maturity Level 1 and facilitating the transition to a sustainable CC. Therefore, overcoming these barriers requires a governance mechanism capable of coordinating the different dimensions influencing urban circularity.

Although all dimensions interact, the political dimension emerges as the main enabling factor because it directly influences institutional coordination, policy continuity, stakeholder engagement, and the implementation of economic, legal, technological, social, and environmental strategies. This interpretation is consistent with Bourdin and Jacquet (2025), who identify local governments as key actors in the circular transition. According to the authors, political leadership, strategic coordination, and collaborative networks are indispensable for overcoming fragmented governance, organizational inertia, and financial constraints, thus enabling the implementation of more systemic circular strategies.

In this way, the analysis of the factors influencing urban circularity in São Paulo highlighted the need for a central orchestrator capable of driving, coordinating, and integrating the political, economic, social, technological, legal, and environmental factors that shape the circular transition. In this regard, it is proposed that the municipality establish a permanent *Urban Circularity Commission* composed of representatives from municipal departments responsible for the key sectors, organizations directly involved in resource circulation (such as networks of waste picker cooperatives, the National Association of Waste Pickers, Movimento

Circular, and the Brazilian Institute for Circular Economy), institutions dedicated to urban sustainability (such as the National SDG Movement and the Municipal Environmental Council), representatives of civil society (including neighborhood associations, student organizations, among others), private sector organizations, and research groups from local universities (such as University of São Paulo, Mackenzie Presbyterian University, and Federal University of São Paulo).

The joint participation of these stakeholders would facilitate the development of a shared vision for the city, promote the integration of public policies, coordinate cross-sectoral actions, establish long-term strategic priorities. In addition, the commission could monitor performance indicators and identify opportunities for collaboration across different sectors. More importantly, such a commission could serve as the main governance body responsible for orchestrating the long-term circular transition, ensuring the continuity of strategies regardless of changes in government, strengthening institutional coordination, and promoting systemic, participatory, and context-specific solutions.

Furthermore, a permanent governance structure would help address the fragmentation identified in the PESTLE analysis by improving coordination among the different factors that influence urban circularity, enabling political decisions, legal frameworks, technological innovation, economic incentives, environmental objectives, and social engagement to be aligned under a common long-term vision. This would allow circularity to move beyond isolated initiatives and become a cross-cutting principle guiding urban planning and decision-making. Consequently, the circular transition would be understood as a continuous process of territorial transformation, sustained through cooperation among government, academia, the private sector, and civil society.

Finally, the commission could also use the *CIRCCITY* tool as a decision-support instrument to guide strategic planning, monitor the evolution of urban circularity, assess how the different influencing factors evolve over time, and support the periodic review and adaptation of circular transition strategies.

7.5 Discussion

The application of *CIRCCITY* in the municipality of São Paulo not only enabled the assessment of the city's current stage of urban circularity but also allowed for the evaluation of

the strengths and contributions of the proposed framework in comparison with existing urban circularity assessment approaches.

Unlike many existing urban circularity frameworks, which predominantly focus on indicator systems, governance, or methodological approaches for implementing and monitoring CE initiatives, *CIRCCITY* integrates a maturity model, key sector monitoring indicators, and sustainability impact indicators into a single decision-support framework. Furthermore, by conceptualizing urban circularity as a progressive, cumulative, and systemic transition, the proposed tool extends beyond the traditional emphasis on the economic and technical dimensions of the CE. The tool explicitly incorporates social inclusion and territorial equity as core elements for achieving sustainable urban circularity.

Previous studies have emphasized the development of standardized indicator sets to assess and monitor urban circularity (Bîrgovan *et al*., 2022; Paoli *et al.*, 2022; Nurdiana *et al*., 2021). Similarly, Ferreira and Fuso-Nerini (2019) proposed a framework for monitoring circularity across urban sectors. While these frameworks provide valuable metrics for evaluating urban circularity performance, they generally assess the current state of cities rather than explicitly identifying their stage of transition or providing a structured pathway for progression towards higher levels of urban circularity.

Governance has also received increasing attention in the urban circularity literature. Gargano *et al*. (2023) proposed a governance model supported by a *Territorial Circularity Index* to guide circular economy implementation at the territorial level. In addition, Sánchez Levoso *et al*. (2020) developed a methodological framework to support the planning and implementation of CE initiatives. Together, the frameworks proposed by Gargano *et al*. (2023) and Sánchez Levoso *et al*. (2020) reflect the evolution of the urban circularity literature from performance measurement toward governance, planning, and strategic management of urban circular transitions.

The *Urban Circularity Assessment Framework* (UCAF) proposed by Vanhuyse (2024) represents one of the most comprehensive frameworks for supporting planning, monitoring, evaluation, and learning in urban CE transitions. Based on the Theory of Change, its primary objective is to understand how a city's CE strategy is structured, how its different elements are interconnected, and where gaps exist to guide improvements. While the UCAF explains and evaluates a city's CE strategy, *CIRCCITY* operationalizes and supports the management of the transition toward sustainable urban circularity.

Building upon these contributions, *CIRCCITY* integrates maturity assessment, key sector monitoring indicators, and sustainability impact evaluation into a unified decision-support framework, bringing together dimensions that have traditionally been addressed separately in the urban circularity literature. Rather than simply measuring circularity performance or identifying strategic gaps, *CIRCCITY* enables municipalities to determine their current stage of transition, prioritize actions according to their maturity level, and monitor progress toward higher levels of sustainable urban circularity.

Finally, *CIRCCITY* operationalizes the holistic conceptualization of sustainable urban circularity proposed in this thesis by integrating social inclusion, territorial equity, and adaptive and regenerative principles into a practical decision-support tool.

8. CONCLUSIONS

The objective of this study was to develop a tool to support the transition to sustainable urban circularity; the study's conclusions are presented in the following sections.

8.1 Implementation of Urban Circularity in European Cities

To develop the *CIRCCITY* tool, an exploratory study was first conducted to understand how cities have implemented circular actions and strategies. This study focused primarily on European cities (and urban areas) and demonstrated that such localities concentrate their initiatives on closing material cycles (recycling, repair, and reuse) and nutrient cycles (collection and recovery of organic waste).

Although these cities are making progress in closing material and biological cycles, approaches focused on downstream processes and technological innovation (rooted in a technocentric view of CE) still predominate, with little attention paid to upstream initiatives to reduce resource and virgin material consumption. Similarly, there is limited incorporation of adaptive and regenerative actions to restructure urban infrastructure and promote the better use and preservation of natural resources. Finally, the study demonstrated that many European cities still face limitations in incorporating social justice into their circular initiatives.

Brazilian cities can look to European initiatives for inspiration, but they must focus on solutions that reduce consumption, prevent waste, and promote social inclusion, especially considering Brazil's socioeconomic realities. Implementing urban circularity in Brazil should also include adaptive and regenerative measures to enhance urban resilience and combat climate change.

The CPS analysis was also particularly relevant to the development of this study, as it allowed us to observe, from an applied perspective, how a European urban area structures its circular transition by coordinating spatial planning, intermunicipal governance, research institutions, economic actors, and local initiatives. Furthermore, the Paris-Saclay urban area demonstrates that universities can serve as strategic actors in the circular transition, contributing to knowledge production and solution development.

Thus, the study of cities that have already implemented circular strategies has provided insights into how a tool to support the circular transition can be structured to help managers address the challenges they face. This study concluded that the tool should enable the diagnosis,

monitoring, and evaluation of the impacts of the sustainable urban circular transition, thereby avoiding potential negative rebound effects. Furthermore, these results allowed us to answer the first research question (how is urban circularity being implemented in cities considered benchmarks, and what lessons can be applied to the Brazilian context?).

8.2 Development of the decision support tool

The main objective of this study was to develop a decision-support tool to help public managers in the transition toward sustainable urban circularity. This objective was achieved through the Design Science Research (DSR) approach, which guided the development of the artifact named *CIRCCITY (Circular City Transition Tool).*

The adoption of the DSR approach enabled the integration of theoretical and practical knowledge throughout the entire research process, from problem identification and the definition of solution requirements to the construction, validation, and demonstration of the tool in a real-world context. As a result, a structured solution was developed to support the diagnosis, monitoring, and planning of the transition toward sustainable urban circularity. Therefore, DSR proved to be an effective approach for supporting the development of tools aimed at complex systems, such as urban systems, and for assisting public managers in decision-making processes.

Based on the exploratory study, the *CIRCCITY* artifact was proposed and structured into three components: (1) a maturity model, which allows for the diagnosis of the current situation and supports the planning of future stages of the circular transition; (2) a set of sectoral indicators, aimed at monitoring results in key sectors; and (3) a set of sustainability indicators, designed to assess environmental, social, and economic impacts. Thus, it was possible to answer the second research question (what are the support needs of urban managers in the circular transition, and how can a tool be structured to meet these needs?).

Thus, the decision-support tool can integrate, within a single framework, the diagnosis of a city's current state of circular development, a set of indicators for monitoring circular actions, and the assessment of impacts on urban sustainability. With this structure, the tool offers urban managers an integrated resource that supports a sustainable circular transition in the long term.

By linking these three components, the *CIRCCITY* allows public managers to understand not only the city's current stage but also the possible paths to advance toward urban

circularity that can promote social, environmental, and economic benefits. Besides, the tool helps identify gaps and opportunities for improvement in urban management, enabling public policies to be implemented in a more strategic, integrated manner aligned with the principles of sustainable development. It is worth noting that the tool can be used cyclically to ensure continuous improvement.

Furthermore, making *CIRCCITY* available on a free online platform expands the study's potential for practical application. This is because it allows public managers, researchers, and other actors involved in the urban circular transition to access the three components of the developed tool. On the platform, users can complete the model's rubric questionnaire to assess a city's maturity level (component 1) and access the indicators proposed in components 2 and 3.

Thus, the study contributes to the development of urban circularity by proposing an integrated decision-support framework to assist public managers in diagnosing, monitoring, and evaluating the circular transition in cities. Unlike studies that address urban circularity in a sectoral or fragmented manner, the proposed *CIRCCITY* tool integrates different aspects of the circular transition into a single decision-support framework.

8.2.1 Component 1: Maturity Model

Regarding the development of the maturity model, the adopted methodology proved appropriate and consistent for the proposed tool. The proposed maturity levels were developed based on academic literature on the subject, documentary analysis, and practical observation. These studies ensured the model's relevance and rigor, as proposed by DSR (the rigor and relevance cycles).

In constructing the maturity model, the learning (co-creation) stage, in which experts are directly involved in implementing urban circularity, stands out. In total, 18 experts from 12 countries participated in the study, broadening the diversity of perspectives considered and enabling the incorporation of contributions from professionals working in urban contexts at varying levels of development. This process strengthened the proposal's robustness and relevance by integrating knowledge and experience from diverse socioeconomic and urban contexts. The participatory and iterative nature aligns with the principles of DSR, more specifically with the design cycle.

In this study, four maturity levels are proposed to represent the transition from a linear city to a circular, sustainable model. The levels are: Level 0 – Linear City (in which the city shows no concern for the efficient use of resources); Level 1 – Waste Management (in which cities begin to structure actions focused on waste management); Level 2 – Circular Economy (characterized by the creation of conditions favorable to the development of the CE); and Level 3 – Sustainable Circular City (in which urban circularity is implemented in a systemic and integrated manner, oriented toward promoting urban sustainability).

These levels are assessed in categories, determined by the theoretical framework and expert input. These categories are: Vision, Governance and Actors, Material Cycle, Biological and Water Cycle, Space and Built Environment, and Equity and Social Justice. The degree of maturity can be calculated for each of these categories, adding greater detail to the model and allowing measurement of the evolution of different aspects of cities toward sustainable circularity.

It is worth noting that the progression of levels within each category shows that the urban circular transition entails transformations that extend beyond the implementation of CE practices. It incorporates structural changes related to urban management, land use, the preservation of natural resources, and the integration of social and territorial aspects of sustainability.

It is also worth noting that the rubric questionnaire and the scoring system for calculating the circularity index were fundamental for operationalizing the assessment of urban circularity. These instruments enabled the transformation of theoretical and qualitative concepts into structured criteria for analysis.

Thus, it is concluded that the maturity model developed in this study enables not only the diagnosis of cities' maturity stages but also the prioritization and guidance of strategies for the transition toward urban circularity across different aspects of urban systems. Consequently, the model contributes to the planning and strategic direction of the sustainable urban circular transition.

8.2.2 Components 2 and 3: Monitoring Indicators for Key Sectors and Impacts

Components 2 and 3 of the *CIRCCITY* tool were developed based on indicators identified through a literature review. This review concluded that although studies on indicators for circular cities have increased in recent years, gaps remain in this field. Among these gaps,

the following stand out: the need to develop indicators capable of assessing the quantity of resources in stock in cities; the development of social indicators that allow for the assessment of structural and behavioral changes related to the circular transition; and environmental indicators that measure the impacts of local circular actions on the resource footprint beyond the local territory.

Regarding the selection of the indicators that comprised these components, this was initially carried out using pre-established criteria, namely: consistency, applicability, redundancy, and utility. When analyzing and selecting the indicators based on these criteria, it became apparent that a large portion was excluded due to redundancy. This finding leads to the conclusion that, despite the high number of identified indicators, many measured the same aspects, primarily related to the monitoring of downstream actions.

The iterative process of the DSR stood out in the development of components 2 and 3. It involved consulting 22 experts from five countries, who evaluated, validated, and suggested improvements to the proposed set of indicators. This process enabled the incorporation of these professionals' practical experience into the developed tool, helping ensure its applicability in line with the DSR's objectives.

It is worth noting that, among the studies identified in the SLR on urban circularity indicators, few were dedicated to consulting experts and validating the proposed indicators. Thus, the iterative process carried out in this study differs from the others by incorporating practical and technical contributions from experts directly involved in urban circularity.

Regarding the indicators, the proposed set was deemed useful by the experts, as all indicators showed agreement exceeding 50%. In total, 57 indicators were proposed, with 37 related to the monitoring of key sectors and 20 focused on assessing environmental, social, and economic impacts.

However, it is worth noting the difficulty in measuring the indicators (especially in the Brazilian context), pointed out by the experts and confirmed during the tool's application in São Paulo. This challenge highlights the need for Brazilian municipalities to collect strategic data to develop public policies on circularity and urban sustainability. Furthermore, there is also a need to periodically update this information and make it publicly available.

In light of this, it is concluded that this study contributes to research on monitoring urban circularity by identifying gaps that remain in this field. Furthermore, it enabled the selection

and validation of indicators to assist public managers in monitoring and evaluating circular strategies, thereby contributing to the development of more effective public policies for a sustainable urban circular transition.

8.3 Application of the *CIRCCITY* Tool in São Paulo

The application of *CIRCCITY* in the city of São Paulo demonstrated its ability to support the diagnosis of urban circularity in a structured manner, enabling an understanding of the progress, weaknesses, and challenges associated with the circular transition in the Brazilian context. In addition, the tool enabled the collection of relevant information to inform urban planning and the formulation of future strategies, thereby addressing the third research question (what does the application of the tool reveal about the stage and challenges of the circular transition in a Brazilian city?).

Applying the maturity model, we determined that the municipality is at Level 1 (Waste Management) according to the classification proposed in this study, based on an average circularity index across the categories of 48,85%. This result indicates that the municipality has made progress in incorporating circular practices, though actions focused on waste management still predominate and lack a consolidated systemic approach.

The analysis by category shows that three categories stand out in circular development: Vision, with a circularity index of 61.1%; Governance and Actors, with a circularity index of 54.4%; and Biological and Water Cycle, with a circularity index of 60%. The result indicates that São Paulo is beginning to view the circular economy beyond waste management, and that practices are being implemented in the Biological and Water Cycle sector. This result is mainly due to the project's use of organic compost in local agriculture and its link to the creation of a market for local production.

However, the implementation of solutions to close nutrient cycles remains limited, and a large amount of organic waste is sent to municipal landfills. Regarding São Paulo’s water resources, they suffer from the effects of urbanization, such as the channeling of water bodies and diffuse pollution from waste in rivers, highlighting the need to implement circular practices, such as water reuse, nutrient recovery from sewage, and the regeneration of rivers and riverbanks.

The Material Cycle category was classified as Level 1 (Waste Management), achieving a circularity index of 44.44%. With this result, it can be concluded that although the

municipality recognizes the potential of the circular economy to close the material cycle, implementation is limited in practice. São Paulo's material flows receive solutions related to proper disposal and limited energy recovery; initiatives of greater value for urban circularity are lacking, such as actions aimed at waste prevention, material repair, and remanufacturing, among others.

Regarding the Built Environment category, it achieved a circularity index of 48.1% and was therefore classified as Level 1 (Waste Management). This category analyzes how circular practices are implemented in urban space and demonstrates that the territory is not yet organized to facilitate the closure of material flows or to optimize resource use; furthermore, it does not seek to utilize existing resources ("in stock") in buildings and urban infrastructure. Therefore, it is important for São Paulo to pursue more advanced approaches, such as building retrofits, the reuse of existing structures, the systematic use of circular materials, and urban planning oriented toward the adaptation and regeneration of natural ecosystems.

Finally, the lowest circularity index was observed in the Equity and Social Justice category, classified as Level 0 (Linear City), reflecting deep inequalities in the city's resources and access. Therefore, regarding the benefits of circularity for the population, it is evident that São Paulo still experiences the negative externalities caused by linear thinking. Furthermore, this result suggests that the social dimension has not yet been structurally integrated into urban circularity strategies.

Drawing a parallel between São Paulo and the French urban area of Paris-Saclay, the CPS experience indicates that the Brazilian city can make progress in developing a circular agenda that brings together government, universities, businesses, and civil society, as well as strengthening cooperation among municipalities. This coordination is particularly relevant given the interdependence between São Paulo and the other municipalities in the metropolitan region in closing urban flows and implementing circular initiatives in key sectors.

Regarding the analysis of key sectors, although it is limited by the complexity of each sector, it was observed that actions aligned with the principles of the Circular Economy exist across all sectors. In the Waste key sector, efforts to recover value from waste were evident. In the Agriculture and Food key sector, the implementation of regenerative agriculture using composting stands out. Regarding Local Production and Industry, municipal initiatives that encourage circular business models were observed.

Regarding the Energy key sector, the municipality encourages the use of solar energy and seeks to adapt the infrastructure. In the Mobility and Transportation key sector, the implementation of infrastructure focused on active mobility stands out, particularly the use of bicycles. In the Water and Sanitation key sector, initiatives for the reuse of treated water are observed. Finally, in the Space and the Built Environment key sector, the increase in the municipality's green spaces stands out.

However, the results show that São Paulo's sustainable circular transition still faces significant structural challenges. The main one is the need to recognize and incorporate the principles of urban circularity across municipal planning. Furthermore, the study concluded that the city's prevailing view remains rooted in a technocentric perspective on the circular economy, with a focus on economic opportunities and the creation of circular businesses.

The PESTLE analysis reinforces this finding by showing that technical limitations alone do not constrain this transition. Political, institutional, economic, and social factors hinder the integration of public policies, limit social inclusion, and keep circularity confined to isolated, low-value initiatives.

To achieve results more aligned with sustainability, São Paulo needs to advance in implementing higher-value actions for urban circularity, such as those aimed at waste prevention, reuse, and, at the macro level, encouraging circular product design, as well as promoting social inclusion, not only for waste pickers but also in terms of equitable access to urban resources.

Thus, it is concluded that advancing urban circularity in the municipality depends on adopting a more systemic approach that integrates all key sectors, promotes regenerative solutions, adapts urban structures, localizes production, and, at the same time, creates benefits for economic, environmental, and social sustainability. Therefore, the transition to sustainable circular cities requires not only the implementation of technical solutions but also a structural transformation of urban development models that integrates social, territorial, and environmental dimensions.

8.4 Contributions of the study

This study advances the urban circularity literature through five main scientific contributions. In addition, it provides a practical contribution by making the proposed decision-support tool freely available through a digital platform.

First, this research contributes conceptually by proposing an interpretation of urban circularity as a progressive, cumulative, and systemic transition process toward sustainable urban development. Rather than defining urban circularity solely as the implementation of isolated CE initiatives, this study conceptualizes it as a long-term process involving the gradual integration of governance capacities, institutional arrangements, circular practices, and social transformation.

Second, this study advances theory by arguing that urban circularity should be understood as a continuum of development rather than as a binary condition in which cities are either circular or non-circular. Accordingly, cities may occupy different levels of urban circularity depending on the extent to which governance capacities, institutional arrangements, and circular practices are developed and integrated. This theoretical perspective provides the conceptual foundation for assessing different levels of urban circularity.

Third, this study contributes conceptually by explicitly incorporating social inclusion and territorial equity as fundamental dimensions of sustainable urban circularity. It argues that a sustainable urban circular transition depends not only on circular resource management but also on the social inclusion, inclusive governance, territorial equity, and equitable access to urban resources. By integrating these dimensions into the conceptualization of urban circularity, the study contributes to a more holistic understanding of the transition process.

Fourth, this study makes a methodological contribution by developing *CIRCCITY*, an integrated decision-support tool for sustainable urban circularity. The tool integrates the maturity model, assessment questionnaire, validated indicators, and decision-support functionalities into a single framework for diagnosing, planning, monitoring, and evaluating the urban circular transition. Such an integrated architecture enables public managers to assess current conditions, prioritize actions, and monitor progress throughout the transition process. This contribution is particularly relevant in urban contexts marked by socioeconomic inequalities and institutional constraints, such as those in Brazil.

Although *CIRCCITY* was applied in Brazil, its conceptual structure is not limited to the Brazilian context. The tool was developed based on a broad conceptual foundation of urban circularity, an analysis of international experiences, consultations with experts from different countries, and the identification of key sectors and indicators applicable to a wide range of urban systems. Consequently, the proposed framework has the potential to support urban circular transitions across different territorial and institutional contexts.

Finally, this study contributes empirically by applying *CIRCCITY* in the municipality of São Paulo, thereby expanding knowledge on the urban circular transition in the Global South. Its application demonstrates how an integrated decision-support framework can support public managers operating in contexts characterized by institutional constraints, socioeconomic inequalities, and complex resource management challenges. Furthermore, the findings provide empirical evidence on the current stage of urban circularity in a major Latin American metropolis, contributing to the diversification of a literature that remains predominantly based on European experiences.

In addition to these scientific contributions, *CIRCCITY* is also made freely available through a digital platform. The platform enables urban managers, researchers, and other stakeholders to access the tool's three components, assess urban circularity maturity through the proposed questionnaire, consult the validated indicators, and support the diagnosis, planning, monitoring, and evaluation of urban circularity. By extending the tool beyond the academic environment, this initiative facilitates knowledge transfer and promotes evidence-based decision-making for sustainable urban circularity, particularly in Brazilian municipalities but also in other urban contexts.

8.5 Takeaway message

The main findings of this thesis can be summarized in the following key messages, which highlight the principal theoretical, methodological, and practical insights for advancing urban circularity:

- Urban circularity should be understood as a progressive, cumulative, and systemic transition rather than as the implementation of isolated CE initiatives.
- Current urban circularity strategies remain predominantly technocentric, reinforcing the need to integrate social inclusion and territorial equity as core dimensions of sustainable urban circularity.
- Advancing urban circularity requires integrated decision-support tools capable of diagnosing maturity, guiding planning, monitoring progress, and evaluating sustainability impacts.
- *CIRCCITY* operationalizes this perspective by integrating a maturity model, key sector monitoring indicators, and sustainability impact indicators into a comprehensive decision-support framework.

- The application of *CIRCCITY* classified São Paulo at Maturity Level 1 (Waste Management), indicating that its urban circular transition remains centered on waste management and must advance toward higher levels of urban circularity.

8.6 Limitations and suggestions for future work

This study has some limitations. The first relates to the exploratory nature of the study, which focused on analyzing European cities, thereby limiting the perspective on CCs to the strategies and actions adopted on the European continent. Although Europe is considered a benchmark in the development of the CE, it would be beneficial to this study to understand the implementation and initiatives of urban circularity on other continents. In this regard, it is suggested that future research explore the topic beyond the European context.

In the literature review conducted to identify urban circularity indicators, some limitations should be acknowledged. The criteria used to screen the articles may have excluded relevant studies from the final set analyzed. Furthermore, the articles were identified in only two databases, Scopus and Web of Science, which limits the scope to studies indexed on these platforms. Added to this is the fact that the time frame adopted may have excluded relevant articles published before or after the defined period. Finally, although the systematic review follows rigorous methodological protocols, there may still be some degree of interpretive subjectivity, especially in the stages of analyzing the articles and indicators and in synthesizing the results.

Regarding the maturity model, some limitations are also identified. First, the model is conditioned on the topic's current stage of development, since studies on urban circularity are still recent and the topic remains underexplored in the literature. Thus, future studies may focus on updating the proposed maturity model by considering new theoretical advances and practical experience in implementing CCs. Furthermore, the maturity level assessment developed in this study is based on qualitative questions that may involve some subjectivity in interpreting responses.

Furthermore, this type of assessment relies heavily on respondents' perceptions and knowledge of existing initiatives, which may lead to differences in how practices are reported or understood. Thus, the development of quantitative parameters that enable a more objective assessment of a city's progress toward sustainable circularity is relevant both to advancing

knowledge in the academic community and to supporting urban managers in monitoring and decision-making related to the circular transition.

Regarding the set of indicators proposed in this study, it may be updated in the future as research on the development of urban circularity indicators advances and begins to address aspects that are currently not measurable but are relevant to cities aspiring to become circular. This refinement is necessary, particularly regarding indicators in the Space and the Built Environment key sector and the dimensions of sustainability, especially the environmental and social dimensions, as discussed in Chapter 6.

The application of the tool in the municipality of São Paulo also has limitations. The size of the municipality, combined with its specific sociodemographic characteristics and its spatial and economic dynamics, makes it difficult to conduct comprehensive analyses of the territory. This study presents an initial analysis of the key sectors; however, given the municipality's complexity, further studies are needed to provide a more in-depth analysis of each sector. In this regard, it is suggested that future studies delve deeper into each key sector and analyze the circular transition in a territorialized manner, taking into account the local characteristics of the different regions of the city of São Paulo.

In addition, future studies can help improve the digital platform through user-experience-based research methodologies, such as usability tests, interviews with public managers, and evaluations of interactions with the platform. These methodologies can help verify clarity, accessibility, ease of use, and support for decision-making processes. Such tests can be integrated into future cycles of the DSR.

Despite these limitations, the study demonstrates that the transition to sustainable circular cities can be supported by tools that integrate diagnosis, planning, monitoring, and impact assessment. In this sense, the proposed tool does not conclude the debate on how to measure or implement urban circularity but offers an initial framework to support cities at different stages of transition and paves the way for new studies on the topic.

8.7 Scientific output and academic activities related to the thesis

The development of this thesis also led to academic and scientific contributions on CE and urban circularity, including journal publications and presentations at scientific events, awards, academic grants, and participation in research activities and extension projects.

- **Awards and scholarships**

1. Award for one of the best works in Industrial Engineering at the IEPG Summit 2023.
2. Award-winning work among the best presentations at the WREN Symposium 2024.
3. Honorable Mention at the 7th Scientific Initiation Symposium of the Federal University of Itajubá.
4. Competed for the AMS Young Scientist Award (AYSA).
5. Awarded a short-term internship scholarship abroad by the Federal University of Itajubá in 2022.
6. Awarded a scholarship from the Sandwich Doctoral Program of the Coordination for the Improvement of Higher Education Personnel in 2022/2023.
7. Recipient of the AMS Scientific Conference 2026 Scholarship for Visiting Researchers.

- **Publications in scientific journals and book chapters**

1. **Moraes, F. T. F**.; Campos, M. L.; Hugo, A.; Lima, R. S. (2026). The Influence of Public Policies on Advancing Fashion Circularity. In: *Fashion, Textiles and CE*. Routledge. Book chapter accepted for publication.
2. Bernardes, M.; **Moraes, F. T. F**.; Tanaka, K. H.; Lima, R. S. (2023). Engaging the End User in Waste from Electrical and Electronic Equipment Management: An Action-Research Study. *Systematic Practice and Action Research*, v. 1, p. 1–22. DOI: 10.1007/s11213-023-09646-y.
3. **Moraes, F. T. F**.; Gonçalves, A. T. T.; Lima, J. P.; Silva, R. S. (2022). Transitioning Towards a Sustainable Circular City: How to Evaluate and Improve Urban Solid Waste Management in Brazil. *Waste Management and Research*, v. 1, p. 0734242X2211422-0. DOI: 10.1177/0734242X221142227.
4. **Moraes, F. T. F**.; Gonçalves, A. T. T.; Lima, J. P.; Lima, R. S. (2021). An Assessment Tool for Healthcare Waste Management in Brazilian Municipalities During the COVID-19 Pandemic. *Waste Management and Research*, v. 40, p. 607–608. DOI: 10.1177/0734242X21104520.

- **Publications in scientific events.**

1. **Moraes, F. T. F**.; Bouillass, G.; Lima, R. S. (2026). Proposal of a Maturity Model to Support the Urban Circular Transition. In: AMS Scientific Conference 2026, Amsterdam.

2. **Moraes, F. T. F**.; Almeida, L. F.; Lima, R. S. (2025). Prioritization of Strategic Actions for Glass Reverse Logistics in Brazil: An Application of the AHP Method. In: XLV National Meeting on Production Engineering, Natal.
3. Souza, L. C.; Alves, R.; **Moraes, F. T. F**.; Nascimento, K. M.; Santos, J. B. (2025). Life Cycle Assessment (LCA) of an airline's snack packaging. In: XLV National Meeting on Production Engineering, Natal.
4. **Moraes, F. T. F.**; Santiago, D. P. M.; Lima, R. S. (2024). Circular Economy: An analysis of the development of Circular Cities in Brazil. In: 10th PLURIS, Guimarães.
5. **Moraes, F. T. F**.; Ribeiro, A. J.; Lima, R. S. (2024). Development of Circular Cities: A SWOT Analysis. In: WREN Symposium 2024.
6. **Moraes, F. T. F**.; Lima, R. S. (2023). Circular Economy in Brazil: A survey of indicators for monitoring circular cities. In: IEPG Summit 2023, Itajubá/MG, Brazil.
7. Ribeiro, A. J.; **Moraes, F. T. F**.; Lima, R. S. (2023). Transition to Circular Cities: An initial study on the Circular Economy in the city of São Paulo. In: Scientific Initiation Symposium of the Federal University of Itajubá.
8. **Moraes, F. T. F**.; Ribeiro, A. J.; Lima, R. S. (2023). Circular Cities: An analysis of Circular Economy initiatives in European cities. In: ENEGEP 2023, Fortaleza/CE, Brazil.
9. **Moraes, F. T. F**.; Bouillass, G.; Ribeiro, A. J.; Yannou, B.; Lima, R. S. (2023). How Circular Economy Initiatives in Urban Areas Can Help Achieve the Sustainable Development Goals (SDGs). In: The 1st WREN Symposium, Online.
10. **Moraes, F. T. F**.; Santos, J. B.; Lima, J. P.; Lima, R. S. (2022). Forecasting household waste collection: A SARIMA model applied to the city of São Paulo. In: ENEGEP 2022, Foz do Iguaçu, Paraná, Brazil.
11. Silva, C. M. P.; **Moraes, F. T. F**.; Mello, C. H. P.; Pinto, W. G. M.; Amaral, J. V. S. (2022). Application of Computer Simulation for Decision Making in a Clinical Analysis Laboratory in the Municipality of Itajubá/MG. In: ENEGEP 2022, Foz do Iguaçu/PR, Brazil.
12. Almeida, L. F.; **Moraes, F. T. F**.; Leal, F.; Lima, R. S. (2021). Comparative analysis and process mapping of reverse logistics for glass containers: Brazil vs. Austria. In: ENEGEP 2021, Online.

- **Other activities**

1. Participation in Final Course Project committees: 6 committees.

2. Co-supervision of Final Course Projects: 3 co-supervisions
3. Undergraduate research projects: 4 projects.
4. Review of articles in journals: *Waste Management & Research*; *Cleaner Waste System*; and *Systemic Practice and Action Research*
5. Scientific committee for academic events: WREN *Symposium*, ENEGEP, and Unifei Scientific Initiation.
6. Extension project: 1 project (Women's Research Engineers Network)
7. Organization of academic events: 7 events

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APPENDIX A - Expert panel profiles for the co-creation of the Maturity Model

Expert	Profile
1	Engineer with expertise in circular cities, smart cities, and the circular economy.
2	PhD in Economic Geography specializing in regional development, with an emphasis on the territorial implementation of the circular economy.
3	Researcher in Spatial Planning and Urban Development specializing in the spatial dimensions of the circular economy.
4	PhD in Economics with expertise in spatial and industrial economics, territorial dynamics, and the circular economy.
5	PhD in Urban Planning with expertise in resource circularity and sustainable urban systems.
6	PhD in Environmental Science with expertise in the circular economy, political-industrial ecology, care studies, and circular cities.
7	Specialist in Urban and Regional Planning with expertise in the spatial dimensions of circular, sustainable, and just transitions.
8	MSc in Architecture with expertise in the circular economy, public spaces, and sustainable urban development.
9	Sustainability specialist with expertise in circular cities and the implementation of the circular economy in public administration.
10	Environmental Manager with expertise in the circular economy, urban public policies, and solid waste management.
11	MSc in Public Administration with expertise in circular cities and sustainable urban governance.
12	PhD in Public Administration and public manager specializing in the application of the circular economy to urban governance.
13	Architect with expertise in material reuse, urban industry, and urban circularity.
14	Environmental Economist with expertise in public policies, circular cities, and eco-industrial parks.
15	Business Administration specialist with expertise in developing indicators and indices for assessing the progress of circular cities.
16	Architect and Urban Planner specializing in the circular economy and circular cities.
17	Environmental Scientist with expertise in circular cities, waste management, and smart urban systems.
18	Researcher specializing in the circular economy and society, urban political ecology, and sustainable urban transitions.

APPENDIX B - Articles used in the SLR

	Title	Journal	Author
1	Evaluation of urban circular economy performance: A novel fully fuzzy data envelopment analysis with large datasets	*Journal of Cleaner Production*	Wang *et al.* (2021)
2	Unraveling how the concept of circularity relates to sustainability: An indicator-based meta-analysis applied at the urban scale	*Journal of Cleaner Production*	Superti *et al.* (2021)
3	Toward the construction of a circular economy eco-city: An emergy-based sustainability evaluation of Rizhao city in China	*Sustainable Cities and Society*	Li *et al*. (2021)
4	Regional development of the circular economy in the European Union: A multidimensional analysis	*Journal of Cleaner Production*	Silvestri *et al*. (2020)
5	Pathways toward a regional circular economy evaluated using material flow analysis and system dynamics	*Resources, Conservation and Recycling*	Gao *et al.* (2020)
6	Moving Towards the Circular Economy/City Model: Which Tools for Operationalizing This Model?	*Sustainability*	Girard and Nocca (2019)
7	A More Circular City in the Energy and Ecological Transition: A Methodological Approach to Sustainable Urban Regeneration	*Sustainability*	Balletto *et al.* (2022)
8	Monitoring progress toward a circular economy in urban areas: An application of the European Union circular economy monitoring framework in Umeå municipality	*Sustainable Cities and Society*	Henrysson *et al*. (2022)
9	Methodological framework for the implementation of the circular economy in urban systems	*Journal of Cleaner Production*	Sánchez Levoso *et al*. (2020)
10	Indicators for the Circular City: A Review and a Proposal	*Sustainability*	Paoli *et al*. (2022)
11	How Should We Measure? A Review of Circular City Indicators	*Environmental Research & Public Health*	Bîrgovan *et al.* (2022)
12	Evaluation of Urban Circular Economy Development: An Empirical Study of 40 Cities in China	*Journal of Cleaner Production*	Wang *et al*. (2018)
13	Comparative assessment of circular economy development in China's four megacities: The case of Beijing, Chongqing, Shanghai, and Urumqi	*Journal of Cleaner Production*	Guo *et al*. (2017)
14	Circular Economy Strategies in Eight Historic Port Cities: Criteria and Indicators Towards a Circular City Assessment Framework	*Sustainability*	Gravagnuolo *et al*. (2019)
15	Assessment of the urban circular economy in Sweden	*Journal of Cleaner Production*	Heshmati and Rashidghalam (2021)
16	A Framework for Implementing and Tracking the Circular Economy in Cities: The Case of Porto	*Sustainability*	Ferreira and Fuso-Nerini, (2019)
17	How Shall We Start? The Importance of General Indices for Circular Cities in Indonesia	*Sustainability*	Nurdiana *et al*. (2021)
18	Assessment of municipal waste in a circular economy: Do European Union countries share identical performance?	*Cleaner Waste Systems*	Marques and Teixeira (2022)
19	Assessing water circularity in cities: Methodological framework with a case study	*Resources, Conservation and Recycling*	Arora *et al*. (2022)

20	Inflows and Outflows from Material Stocks of Buildings and Networks and their Space-Differentiated Drivers: The Case Study of the Paris Region	*Sustainability*	Augiseau and Kim (2021a)
21	Spatial characterization of construction material stocks: The case of the Paris region	*Resources, Conservation, and Recycling*	Augiseau and Kim (2021b)
22	Human-Centered Indicators (HCI) to Regenerate Vulnerable Cultural Heritage and Landscape toward a Circular City: From the Bronx (NY) to Ercolano (IT)	*Sustainability*	Bosone and Ciampa (2021)
23	Mapping sustainability and the circular economy in cities: A methodological framework from Europe to the Spanish case	*Journal of Cleaner Production*	Alonso *et al*. (2022)
24	Towards circular water neighborhoods: Simulation-based decision support for integrated decentralized urban water systems	*Water*	Bouziotas *et al*. (2019)
25	Sustainability assessment of increased circularity of urban organic waste streams	*Sustainable Production and Consumption*	Ddiba *et al*. (2022)
26	ICT as innovative tools for circular planning in urban areas	*TECHNE - Journal of Technology for Architecture and Environment*	Filippi *et al*. (2021)
27	Embedding Circular Economy Principles into Urban Regeneration and Waste Management: Framework and Metrics	*Sustainability*	Domenech and Borrion (2022)
28	Seeking Circularity: Circular Urban Metabolism in the Context of Industrial Symbiosis	*Sustainability*	Feiferytė-Skirienė and Stasiškienė (2021)
29	Evaluating circular economy performance based on ecological network analysis: A framework and application at the city level	*Resources, Conservation, and Recycling*	Gao *et al*. (2021)
30	Transitioning towards a sustainable circular city: How to evaluate and improve urban solid waste management in Brazil	*Waste Management & Research*	Moraes *et al*. (2022)
31	Water Cycle and Circular Economy: Developing a Circularity Assessment Framework for Complex Water Systems	*Water Research*	Nika *et al*. (2020)
32	Towards circular cities—Conceptualizing core aspects	*Sustainable Cities and Society*	Pahio *et al*. (2020)
33	Governance Model for a Territory Circularity Index	*Sustainability*	Gargano *et al*. (2023)
34	Operationalizing the Circular City Model for Naples' City-Port: A Hybrid Development Strategy	*Sustainability*	Cerreta *et al*. (2020)
35	An Assessment Approach to Circular Business Models within an Industrial Ecosystem for Sustainable Territorial Development	*Sustainability*	Gamidullaeva *et al*. (2022)
36	Exploring circular water options for a water-stressed city: Water metabolism analysis for Paju City, South Korea	*Sustainable Cities and Society*	Hong and Park (2023)
37	Eco-Efficiency Evaluation of Regional Circular Economy: A Case Study in Zengcheng, Guangzhou	*Sustainability*	Liu *et al*. (2018)
38	Prospects for a circular bioeconomy in urban ecosystems: Proposal for a theoretical framework	*Journal of Cleaner Production*	Paes *et al*. (2022)
39	Combining LCA and circularity assessments in complex production systems: the case of urban agriculture	*Resources, Conservation and Recycling*	Rufí-Salis *et al*. (2021)
40	Including the social in the circular: A mapping of the consequences of a circular economy transition in the city of Umeå, Sweden	*Journal of Cleaner Production*	Vanhuyse *et al*. (2022)

41	The Circular Regeneration of a Seaport	*Sustainability*	Williams (2019c)
42	The material footprints of cities and the importance of resource use indicators for urban circular economy policies: A comparison of the urban metabolisms of Nantes-Saint-Nazaire and Gothenburg	*Cleaner Production Letters*	Bahers and Rosado (2023)
43	Assessing city performance and resource improvement in China: A sustainable circular economy framework approach	*Environmental Impact Assessment Review*	Wu *et al*. (2022)
44	Consequence CO2 footprint analysis of circular economy scenarios in cities	*Cleaner Production Letters*	Liu *et al*. (2023)
45	The Urban Circularity Assessment Framework (UCAF): a Framework for Planning, Monitoring, Evaluation, and Learning from CE Transitions in Cities	*Circular Economy and Sustainability*	Vanhuyse (2023)
46	Measuring urban water circularity: Development and implementation of a Water Circularity Indicator	*Sustainable Production and Consumption*	Kakwani and Kalbar (2022)
47	Rural–Urban Metabolism: A Methodological Approach for Carbon-Positive and Circular Territories	*Sustainability*	Pianegonda *et al*. (2022)
49	Circular City Index: An Open Data Analysis to Assess the Urban Circularity Readiness of Cities to Address the Green Transition—A Study on Italian Municipalities.	-	Muscillo *et al*. (2021)
50	Circular Economy Indicators	-	Institut Paris Region (2022)
51	Circular City Indicator Set	-	ICLEI (2020)
52	A Guide to Circular Cities	-	UNECE (2020)
53	The Circular Economy in Cities and Regions	-	OECD (2020)
54	Circular economy indicators for buildings and housing	-	CE-CENTER (2021)
55	Circular economy indicators for personal mobility and transport	-	CE-CENTER (2020)
56	A Holistic Self-Assessment Tool for Circular Economy Transitions in Cities and Regions	*Europa XXI*	Wandl *et al. (*2023)
57	A methodological proposal for developing a Municipality Indicator of Circular Economy (MICE)	*Resources, Conservation & Recycling*	Ghinoi et *al*. (2024)
58	A novel assessment framework for circular urban areas with its application to a Swedish municipality	*Sustainable Production and Consumption*	Papageorgiou *et al.* (2024)
59	Adaptive reuse of urban cultural resources: Contours of circular city planning	*City, Culture, and Society*	Gravagnuolo *et al*. (2021)
60	Circular cities: the case of Singapore	*Built Environment Project and Asset Management*	Carrière *et al*. (2020)
61	How to decide upon circular cities: The role of evidence in local tender procedures	*Journal of Cleaner Production*	Chartier *et al*. (2025)
62	Measuring Circularity in Cities: A Review of the Scholarly and Grey Literature in Search of Evidence-Based, Measurable, and Actionable Indicators	*Sustainability*	Kapoor *et al*. (2023)
63	Municipal circular economy indicators: Do they measure the cities' environmental ambitions?	*Sustainable Production and Consumption*	Kopp *et al*. (2024)

APPENDIX C - Expert panel profiles for the Indicator Validation

Expert	Profile
1	Environmental engineer with experience in municipal solid waste management, working in different municipalities.
2	Sanitary and environmental engineer with experience in municipal sanitation and waste management.
3	Master's degree holder in Circular Economy, working in the agriculture and food sector.
4	PhD in Environmental Science and Technology, specialist in Industrial Ecology, conducting research on circular cities and environmental indicators.
5	Civil engineer with experience in sustainable urban planning, mobility, transport, and environmental sanitation.
6	Civil engineer, Master's degree holder in Circular Economy, who has developed projects on circular and smart cities.
7	PhD in Circular Economy, with experience in waste management and circular economy indicators.
8	Biologist and Master's degree holder in Circular Economy, with experience in circular development in agriculture.
9	Master's degree holder in Environment and Water Resources, with experience in urban planning and territorial planning.
10	Civil engineer, Master's degree holder in Water Resources, with experience in urban planning and urban resilience.
11	Environmental chemist with experience in circular economy and waste management, who has developed studies on indicators for circular cities.
12	PhD in Civil Engineering, with experience in urban engineering and sustainable mobility, who participated in projects on circular cities.
13	Environmental engineer working on topics related to environmental licensing in urban areas.
14	Specialist in Circular Economy, working on topics related to sustainability and indicators based on the concepts of the triple bottom line and circular economy.
15	Graduate in Environmental Sciences, working on Circular Economy and Sustainability topics, and participated in projects on circular territories.
16	Environmental engineer, specialist in smart cities and planning tools aimed at urban sustainability.
17	Master's degree holder in sustainable resource management, specialist in waste management and circular economy, with experience in several international organizations.
18	Master's degree holder in Management and Governance, with experience in sustainability and circular economy, having worked in several international organizations.
19	Sanitary engineer specialized in urban water supply and wastewater treatment.
20	Environmental engineer with experience in waste management and circular city projects.
21	PhD in Urbanism, with experience in urban sustainability, who participated in projects on circular cities.
22	Biologist with experience in waste management, reverse logistics, and circular economy.

Declaration on the Use of Artificial Intelligence

During the preparation of this work, the generative artificial intelligence tool GPT-5.5 was used to assist in the creation of illustrative figures. In addition, DeepL Translator (DeepL SE) was used to support translation tasks, and Grammarly (Grammarly Inc.) was used for grammatical review and language refinement of the English version of the manuscript.