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Solid Waste and Urban Sustainability: Urban metabolism indicators under solid waste treatment

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Resíduos Sólidos e Sustentabilidade Urbana: Indicadores de metabolismo urbano sob tratamento dos resíduos sólidos

RESUMO

Objetivo - Este artigo tem por objetivo apresentar uma revisão crítica acerca dos estudos de metabolismo urbano com foco em resíduos sólidos urbanos (RSU) e seus métodos de tratamento disponíveis.

Metodologia - O método PRISMA foi utilizado para analisar e classificar as pesquisas relevantes.

Originalidade/relevância – Há uma integração reduzida entre metabolismo urbano e os métodos de tratamento dos resíduos; lacuna importante nos estudos relacionados a metabolismo e caracterização dos impactos dos métodos.

Resultados - Verificaram-se lacunas em estudos abrangentes e que considerem fluxos diversificados; assim como a escassez de estudos com análises de contaminantes e diversos outros aspectos que podem ser analisados e utilizados em indicadores metabólicos, tais como micro plásticos presentes em água, materiais particulados no ar, etc.

Contribuições teóricas/metodológicas - Verificou-se a existência de diversos estudos correlacionando fluxos e indicadores metabólicos no contexto dos RSU, porém poucas pesquisas relacionam os métodos de tratamento.

Contribuições sociais e ambientais - Aponta-se para perspectivas futuras de pesquisa que incorporem os aspectos pertinentes ao metabolismo urbano associado aos métodos de tratamento de resíduos sólidos urbanos.

PALAVRAS-CHAVE: Resíduos sólidos urbanos. Metabolismo urbano. Indicadores chave de performance.

Solid Waste and Urban Sustainability: Urban metabolism indicators under solid waste treatment

ABSTRACT

Objective – This article aims to present an urban metabolism studies critical review focusing on urban solid waste (MSW) and its available treatment methods.

Methodology – To analyse and classify the relevant research the PRISMA method was used.

Originality/Relevance – There is limited integration between urban metabolism and waste treatment methods; an important gap exists in studies related to metabolism and the characterization of the impacts of these methods.

Results – Comprehensive studies with diversified flows were found, still having gaps in the diversification. Likewise, the scarcity of studies with contaminant analyses and several other aspects that can be analysed and used in metabolic indicators; such as micro plastics present in water, particulate matter in the air, etc.

Theoretical/Methodological Contributions – Several studies were found correlating metabolic flows and indicators in the context of MSW, however few studies report treatment methods.

Social and Environmental Contributions – Future perspectives research are pointed out that incorporate pertinent aspects to urban metabolism associated with treating urban solid waste methods.

KEYWORDS: Urban solid waste. Urban metabolism. Key Performance Indicators.

Residuos Sólidos y Sostenibilidad Urbana: Indicadores del metabolismo urbano bajo tratamiento de residuos sólidos

RESUMEN

Objetivo – Este artículo tiene como objetivo presentar una revisión crítica de los estudios sobre el metabolismo urbano centrados en los residuos sólidos urbanos (RSU) y sus métodos de tratamiento disponibles.

Metodología – Se utilizó el método PRISMA para analizar y clasificar las investigaciones relevantes.

Originalidad/Relevancia – Existe poca integración entre el metabolismo urbano y los métodos de tratamiento de residuos; una brecha importante en los estudios con el metabolismo y la caracterización de los impactos.

Resultados – Hubo lagunas en los estudios integrales que consideran flujos diversos; así como la escasez de estudios que analicen contaminantes y otros aspectos diversos que puedan ser analizados y utilizados en indicadores metabólicos, como micro plásticos presentes en el agua, material particulado en el aire, etc.

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Contribuciones Teóricas/Metodológicas – Se verificó la existencia de varios estudios que correlacionan flujos e indicadores metabólicos en el contexto de los RSU, pero pocas investigaciones relacionan los métodos de tratamiento**.**

Contribuciones Sociales y Ambientales – Por lo tanto, apunta a perspectivas futuras de investigación que incorporen aspectos relevantes al metabolismo urbano asociados a los métodos de tratamiento de residuos sólidos urbanos.

PALABRAS CLAVE: Residuos sólidos urbanos. Metabolismo urbano. Indicadores Clave de Desempeño.

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1 INTRODUCTION

The continuous increase in urban populations has resulted in various environmental impacts stemming from their production and operation, thus sparking interest in concepts such as urban metabolism (UM). This serves as a basis for cities to become sustainable and to gain better control over their internal dynamics (Pincetl et al., 2014). The need to manage these flows led to the concept of urban metabolism, which utilizes internal urban processes to monitor and to create metrics for growth, energy production, and waste elimination (Kennedy, Cuddihy e Engel-Yan, 2007).

The concept of urban metabolism is used to the integrated quantification of various inputs, outputs, and storage of energy, materials, water, and different types of waste (Kennedy, Pincetl e Bunje, 2011). These quantitative assessments have enabled a broad evaluation of the urban environment based on structural system information, substances present in the environment, and dynamic interactions within urban flows (Huang et al., 2012).

However, despite significant advancements related to the concept of urban metabolism and continuous studies addressing the metabolic aspects of major urban centers, such studies of Sahely, Dudding e Kennedy, (2003), Pincetl et al., (2014), e Liu et al., (2024); yet it has not be fully explored in terms of the comprehensiveness of the analyzed flows. A large portion of studies still select indicators randomly or focus on limited regions and/or processes, leading to a lack of analyses standardization that would allow for comparative studies as well as practical applications for decision-makers.

This also occurs due to the concept similarity to life cycle assessment (LCA), which evaluates the impact of a product from its production until it becomes (Hayatina, Auckaili e Farid, 2023). The concept it is also analogous to the circular economy, which refers to the flow of a material within the system while eliminating the concept of waste and replace it for reuse (Usman et al., 2024). Additionally, there is a resemblance to the water-energy nexus, which assess the interconnections and interdependencies within this system, promoting integrated management of nexus components in any environment to prevent negative impacts on its balance (Kumar e Saroj, 2014).

Urban metabolism primarily differs in its foundation and objective, considering the urban boundaries as a dynamic system that functions similarly to the human body, where inputs are transformed into flows—such as water, energy, pollutants, and general waste—that are later quantified by outputs. These metrics are called system performance indicators, the focus of metabolic analyses for assessing impacts and serving as a tool to support integrated, efficient, and sustainable management (Kennedy, Pincetl e Bunje, 2011).

Indexes and indicators are of great importance as they provide diagnostics and guide public policies by presenting the sanitary and environmental situation (Alvares and Ventura, 2024). Solid waste is one of the main challenges currently faced by public authorities, requiring proper management. On the other hand, implementing sustainability in waste management has been an even greater challenge. Urban metabolism aligns with this need by providing support for assessing urban sustainability (Liu et al., 2024).

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In this context, the present article examines studies on the solid waste landscape through the lens of urban metabolism concepts, analyzing which input data are been considered, as well as the commonly analyzed flows and their performance indicators.

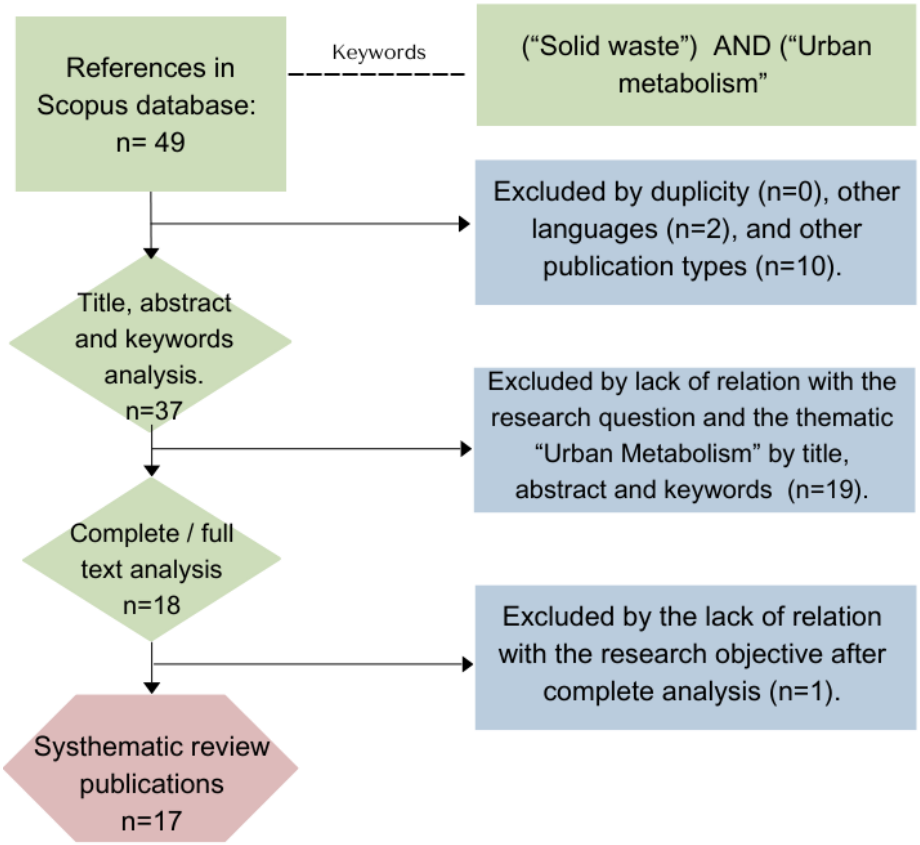
2 OBJECTIVES

The objective of this study is to incorporate urban metabolism into the context of municipal solid waste (MSW), with emphasis on treatment methods and how it affects the applied indicators.

3 METHODOLOGY

This work is a systematic literature review conducted with the PRISMA method structure, highlighting the relevance of solid waste treatment types in urban metabolism analyses. The Figure 1 shows the flowchart of this research method, and the detainment follow in the subsequent sections.

Figure 1 – Sample definition flowchart based on PRISMA method (MOHER et al., 2015).



3.1. Identification

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The articles search for this integrative literature review proceedings using the Scopus abstract database. We performed the search on titles, abstracts, and keywords with the association: *solid waste* and *urban metabolism*. There were no date restrictions in the research to ensure that no article aligned with the objective were keep out from the sample.

3.2. Screening

As English is the primary language of the Scopus database and the most widely used in scientific research, the searched terms used English. Therefore, in the first screening phase, we eliminated the scientific publications not available in English, along with other types of publications such as conference papers and editorials.

3.3. Eligibility criteria

After screening and listing the articles, we conducted a second phase based on titles and abstracts, selecting those that addressed solid waste from an urban metabolism perspective. Eliminating articles that focused on other types of metabolism or different study areas.

3.4. Inclusion

In the final stage, we analyzed the selected articles—excluding all previously mentioned— to enable classification and discussion focused on the research objective. The group consists of seventeen scientific articles, and follow their assessments.

4 RESULTS

The study of urban metabolism allows for measuring the intensity of urban interactions, their dynamics, and their impacts (Kennedy, C.; Cuddihy; Engel-Yan, 2007), contributing to the control of urban processes such as the accumulation and/or disposal of nutrients, water quality, and other markers that can be used for long-term analysis (Kennedy, C.A. et al., 2015).

Therefore, to achieve a comprehensive understanding, it is important that solid waste is also explored from an urban metabolism perspective, considering processes, materials, several study dimensions, and multiple performance indicators to ensure a good representation of real-world conditions. This approach can contribute to the management of municipal solid waste (MSW) and the urban environment as a whole, enhancing sustainability and minimizing the process impacts (Facchini; Mele; Caldarelli, 2021).

The Figure 2 resume the result analysis of the 17 publications. Five topics were created with these results and subsequently discussed, named: the context of MSW and urban metabolism studies, types of solid waste treatment and their implications in metabolic analyses, and metabolic indicators analyzed in MSW.

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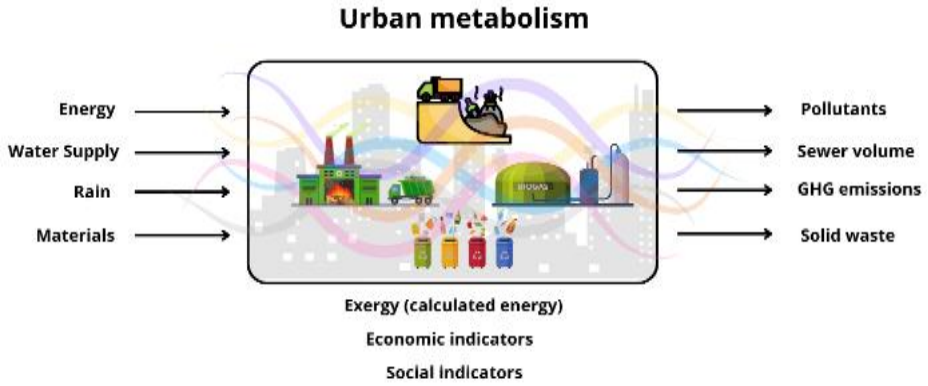
Figure 2 – Inputs and outputs abstract.



4.1. MSW Context and Urban Metabolism

In

Figure *3*(a), the analyzed articles were temporally distributed, showing a temporal consistency in studies related to the general concept of urban metabolism (UM). The first case study was presented by Sahely; Dudding; Kennedy, (2003), focusing on the varied mass flows in the urban environment of Toronto, Canada. The same figure also highlights the recent interruption in the analysis of new indicators.

Figure *3*b shows that most of the articles found refer to the general concept of urban metabolism, with only a few focusing on the metabolism of processes and materials in the urban environment, others addressing individual indicators, and some exploring different study objects.

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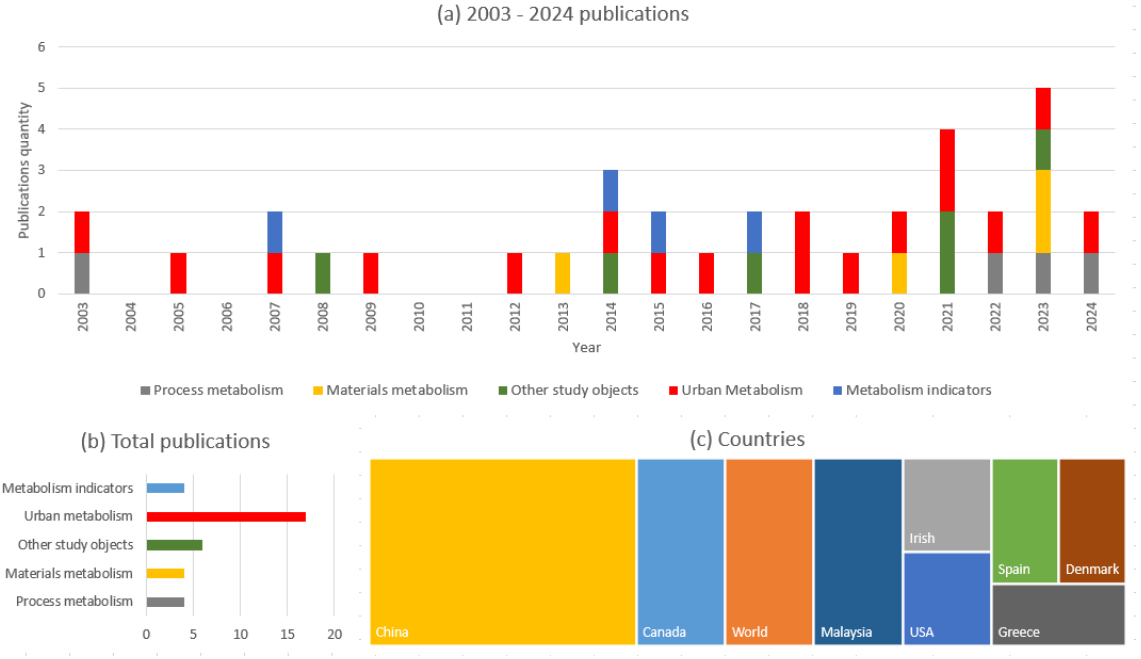
Figure 3 - Research Perspectives: (a) Publications per year related to MSW and urban metabolism; (b) Total publications with relationships illustrated in Figure "a."; (c) Analyzed application locations.



The most recent study, conducted by Liu et al., (2024), explores new metabolic perspectives related to the conversion of indicators into energy work. This study presents a possibility of using energy work as a unified index for MSW representation, which is crucial for creating a general index that allows for comparisons.

Most studies on MSW and UM have been conducted in Asia, accounting for 46% (China and Malaysia), followed by Europe at 24% (Ireland, Spain, Denmark, and Greece), North America at 18% (USA and Canada), and only 12% distributed globally, as observed in

Figure *3*c. This highlights the need for more globally distributed studies to obtain a comprehensive perspective on the metabolic impacts of MSW.

4.2. MSW Treatment and Its Implications in Metabolic Analyses

Various methods are currently used for MSW disposal, including landfilling WEN et al. (2018), waste-to-energy conversion (Liu et al., 2021), recycling (Liang; Zhang, 2012), and other approaches. These processes also impact urban metabolism, as they can return materials to the system, interfere with mass balances, supply and/or consume energy, and transform materials into different substances (pollutants or non-pollutants), among other effects. Therefore, the metabolic analysis must include and consider it.

Only 18% of the studies analyzed assess treatment types—Recycling (Liang; Zhang, 2012), Landfilling (Wen et al., 2018) and Waste-to-Energy processes (Liu et al., 2021; Wen et al., 2018) —as contributors to urban metabolism. Among these, some studies focus on material flows (Liang; Zhang, 2012; Liu et al., 2021; Wen et al., 2018) and energy (Liu et al., 2021), but do not consider fundamental flows such as water, contaminants, or food.

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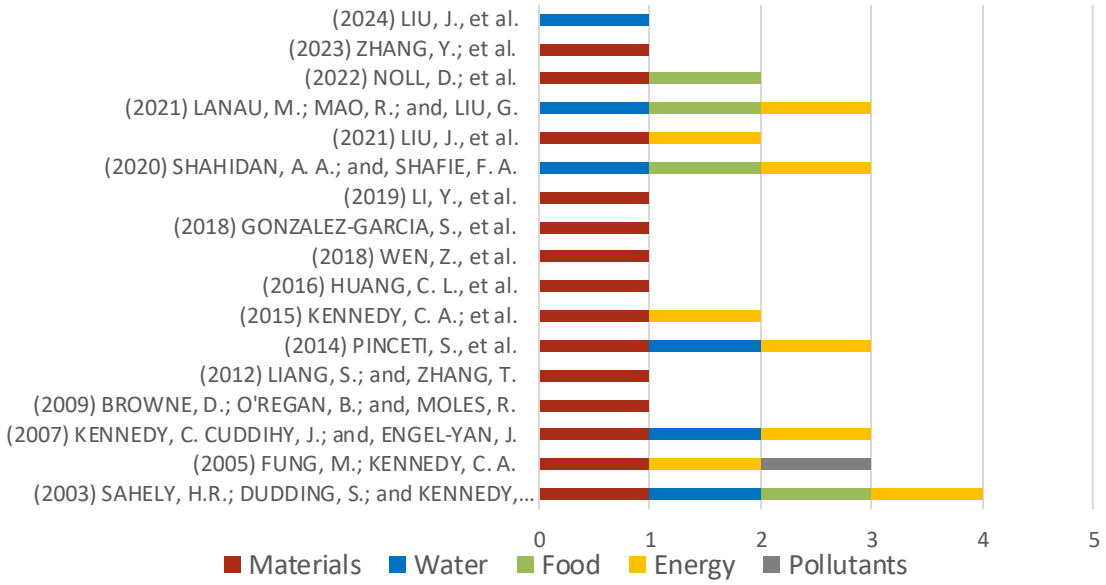
However, some analyses show limitations due to variety restrictions of waste types analyzed (Liu et al., 2021) and flow types (Liang; Zhang, 2012; Wen et al., 2018). Therefore, it is essential that future studies explore variations in material flows and treatment methods. Figure 4 presents the stratification by material, water, food, energy, and contaminant flows.

Figure 4 – Flow types in MSW and urban metabolism publications.



Despite many authors correlating urban metabolism with material flow analysis (MFA)—as evidenced by the high incidence of studies focusing on material flows—the presence of this type of flow in analyses has remained practically constant over the years and across studies. The relation between the concepts of mass balance, the foundation of urban metabolism, and material balance can explain this frequency.

Studies analyzing water and energy flows also appear with a certain frequency in publications, while research on food flows and contaminant flows occurs only occasionally—with only one study found on contaminants (FUNG; KENNEDY, 2005). It is worth noting that no studies have analyzed all classified flows simultaneously, nor have any investigated solid waste in relation to other flows, such as temperature, social aspects, or ecosystem impacts.

4.3. Metabolic Indicators in MSW

Similar to the flows in the publications, it is also essential to assess the evaluated indices to context characterization. The key performance indicators (KPIs) of metabolism represent the outputs of the flows.

Waste generation volume has been widely used as an indicator over time—also observable in Figure 5 – under the influence of material flows.

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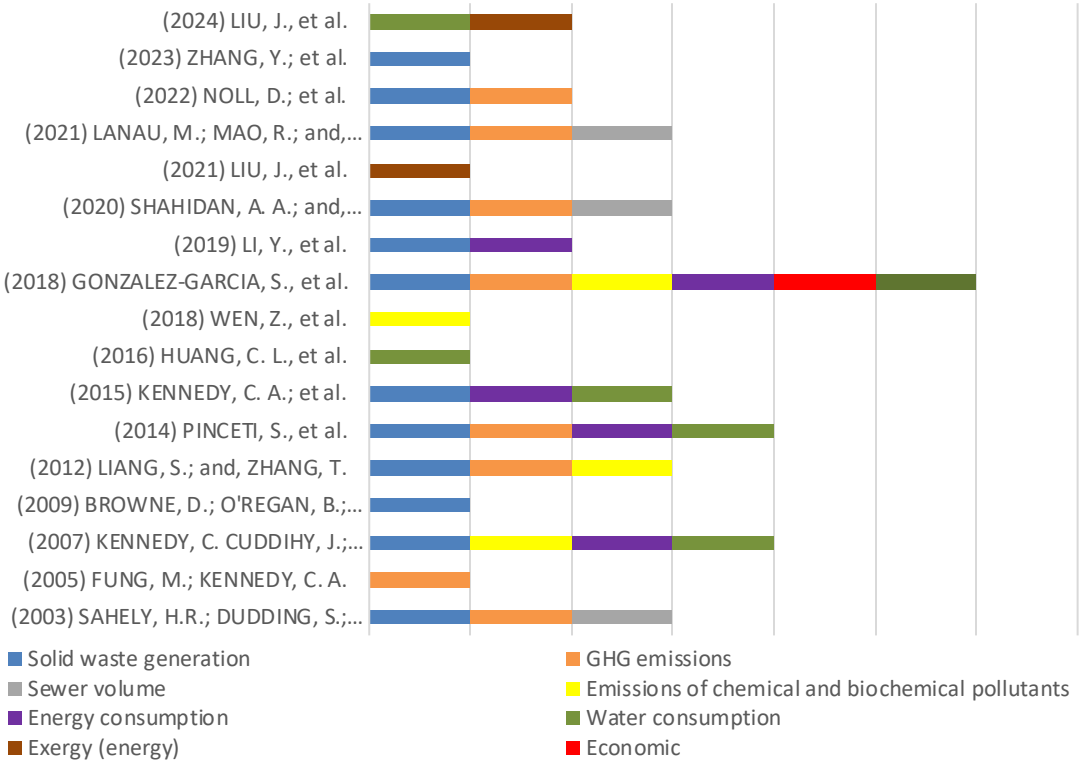
Figure 5 – Analyzed Key performance indicators.



Recent studies (Liu et al., 2021, 2024) explore energy work as an output indicator representing urban metabolism, referring to it as a sustainable urban metabolism indicator. However, this indicator has only been presented from the perspective of gasification and incineration methods (Liu et al., 2021); or within its urban cycle, from collection to final disposal (Liu et al., 2024).

Another well-explored indicator is greenhouse gas (GHG) emissions, driven by the growing concern for sustainability. This is the only indicator widely analyzed on the list across all identified flows, though not simultaneously.

For less explored indicators, such as sewage volume and energy work, significant flow variations exist. Meanwhile, alternative indicators, such as economic and social factors, are scarcely studied.

It is also important to highlight that the study analyzing the greatest number of indicators is the one conducted under the sole influence of material flow. Additionally, there is a tendency to examine GHG emissions and materials when analyzing sewage volume, which is most frequent considered under the water, energy, and food flows.

Figure 6 shows that most of the analyzed publications focus on MSW as a control zone for observations. Additionally, they analyzed all performance indicators at least once in generalizations of MSW within an urban area.

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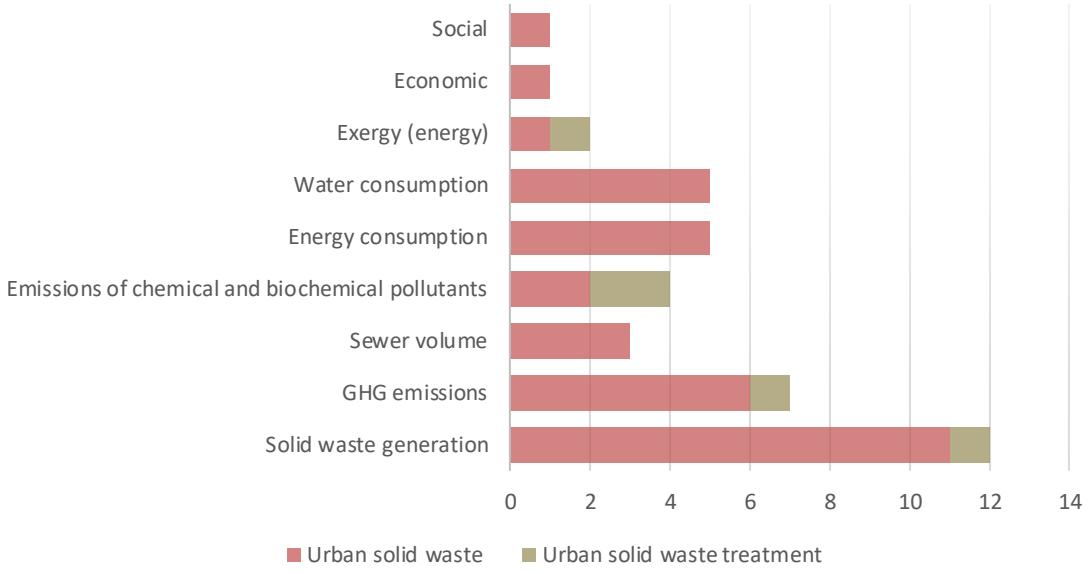
Figure 6 – Publications focus and KPIS.



We cannot say the same for indicators in MSW treatment methods, as these addressed only a few. They address the quantity of waste generated in the urban environment, energy work in recent approaches, and the emission of chemical and biochemical pollutants—limited to nitrogen disposal control (Wen et al., 2018) and a broader range of chemicals from a recycling perspective (Liang; Zhang, 2012).

All studies that examine MSW treatment methods within the context of urban metabolism are case studies conducted in Chinese cities, and primarily exploring material and energy flows.

Liang e Zhang (2012) present analyses measuring various impacts of a specific treatment method—MSW recycling—on waste volumes after treatment and the emissions of several pollutants, including COD, petroleum, ammonia, heavy metals, CO_2, among others. On the other hand, other studies explore various MSW treatment methods using specific indicators, such as chemical pollutant emissions (Wen et al., 2018) and energy work (Liu et al., 2021).

4.4. Discussions

The publications focused on proposing and testing new individual indicators, and analyzes the metabolism of a single material, process, or specific product, as well as exploring other control dimensions.

All the articles analyzed within the topics of urban metabolism and MSW classified the publications as case studies. However, only 18% of them focused on the impacts of different solid waste treatment methods, with no proposals for new indicators in this regard. The introduction of new indicators is crucial to enable decision-makers to make accurate and relevant recommendations (Liu et al., 2024).

This relative lack of attention to specific treatment methodologies within the urban metabolism literature represents a notable oversight. Given that the selection and

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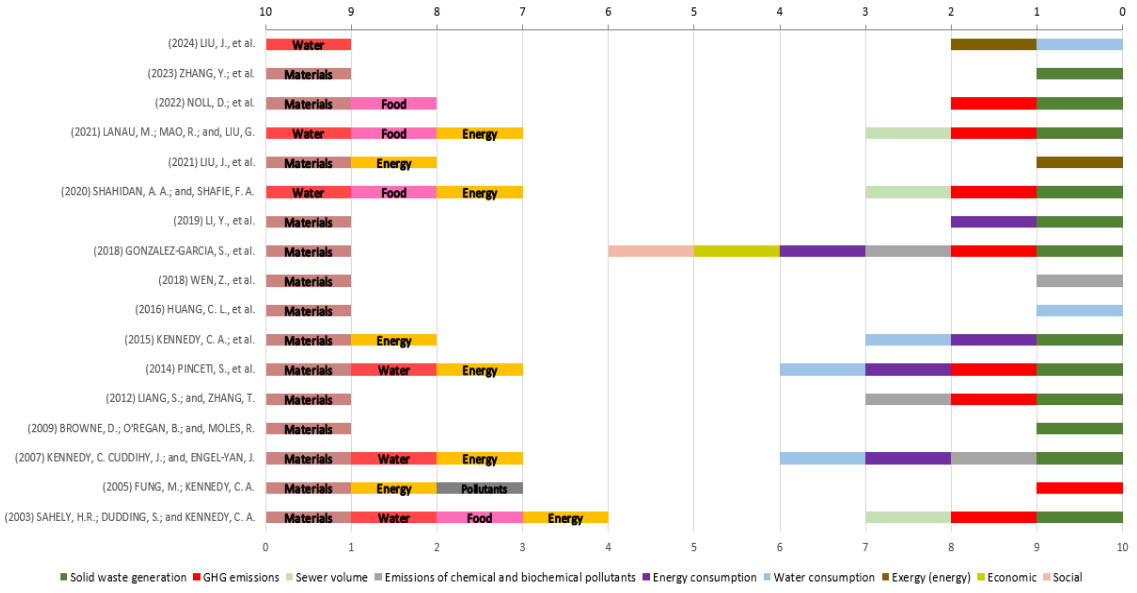
implementation of MSW treatment technologies directly influence material flows, energy consumption, emissions profiles, and ultimately the sustainability of urban systems, a more explicit integration of treatment processes into urban metabolism studies is crucial for providing actionable insights for decision-makers.

The development of novel key performance indicators (KPIs) that specifically address the environmental, economic, and social impacts of various MSW treatment methods is therefore essential. For instance, indicators could be developed to assess the circularity potential of different recycling technologies, the energy efficiency and emissions associated with waste-to-energy processes, or the environmental burdens of landfilling. Such indicators would provide a more nuanced understanding of how different treatment options contribute to or detract from urban sustainability goals, including resource efficiency (as touched upon in Liu et al., 2024) and pollution reduction.

Figure 7 presents the analyzed flows (left) and KPIs (right) from the studies that address metabolism within the urban environment context, allowing for a visualization of how KPIs are distributed among the flows studied by different authors over the years.

Comprehensive studies are also essential for an accurate overview of urban metabolic conditions. The existing studies consistently show an discrepancy between the number of analyzed flows and the number of indicators, leading to an abundance in one area (flows vs. KPIs) while leaving significant gaps in the other.

Figure 7 – Flows vs generated indicators.



A trend toward new indicators (Liu et al., 2021, 2024) and more specific analyses (Noll et al., 2022; Zhang et al., 2023), can also be observed, while broader evaluations are relatively older (Fung; Kennedy, 2005; Kennedy, C.; Cuddihy; Engel-Yan, 2007; Sahely; Dudding; Kennedy, 2003). This highlights the need for new holistic analyses incorporating recent indicators.

No studies were found that simultaneously address:

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- Solid waste generation and contaminants, which could be important, particularly in areas with uncontrolled waste disposal, despite specific studies as Rodrigues, G. S. M.; Kaiser, I. M. e Peixoto, A. S. P. (2023);
- Chemical and biochemical pollutant emissions alongside contaminant flows, which is essential since proper measurement should assess direct contamination, not just those derived from material, water, and energy flows;
- GHG emissions throughout the food flow, from production to disposal, as production can significantly impact emissions;
- Energy consumption and contaminant flow, especially concerning contaminant control and remediation;
- Economic and social indicators across all flows, not just materials.

Studies covering different locations (Kennedy, C.A. et al., 2015; Kennedy, C.; Cuddihy; Engel-Yan, 2007) and time intervals (Noll et al., 2022) should be applied to MSW treatment methods, aiming to observe trends, variations, and potential shifts over time.

Although the analyses focus only on currently evaluated key performance indicators, many other indices and aspects could help assess quantitatively and qualitatively the metabolism of a city. These include airborne particulate matter, metal contamination in water and/or food, ambient temperature, microplastics in water, air, and/or food, the extent of natural ecosystems within the urban environment, and more.

Incorporating urban metabolism analyses enables policymakers to identify critical points and implement improvements in efficiency and sustainability. Urban sustainability is a very complex topic, requiring a systemic analysis, which highlights the importance of developing a multiple-indicator system (Silva et al., 2024).

Additionally, using this concept and its data as a management support tool can lead to various benefits in economic performance, resource utilization, and environmental impact mitigation. Consequently, policymakers can develop multiple public policies to facilitate the implementation of integrated waste management.

Furthermore, the observed predominance of case studies in specific geographical locations highlights the need for more comparative research across diverse urban contexts. Metabolic characteristics and the effectiveness of different treatment methods can vary significantly depending on local factors such as waste composition, climate, economic conditions, and regulatory frameworks. A broader geographical scope in future research would enhance the generalisability of findings and support more context-specific policy recommendations.

5 CONCLUSION

This study aimed to systematically analyze urban metabolism from the perspective of solid waste through an integrative literature review, specifically highlighting the gap in research that explicitly connects urban metabolism frameworks with the diverse methods of municipal solid waste treatment.

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The studies revealed significant gaps in broad and integrated research, with a scarcity of work focused on contaminants and the various associated flow types. Notably, while older studies were more complex and comprehensive, recent ones have been more specific and limited to a few flows and indicators.

In addition, studies on solid waste treatment methods primarily estimates material and energy flows, with few performance indicators such as energy labor, chemical and biochemical pollutant emissions, and solid waste generation.

The analyses considered only the flows of water, energy, food, contaminants, and materials—along with key performance indicators such as solid waste generation and sewage volume, GHG and contaminant emissions, energy consumption, labor, water use, and social and economic aspects—already covered in the literature. However, we suggest future works take into the account other indices to represent a city's metabolic state, such as airborne particulate matter, metal contamination in water and/or food, ambient temperature, microplastics in water, air, and/or food, and the extent of natural ecosystems within the urban environment, among others.

Moreover, future studies are suggested to prioritise the explicit integration of MSW treatment methods into urban metabolism analyses. This should include the development and application of new, comprehensive metabolic indicators that capture the multifaceted impacts of these treatments, considering not only mass and energy flows but also the presence of contaminants such as microplastics in water and air, and the interaction with natural ecosystems within the urban environment. Such research will be vital for providing a more holistic understanding of urban sustainability in the context of solid waste management and for informing the development of more effective and sustainable waste management strategies for cities.

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DECLARAÇÃO DE CONFLITOS DE INTERESSE

Nós, **Maria Vitória da Silva Garcia, Giulliana Mondelli e Rodrigo Braga Moruzzi**, declaramos que o manuscrito intitulado "**Resíduos Sólidos e Sustentabilidade Urbana: Indicadores de metabolismo urbano sob tratamento dos resíduos sólidos**":

1. **Vínculos Financeiros**: Não possui vínculos financeiros que possam influenciar os resultados ou interpretação do trabalho. "Este trabalho foi financiado por Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Código de Financiamento 001".
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