Results in Engineering 25 (2025) 104278

Contents lists available at ScienceDirect

Results in Engineering

journal homepage: www.sciencedirect.com/journal/results-in-engineering

Review article

Urban metabolism, sustainability and energy transition in cities: A comprehensive review

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ARTICLE INFO

Keywords:
Urban metabolism
City
Sustainability
Sustainable development
Environment

ABSTRACT

This research article conducts a comprehensive literature review on the concept of urban metabolism (UM), with a special focus on the transition from a linear to a circular model. In the context of climate change, increasing urbanisation, and resource depletion, cities are recognised as playing a crucial role in environmental sustainability. A bibliometric analysis of scientific literature shows an increasing interest in circular UM as a comprehensive approach to managing energy and material flows in urban settings. This article aims to further explore the transition from a linear to a circular model by reviewing the evolution of the urban metabolism concept, its key components, and relevant case studies from cities that have successfully implemented circular strategies. By identifying barriers and challenges cities face in adopting circular practices within their urban metabolism, the article proposes recommendations to overcome these obstacles. Furthermore, it examines the interrelationships between circular UM and the Sustainable Development Goals (SDGs), particularly in terms of sustainable urban planning and energy transition. However, important challenges remain, such as the lack of standardised and accessible data that hinder comparisons between cities and their evolution. Finally, future lines of research are proposed that focus on the integration of new technologies, such as artificial intelligence and neural networks, as well as the development of circular urban models that can tangibly measure their impact on climate change. This review provides a comprehensive overview of the current state of the art of UM while enriching the existing body of knowledge on emerging trends in this field.

List of abbreviations

EF	ecological footprint
ENA	ecological network analysis
EU	European union
GDP	gross domestic product
LCA	life cycle analysis
LEAP	low emissions analysis platform
MFA	material flow analysis
MoC	metabolism of cities
PNIEC	national integrated energy and climate plan (Spain)
SDGs	sustainable development goals
UM	urban metabolism
UNA	urban network analysis
WOS	web of science

1. Introduction

Today, concern about climate change and its consequences is a fact. Human activity is one of the main factors in the depletion of natural resources, as the economic development of our society requires increasing energy consumption. This increase in energy demand contributes directly and indirectly to global warming. Between 1970 and 2017, almost 2.5 trillion tonnes of materials were extracted and used, with higher income countries being the most responsible due to the excessive use of materials accumulated at around 74 % [1]. In addition, more than half of the world's population is concentrated in cities, which occupy only 3 % of the earth's surface, but are directly responsible for two-thirds of global energy consumption and 75 % of carbon emissions, according to the United Nations (2023) [2]. Cities concentrate on human activities and represent an important interface between natural and

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https://doi.org/10.1016/j.rineng.2025.104278
Received 7 November 2024; Received in revised form 6 January 2025; Accepted 4 February 2025
Available online 15 February 2025

socio-economic systems. Therefore, unsustainable urban development is generating serious ecological and environmental problems [3]. >50 % of the world's inhabitants have lived in cities since 2008, and this proportion is projected to increase to almost 70 % by 2050 [4,5]. As a consequence, energy demand exceeds global energy needs by three-quarters, resulting in between 71 % and 86 % of greenhouse gas emissions occurring in urban areas [6–9] Due to this situation, highlighted by the various scientific reports of the recent COP28 in Dubai [10], and in order to avoid planning cities subject to energy shortages, energy policies need to be revised [11].

Since cities exchange resources and energy with their environment, they have sufficient autonomy to plan energy consumption in different sectors (transport, industry, services…) and to manage the waste caused by this energy consumption [12]. Researchers compare this environment to a large-scale organism, and its urban metabolic processes (UM) can be examined using approaches similar to those used to analyse natural organisms and the ecological systems in which they reside. This analogy facilitates the understanding of UM as an essential tool in the promotion of sustainable cities and communities. UM enables the analysis of energy resources and is defined as 'the sum total of technical and socio-economic processes that take place in cities to manage growth, energy production and disposal' [13].

Research agrees that urban size is positively correlated with energy consumption, as larger cities tend to have higher levels of economic development, population density and traffic demand, all of which contribute to increased energy use [14]. This phenomenon is not unique to one region; studies in various contexts, such as China, have shown that urban land-use patterns significantly impact energy consumption levels, suggesting that effective urban planning is crucial for sustainable development [15]**.** In addition, urbanisation is linked to increased demand for water and food, as cities require large amounts of resources to support their growing populations.

Waste generation is another critical aspect of urbanisation. In Bangladesh, for example, urban centres produce approximately 8000 tonnes of solid waste daily, with Dhaka contributing about 70 % of this total [16]. Similarly, in Ghana, urban areas generate large volumes of waste, mainly composed of putrescible materials due to household consumption patterns [17].The rapid growth of urban populations in developing countries is expected to exacerbate waste management challenges, with projections indicating that global municipal waste generation could increase from 1.3 billion tonnes in 2012 to 2.2 billion tonnes by 2025 [18].

Moreover, the composition of waste generated in urban areas often reflects the socio-economic conditions of the population. For example, urban residents in low-income countries produce between 100 and 200 kg of solid waste per person annually. Although this amount is lower than that in high-income countries, it still poses significant disposal challenges due to rapid urbanization [19]. In many cities, the informal sector plays a critical role in waste management, highlighting the need for inclusive governance strategies that engage diverse stakeholders.

From a practical perspective, urban metabolism (UM) research entails comprehensive measurements of the inputs, outputs, and storage of energy, water, nutrients, materials, and waste within an urban area. The origins of UM research can be traced back to 1965, beginning with the groundbreaking work of Wolman [20]. Since then, its theoretical foundations have developed, expanding its scope from local to global contexts. Furthermore, the examination of urban metabolism is increasingly acknowledged as an essential aspect of initiatives aimed at urban sustainability in future cities, where "the city reintegrates into nature and nature into the city."[21].

The concept of urban metabolism (UM) allows the analysis of energy and resource flows in urban environments at different geographical scales: cities, regions and the global level. According to Beloin-Saint et al. [22], multi-scale analysis is essential to understand the role of cities in sustainable development [23]. The first level focuses on the political boundaries of cities, but this restricted approach may omit relevant impacts occurring beyond their borders [24]. The second level, at the regional level, examines the connections between cities and their immediate surroundings, while the third level analyses the overall impact of urban activities, which provides a more holistic view, although often difficult to pin down due to a lack of detailed data [25].

It is crucial to focus the literature review on cities, as they serve as an ideal context for implementing sustainable strategies that could be replicated at other scales. Cities present the opportunity to study internal dynamics and their interaction with the environment, while aligning with policies such as the National Integrated Energy and Climate Plan (PNIEC) 2021–2030 and Regulation (EU) 2018/1999, which promote the transition towards more sustainable and circular economies at the local and regional level. This potential for replication offers hope for a more sustainable future.

Given the significant impact cities have on the environment, it is proposed that cities should not maintain a linear metabolism, but rather should exploit and maximise the use of inputs and outputs. Circularity is considered a fundamental approach for cities that want to measure and assess their level of metabolism. This emphasis on the role of cities in the transition to circularity empowers them to be integral to the process of urban sustainability [26].

Urban transformation brings about economic, environmental and social change, which puts the philosophy of the Sustainable Development Goals (SDGs) at risk. In particular, SDG 11 (which aims to make cities inclusive, safe, resilient and sustainable) and 12 (which aims to boost sustainable consumption and production) [27]. At the European level, Regulation (EU) 2018/1999 of the European Parliament and of the Council of 11 December 2018 on the governance of the Energy Union and Climate Action sets the framework for ensuring that Member States contribute to the Energy Union objectives and meet the commitments of the Paris Agreement. This regulation reinforces the need to implement national plans such as Spain's National Integrated Energy and Climate Plan (PNIEC) 2021–2030, which sets a target of a 23 % reduction in greenhouse gas emissions by 2030 in line with the EU's energy transition towards a circular, low-carbon economy. This plan promotes an economy that is not based solely on GDP growth but aims to optimise human well-being and the planet's.

The circular and sustainable economy, as discussed at the European Commission conference 'Cities & Regions drive forward Europe's circular transition', is designed to meet human needs by creating multiple benefits for people and the environment. In this way, initiatives such as the PNIEC integrate the principles of environmental and economic sustainability, which are key to a green transition at both national and European levels [28].

Recent studies have enriched the perspective of urban metabolism in relation to energy. For example, **Batinge et al.** [29] highlighted the role of innovative energy services in urban contexts to improve energy security, with a special emphasis on the inclusion of gender-sensitive innovations in urban laboratories. A**cevedo-De-Los-Rios** [30] pointed to the interconnection between energy and food flows in informal settlements through assessments of urban metabolism and urban agriculture. Esfandi [31] explored how advanced technologies, such as artificial intelligence and renewable energy sources, are transforming the dynamics of energy metabolism in cities.

In the following pages, the methodology used to carry out the literature review on urban metabolism is described in detail. This is followed by a historical evolution of the concept, as well as a bibliometric review highlighting the most relevant studies in this area. In addition, the transition from a linear approach to urban metabolism to a more circular and sustainable vision is addressed. Case studies and examples of the implementation of circular strategies in cities around the world are included, providing a solid basis for understanding the challenges and opportunities in sustainable urban management.

2. Methodology

The current research will employ a methodology that involves consulting globally recognised bibliometric databases, such as the Web of Science (WOS) and Scopus. These databases provide a robust source of relevant information for the field of study. This approach allows us to focus on significant types of scientific literature, including articles published in journals, conference proceedings, and book chapters. The methodology includes a systematic literature review across various databases, concentrating on the evolution of the concept of 'urban metabolism' and the diverse approaches present in current studies. Similar methodologies have been applied in other high-impact scientific articles to create concept-based classifications using different databases in fields such as health or green infrastructure, which enable the categorization of application contexts, methods, or terminologies [32,33].

Recent studies such as **Batinge et al.** [29] and **Acevedo-De-Los-Rios** [30] have used systematic reviews to analyse the role of energy services and urban agriculture in energy metabolism, highlighting the need for integrated methodological frameworks that address urban complexities.

The process will consist of collecting all scientific papers related to urban metabolism by filtering those related to environment and urban studies. The path will be from where data exists until December 2023 with emphasis on the number of publications, countries and the evolution of the concept throughout the process, i.e. starting with a simpler methodology to carry out a statistical study and ending with a more systematic literature review methodology to analyse the concept and trends of the study [34]. It can be broken down into the following graph (Fig. 1):

The open-source software Vosviewer.exe is introduced to facilitate the work of analysing results as it consists of a network visualisation software that will allow us to create bibliometric maps from the bibliographic data that we obtain. It is quite popular as it allows us to analyse and visualise scientific information based on citations, co-citations, collaboration between authors and the evolution of research topics. In conclusion, it will help us to identify patterns and relationships while working with a large volume of data. [35].

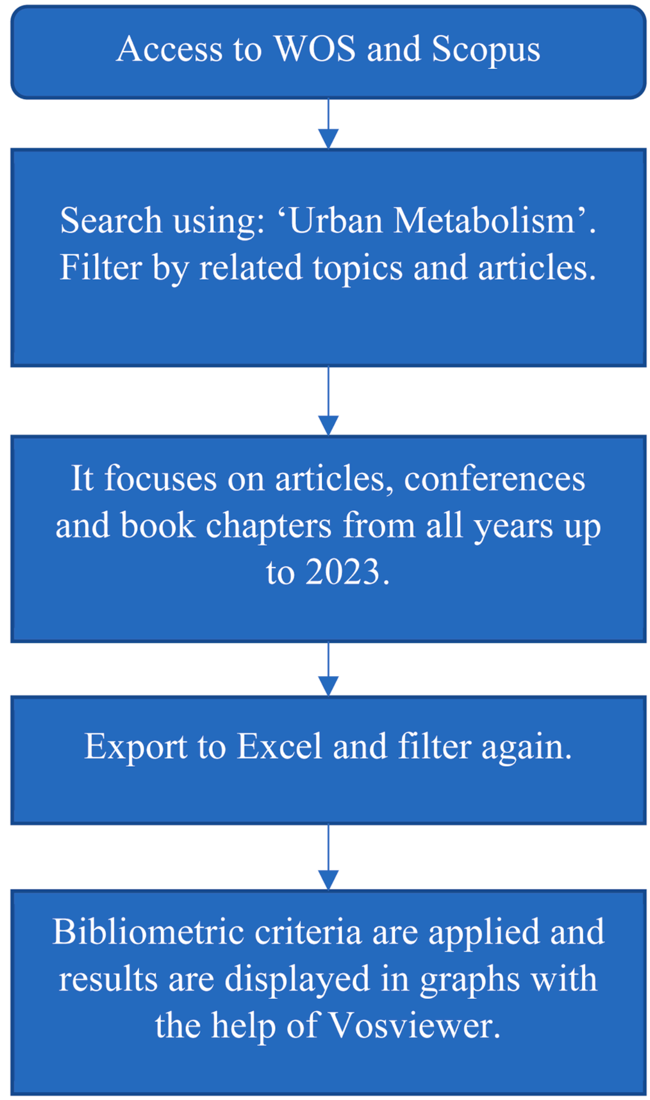

Fig. 1. Steps to follow in order to carry out the work methodology. Source: Own elaboration.

3. Evolution of the UM

3.1. Bibliometric analysis of the term 'urban metabolism'

Urban Metabolism can be discussed in a broad context, with some authors connecting it to cities, biology, and various other scientific fields. Consequently, when utilising prominent bibliometric search engines like Web of Science (WOS) and Scopus, we find 24,099 and 7504 results, respectively. To hone in on the specific concept pertinent to this study, a historical review of the concept and its scope has been deemed essential (Fig. 2).

Therefore, in order to identify the concept that interests us in this study, it is necessary to refine the search by adjusting it to the topics of interest, and to the themes that are related to environmental sciences, urban studies, or sustainable development. In the case of the Web of Science, we will search by Topic (TS='Urban Metabolism') and focus on areas related to urban studies, energy, and cities, as well as focusing on articles, books, and conferences. The result is a total of 912 documents from the WOS database. As for the Scopus database, using the same search specifications, it records about 1020 papers related to urban metabolism.

The first report of citations and publications can indicate at a glance that there is already a direct link to the growing interest in urban metabolism in the decade 2010–2020 due to the need to understand and manage material and energy flows in cities in order to analyse and optimise the use of resources in cities. Furthermore, given the entry of the SDGs in 2015 and their entry into force in 2016, it can also be indicated that this has been key in the growing development of knowing more about the environment of cities.

This study will concentrate on a fundamental analysis that sheds light on research areas pertinent to urban metabolism. In both databases, the predominant research fields are associated with environmental sciences, engineering, social and technological sciences, energy, agriculture, and economics. Areas such as computer science, mathematics, and chemistry are represented to a lesser extent (Fig. 3).

As the data is filtered, it becomes evident that it is necessary to refine the bibliometric analysis in order to provide more detail. For this purpose, we make use of the free software 'VOSviewer', which was introduced earlier [36]. In this case, it has been used to analyse relationships in scientific journals, between authors and co-authors, and between countries. In addition, it also serves to analyse the most relevant keywords among the analysed documents.

From the analysis of the keywords, urban metabolism stands out, followed by industrial ecology and sustainability. It is interesting to note that the term circular economy is also beginning to appear, which will be discussed later because it plays a vital role in urban metabolism.

Among the countries with the most cited papers, China (193) and the USA (175) (whose names in Fig. 4 should appear between Italy and Canada) stand out. We can distinguish 5 clusters that share common citation characteristics.

It is also worth noting that an analysis by bibliographic coupling and

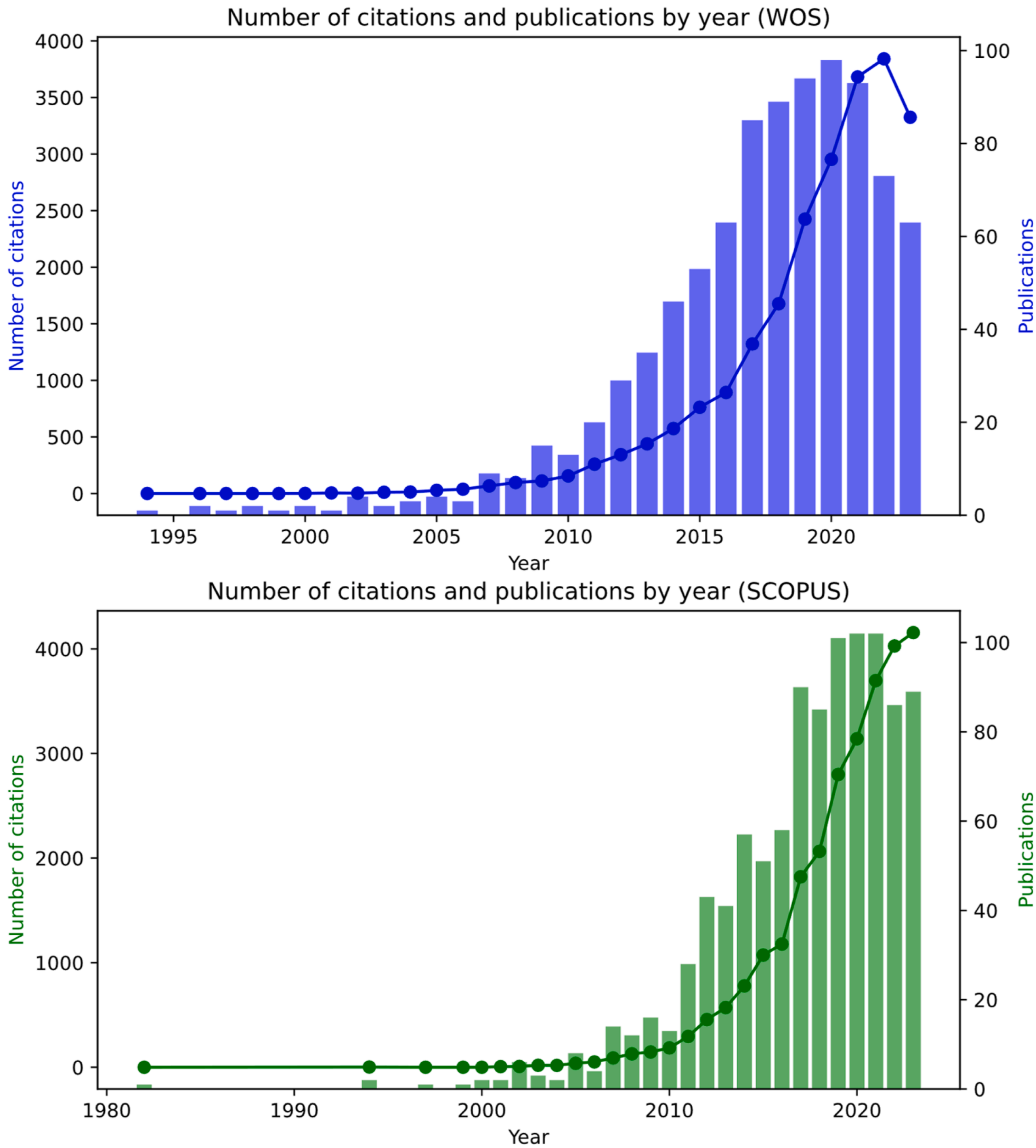

Fig. 2. WOS and SCOPUS publication and citation reports. Source: Own elaboration.

sources has been carried out to examine how scientific documents are related to the main sources or journals. Thus, the journals with the most documents are the Journal of Industrial Ecology, the Journal of Cleaner Production, and Sustainability, with the first two being the ones with the most citations, while the third is in seventh place (Fig. 5).

Between 2022 and 2024, recent studies have pushed the boundaries of urban metabolism. **Umoh** [37] synthesised policy and case studies on incorporating energy efficiency into urban planning, highlighting its relevance for resilient and low-carbon cities. On the other hand, **Guibrunet and Jimenez** [38] revealed important gaps in the consideration of food flows in urban metabolism studies, reinforcing the need for an integrated approach that encompasses energy and food. These data include up to the end of 2023, while in 2024 about 85 more documents were published according to the Scopus database and the search criteria followed, the area with the most publications being environmental sciences with a number of 100 citations as they are still recent publications.

3.2. *Conceptual development*

Once the bibliometric analysis has been completed, it is necessary to take a historical overview (Fig. 6) to understand how the concept has evolved. It is well known that the concept of urban metabolism was proposed by Abel Wolman in 1965 [20]. However, the first organic comparisons with the city appeared in the 17th century thanks to medical advances based on work on circulation, respiration and the nervous system. This work was carried out by authors such as William Harvey, Thomas Willis and Albrecht Von Haller [39].

In the 19th century, with the emergence of the neologism, Karl Marx first spoke of social metabolism when referring to the flows between the economic system and the natural world [40]. Although the notion of social metabolism remained in the background until the second half of the 20th century, several theoretical advances were made during this period, such as the input-output method of the economist Wassily W. Leontief [41].

From the 20th century onwards, three distinct periods emerged with

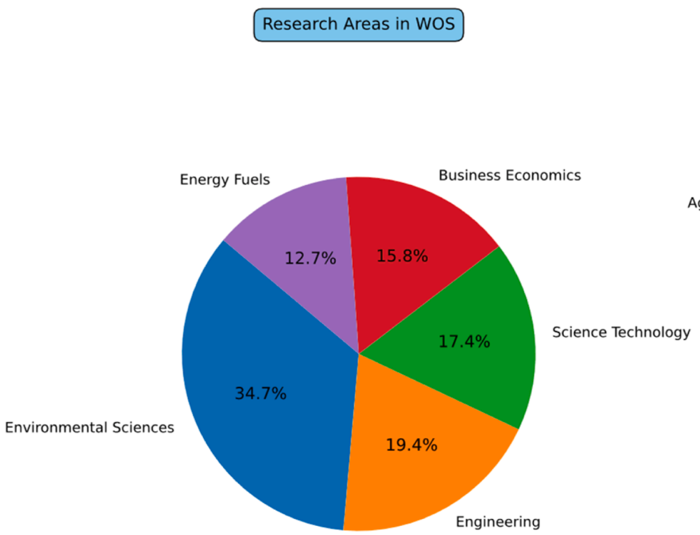

Fig. 3. Most common research areas of search databases. Source: Own elaboration.

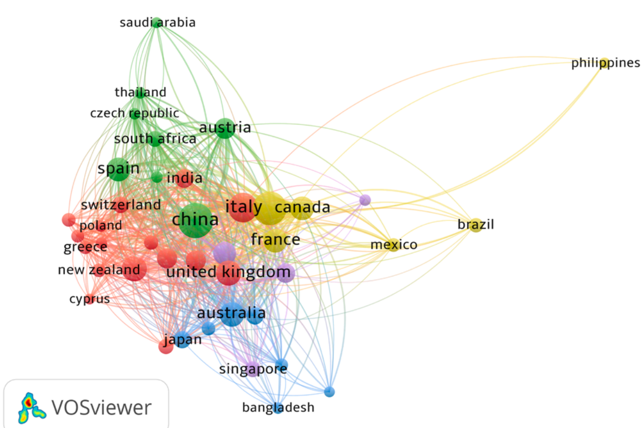

Fig. 4. Citation-country relationship. Database: Scopus. Source: Own elaboration [VosViewer].

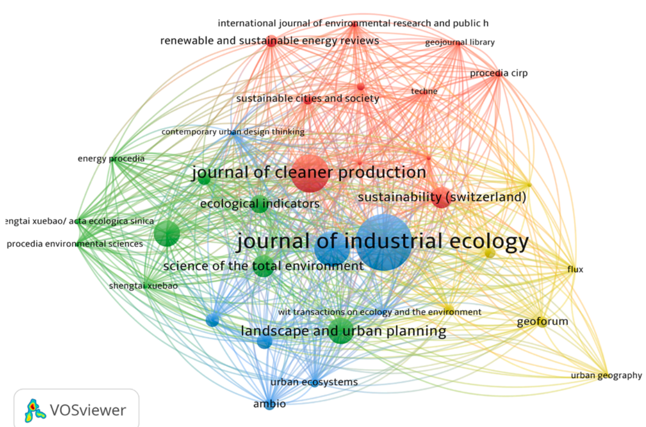

Fig. 5. Source-citation analysis. Database: Scopus Source: Own elaboration [VosViewer].

respect to the study of urban metabolism: from 1965 to 1980, from 1981 to 2000, and from 2000 to the present. In the first period, Abel Wolman initiated the study of the concept of urban metabolism in 1965, based on a quantitative analysis of a hypothetical American city of one million people. He used national-scale data on water, food, and fuel consumption, along with rates of sewage, waste, and air pollutant generation, to calculate per capita inflow and outflow rates. [42]. The first practical research using material and energy flow analysis methods was carried out in the 1970s. These studies took place in Miami, Tokyo, Brussels, and Hong Kong [43–47].

Following the quantitative study approach, H.T. Odum laid the foundations for quantitative analysis in urban metabolism. He also introduced the concept of 'emergy' [48], which allowed him to compare different types of flows, whether material or energy, through the application of a coherent system of units in the context of the city of Miami. Odum also applied his method in Paris, following Zucchetto's study [44] and using data provided by Stanhill [49]. The difficulty in Odum's vision lies in the use of solar energy as a universal measure, as conventional units used by urban planners are more familiar and understandable to them. In the realm of urban metabolism, the mainstream adopts the measures that local officials use in their daily work, thus facilitating communication and decision-making. Although Odum advocated solar energy as a global metric, in practice, it is crucial to find a balance that allows more holistic concepts to be incorporated without losing the connection to the everyday units of measurement that prevail in the governmental sphere. In this early period of research, authors such as Duvigneaud and Denaever-De Smet, and Kalma and Aston, among others, were also prominent in material flow analysis [46, 50–52].

Since the approach proposed by H.T. Odum, research on urban metabolism has slowed down. From the 1980s onwards, a boom period in research began, and researchers developed new methods, resulting in greater difficulty comparing the results of studies using different approaches [53–57]. Other researchers followed with a different approach, applying material flow analysis (MFA) to account for resource flows [50–54]. This stage also saw the publication, in 1987, of the Brundtland Report by the WCED (World Commission on Environment and Development), which introduced the concept of sustainable development and led to the first studies incorporating this concept [58,59] . For example, between 1991 and 1996, Baccini and Barder wrote books on regional material flow analysis. This new MFA perspective differed from Odum's approach in that it measured resource flows in terms of mass.

Subsequently, environmental scientist Girardet laid the groundwork for future methodologies by analysing the interaction between urban metabolism and the development of sustainable cities. [60,61].

In one of his research papers, Newman developed a model of liveability in Sydney, Australia, thereby increasing the frequency of case studies examining material flows in cities [62–64]. Some of these studies

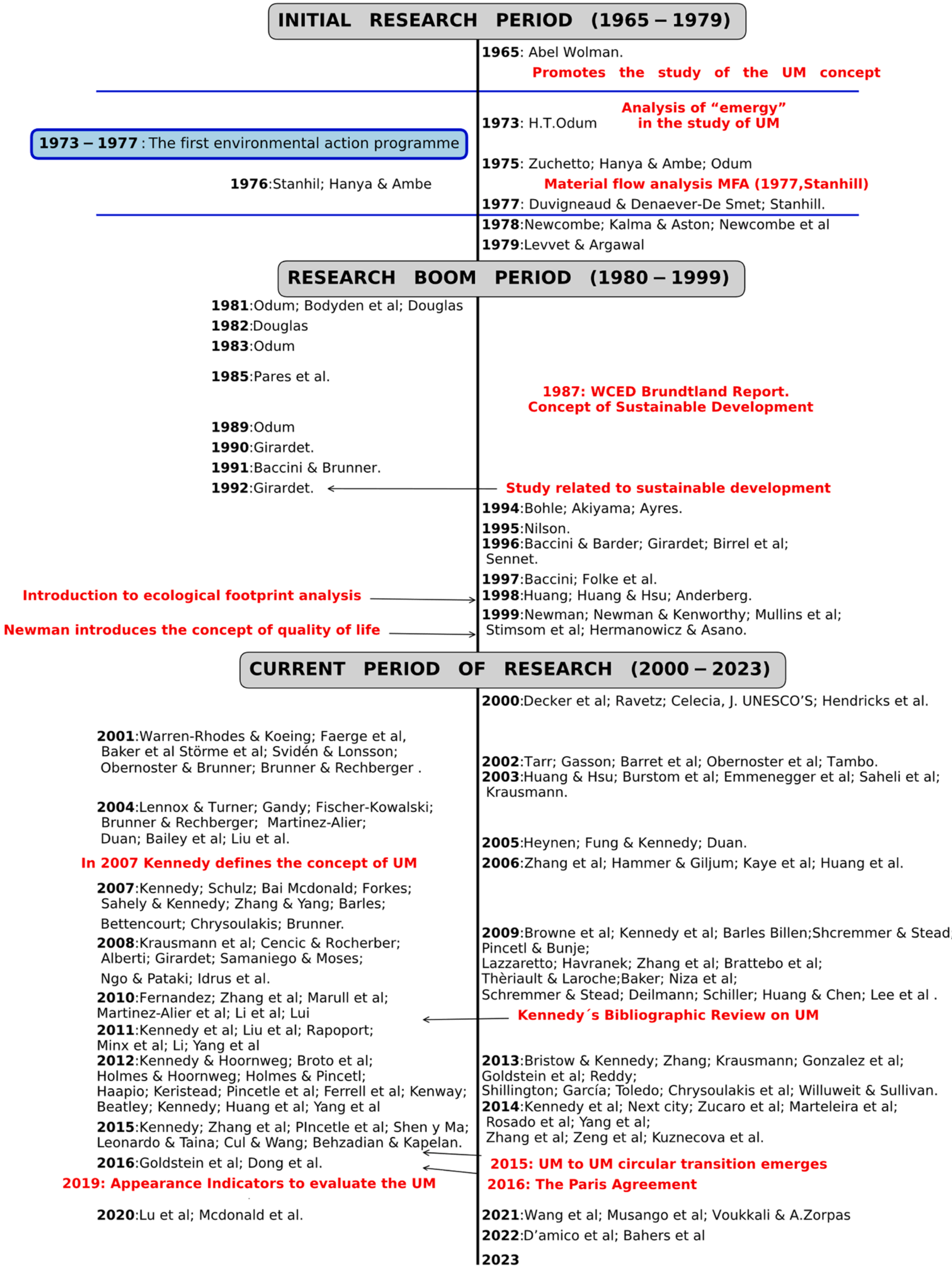

Fig. 6. Timeline of the historical evolution of Urban Metabolism. Source: Own elaboration.

were initiated by the European Union in cities such as Prague, Sweden, Switzerland and Vienna. In addition, Newman proposed a metabolism model that included indicators of health, employment, income, education, housing, leisure and community activities, i.e. he introduced the concept of quality of life. Finally, at this stage, ecological footprint analysis was also introduced to further advance urban studies, while other authors closed this period of booming research [65–105].

Analyses of material and energy flows have primarily been conceptual, making it challenging to compare various urban metabolisms. Consequently, there is a crucial need to establish a standardised methodology to evaluate these flows and delineate the fundamental data requirements, enabling researchers to utilise them in a clearer and more consistent manner.

From the 21st century onwards, the approach to the study of UM began to become more consistent. Current research is distinguished by the emergence of models that allow for the temporal analysis of urban metabolism, as well as by the broadening of the concept to achieve a deeper understanding of its complexity [106]. For example, in 2007, the *Journal of Industrial Ecology* and the American Geophysical Union organised and published conferences on urban metabolism. Additionally, more reports on urban metabolism were carried out, providing a basis for identifying different urban characteristics and formulating management tools and standards [107–116].

Several Australian researchers examined the impact of urban metabolism on residents' well-being [117,118]. A particularly relevant study at the time was conducted in Hong Kong, where the relationships between urban development and environmental impact were analysed as the city transitioned from a manufacturing to a service-based economy [119]. The findings suggest that the increase in Hong Kong's urban metabolism appears to be closely related to the increase in urban prosperity and growth in consumption levels. This highlights the importance of understanding urban metabolism in studies focusing on urban development. The relationship between economic growth, increasing affluence and the resulting increase in consumption patterns can have a significant impact on resource demand and waste generation in urban settings. Therefore, understanding urban metabolism becomes essential to address the challenges associated with sustainable development and efficient resource management in cities such as Hong Kong [120].

The concept of urban metabolism also finds relevant applications in research on water consumption in urban settings. For example, Gandy explores the connection between urban water metabolism and spatial transformations in urban areas [121]. Theriault and Laroche's study in Canada addresses urban water metabolism, focusing on issues such as water availability, supply and treatment infrastructure, as well as consumption patterns [122]. In his analysis of water metabolism in Arizona, Baker examines how specific environmental characteristics, such as Arizona's arid climate, affect urban water demand [123].

In 2007, Kennedy et al. researched and examined the progression of urban metabolism analysis, incorporating studies on London, Cape Town, and Toronto [124–126] Research on urban metabolism continued to grow in cities such as Geneva, Paris, and Los Angeles [127–151].

Since 2010, research has gradually advanced by focusing on specific cities and areas, such as Anhui Province, Sichuan Province, Shanghai, Chengdu, Yulin, Liaoning Province, Shandong Province and Shijiazhuang [152].

According to Kennedy et al., the scope of research has been highly varied, from linking urban metabolism to the appropriation of ecosystems by cities [153], to differences in greenhouse gas emissions in cities, to the accumulation of toxic materials in urban construction [154].

Moving further back in time to focus on a more recent period, some of the most cited research related to the study of energy and material flows in large and complex cities shows that, while policies that pursue resource efficiency may be successful, flows are influenced by urban form, economic activity, scale effects, and so on [155–159]. The concept of urban resilience is also used to address the complexities and dynamics that vary with scale and time, making it a useful term for addressing sustainability issues [160]. Additionally, other researchers focus on urban social metabolism through case studies in various cities (such as Beijing and Barcelona) and theoretical models, exploring sustainable development, material and water flows, as well as ecological conflicts and resource valuation, with a focus on understanding the dynamics between natural and urban systems to improve sustainable planning and management [161–176].

In our study of conceptual evolution, we have observed notable advancements in research. We have not only investigated the interconnections between water, energy, and material use (UM), but we have also developed complementary tools and methodologies related to life cycle analysis [177–183]. This progression has facilitated the creation of indicators aimed at promoting more sustainable management and understanding spatial patterns [184–191]. By the end of the 2010–2020 decade, we witnessed the emergence of inter-regional approaches designed to enhance sustainability, setting the stage for future developments in the field of UM [192–196].

Continuing the journey to the time period between 2020 and 2023, we can conduct a word analysis where 'urban', 'metabolism', and 'cities' continue to stand out among the top three according to their frequency of use. Some studies highlight the combination of the circular economy with urban metabolism to promote the efficient use of resources, especially in the construction industry, but note that the concept has not yet been promoted on a large scale and that the development of a comprehensive framework for integration and methodology is necessary [197]. Among these studies, some focus on the carbon footprint, concluding that about 88 % of physical carbon is imported from outside urban boundaries [194], while others combine Internet of Things (IoT) and big data technologies for smart cities and their planning to build sustainable urban environments [195]. Additionally, some studies focus on waste management, developing methods to estimate waste in order to advance a circular economy and valorise recycled materials for strategic waste management planning [196,197]. Finally, there are studies that analyse how urban metabolism relates to the circular economy and current environmental policies, such as the 'European Green Deal' [198,199].

3.3. Methodological study of the UM

Initially, UM studies used simple approaches such as 'black box' and input-output accounting. This was certainly a precedent for future studies, but over time a more detailed analysis was needed that included aspects such as production, consumption and mobility in urban systems. This helped to understand ecological processes, environmental impacts and the inner workings of urban systems. Thanks to a bibliometric analysis of co-occurrence by keywords, it is possible to determine how closely the different methodologies are associated with the scientific literature.

3.3.1. 'Emergy'

In the research, most studies have used the concept of 'emergy' (Fig. 4), as well as other terms such as 'emergy evaluation', 'emergy synthesis', or 'emergy analysis', and have built models that describe in detail how the system is organised and how its parts are related (i.e. the causes and effects of energy and material flows). Some of these models have also considered the evolution of the system's ecological thermodynamics, allowing for more realistic simulations.

The concept of 'emergy' (Odum, 1980) measures energy as the number of equivalent units of solar energy provided by natural and human activities in an ecosystem [200–203]. It was still a quantitative tool that encompasses all forms of energy in a system, with solar energy being the primary one used to measure all others, and is expressed in units of solar energy [203–205].

This methodological concept marked the beginning of the development of urban metabolism in cities. So much so that the concurrence map by keywords shows only 42 occurrences in the 1020 documents analysed in Scopus, mainly due to the fact that this methodology must analyse input flows, processes, and storage [206–208], and therefore requires a standard measure to express all urban processes. This created several difficulties in combining or comparing materials and energy, leading researchers to turn to energy and material flow analysis, which already focused on quantifying as many material and energy flows as possible in an urban system without worrying about the units of measurement used [209–211].

3.3.2. Material flow analysis (MFA)

It arises as a counterpoint to Odum's 'emergy', but cannot be understood without it. This approach focuses on the existence and flows of resources in terms of mass [21] rather than energy. It proves most useful in quantifying urban metabolism at the national or local level, as observed in the concurrence map, where it is mentioned up to 112 times in the analysis performed.

The popularity of this methodology grew so much that, in 1971, UNESCO led researchers to analyse the situation in cities such as Rome, Barcelona, and Hong Kong [212,213]. In studying these cities, an ecosystem approach was adopted, and researchers examined urban metabolism by viewing cities as both resource consumers and waste generators. Particular attention was paid to the interactions between nature and human activity, identifying the intricate relationships and material flows within the urban system [214].

During the 1990s, its application to cities grew, with works such as *Metabolism of the Anthroposphere* by Baccini and Brunner (1991), focusing on the analysis of material flows at the regional level. This work was the first approach to the mainstream of the urban metabolism school and was significantly enriched by Warren-Rhodes and Koenig (2001) through its application in Hong Kong.

The main problem with the methodology was its conceptualisation [215]. This conceptualisation made it difficult to compare different urban metabolisms and, therefore, limited progress in the field of research. The need then arose to create a standardised methodology for accounting material and energy flows, and for researchers to begin integrating the vast body of available knowledge [216].

3.3.3. Network models

Enter the year 2000, and the UM methodology shifts to a more resilient approach where researchers introduce new concepts such as energy and water analysis and the study of megacities [217–219]. This methodology laid the foundations for identifying urban characteristics, developing tools, and establishing management standards, facilitating collaborative research and enabling the practical application of urban metabolism. With this approach, network models emerged that go beyond the black box model, as they consider internal system processes. Additionally, these are multidisciplinary models, applied to the metabolic analysis of water, energy, and materials.

Although the models had this multidisciplinary quality, it is true that there is a need for more spatially explicit analysis [220]. A combination of approaches is now being sought to study individual cities in order to obtain information to analyse the region surrounding that city.

3.3.4. Input-output analysis: simulation modelling

Currently, to analyse the concept of urban metabolism, particularly regarding energy, various simulation and optimisation models have been developed. These models integrate policy scenarios with specific parameter values to enhance their accuracy. Additionally, case studies are utilised to support the simulation results.

These models are based on the economic input-output analysis developed by Wassily Leontief and can be applied using software designed for this purpose. A clear example of such software is the Low Emissions Analysis Platform (LEAP) [221]. This tool is designed for planning energy alternatives over the medium to long term and is valuable for studying urban metabolism and the energy prospects of a city. Metabolism of Cities (MoC), Urban Network Analysis (UNA), CityScope, and CityInSight are also software platforms whose purpose is the aforementioned planning and optimisation of urban development by providing analysis that allows for the evaluation of material, energy, and resource flows in urban environments.

These models represent a perfect opportunity for the analysis of urban metabolism in cities, as it is not yet widespread in the literature. The concurrence map shows up to 18 occurrences in the 1020 papers, with a total of 122 papers mentioning this analysis, including some of the most cited ones, which manage to unify the urban use of energy and water in Beijing to study the impacts of different sectors such as agriculture, transport, and construction [222].

3.3.5. Life cycle analysis (LCA)

This type of analysis is found in up to 263 documents out of 1020 studied and is a keyword with up to 36 occurrences in the map studied, indicating that it is a very hot topic among researchers. Historically, it has been studied as applied to products, but in the context of urban metabolism, it is mainly used to assess the environmental impacts of material and energy flows within cities and thus identify at which stages of the life cycle improvements can be implemented to reduce the environmental impact [223,224]. Nowadays, there is also some software such as open LCA (https://www.openlca.org/) to study environmental impacts or even the leader in life cycle analysis systems such as 'Simapro' [225].

4. Transition from a linear urban metabolism to a circular urban metabolism

Modern cities have a linear urban metabolism, which means that products and waste are not reused and do not contribute to sustaining the environment. This contrasts with the circular metabolism of nature, where every product produced by an organism is transformed into an input that sustains and nurtures the environment. The current linear pattern of production, consumption, and disposal in our cities does not account for sustainability, nor does it recognise the interconnectedness of inputs and outputs. In contrast, the circular metabolism seen in nature ensures that products and waste are reused, contributing to environmental balance and sustainability [211].

According to Zhang et al. [226], an urban system is not simply a built space subject to planning or management; rather, it should be considered as a 'superorganism' in which its metabolic processes need to be regulated [227]. These processes generate and alter flows that are dynamic and recurrent. Understanding how these flows change over time allows planners to reduce waste generation and improve waste treatment and reuse in cities.

Given the negative impact cities have on the environment, it is suggested that cities adopt a more sustainable approach, rather than following a linear resource use model. This involves making the best use of resources and inputs, maximising efficiency in product use, minimising waste generation, and promoting reuse and recycling. From a sustainability perspective, circularity is recognised as essential, particularly for cities seeking to quantify and analyse their rates of consumption and production. This means that cities are prioritising reuse and recycling, not only to alleviate pressure on natural resources but also to gain better control and understanding of how resources are managed within their urban environment [228].

When analysing circularity in the functioning of cities, it is crucial to address the concept of the circular economy. This approach presents a valuable opportunity for production and consumption in both urban and near-urban areas, offering significant advantages for the sustainable development of cities [204].

The importance of this concept is such that it has led to the development of eco-industrial parks to significantly encourage the reuse of waste by partner companies, inspiring a new approach to urban sustainability [229,230]. This transforms what would otherwise be a pollution problem into a valuable resource.

The relationship between simulation models and circularity in urban metabolism is that as researchers have incorporated circular metabolic flows, simulation models have become more effective in representing and understanding how cities function from a circular perspective. Circular metabolic flows are essential in the circular economy, as they involve the reuse and recycling of resources rather than a linear use-and-dispose approach [231].

Girardet was based on the idea of a cyclical model of urban metabolism. His perspective recognises that a linear approach—from the input of environmental resources into a city to the production of goods and the generation of waste—does not adequately reflect how natural systems interact and affect the Earth's life-support balance [232]. In 2007, Brunner strongly emphasised the importance of metabolic processes for a city that prioritises recycling. These processes have been studied from two distinct perspectives: management, which focuses on how material flows in the city are managed and optimised; and metabolic activity, which focuses on how the city uses and reuses its resources in a sustainable manner. Both perspectives are crucial for understanding and moving towards a more efficient and environmentally friendly city [216,233].

The shift from a linear to a circular urban metabolism requires the establishment of circular urban systems. This transformation necessitates the adoption of new technologies, the modification of material flows, changes in organisational practices, and the adaptation of institutions. The challenge lies in understanding how various systems—incorporating both social and technological elements—can interact and evolve in tandem. Additionally, considerations must be made regarding the adjustment of organisational structures and the coordination, ideally the simplification, of these processes [234].

Arguing for the concept of circular urban metabolism to change the way we think about resources and waste in cities is not sufficient to address the necessary changes. Vernay and Singh [137] suggest four areas of research: understanding the emergence of circular urban systems, identifying theories and conceptual frameworks for understanding these systems, investigating the transition from linear to circular urban systems, and developing approaches, policies, and implementation strategies based on knowledge of ecology, innovation, and socio-technical transitions [234].

Esfandi [31] highlighted the transformative potential of advanced technologies, such as artificial intelligence and renewable energy, in urban energy planning. These tools not only improve urban energy efficiency, but also facilitate the transition to a more efficient circular metabolism, aligning with urban sustainability goals.

A lot of research is currently being conducted in relation to the concept of the Circular Economy (Fig. 7). These studies take a holistic approach, combining several methods, such as Material Flow Analysis (MFA), Ecological Footprint (EF), Life Cycle Analysis (LCA), and the Circular Economy simultaneously.

4.1. *Circular urban metabolism in the literature*

Once urban metabolism was introduced, this literature review has shown a growing interest in circular urban metabolism. So much so that we have decided to use keywords related to circular urban metabolism within the 1020 documents we are analysing: 'Circularity' (83 documents), 'Circular economy' (204 documents), 'Circular Urban Systems' (5 documents), 'Circular Urban Metabolism' (33 documents), and 'Circular city' (42 documents). This already indicates that when we start to discuss urban metabolism, relationships with circularity begin to emerge from 2013 onwards. By 2018, the topic started to gain momentum, with an exponential increase in documents related to the circular economy (Fig. 8).

Circular urban metabolism aims to provide a more sustainable solution by reducing resource extraction through the regeneration of materials and resources within the urban system. This concept goes hand in hand with the circular economy, as both must coexist to achieve their objectives. When using the keywords 'Urban Metabolism' and 'Circular Economy', the range becomes much narrower, suggesting that it remains a topic inviting further innovation, with 2 articles published in 2015 and 42 articles published in 2022, according to the Scopus database. Between 2013 and 2023, a total of 204 articles address the topics of urban metabolism and the circular economy. Among them, there are currently 16 articles, 3 of which are the most cited, that review tools for implementing the circular economy through a collection of strategies and case studies categorised by scope, strategy, and implementation to assist in introducing the concept [235], through industrial symbiosis to enable cooperation between entities and companies to improve profits and resource management [236], or through environmental reserves

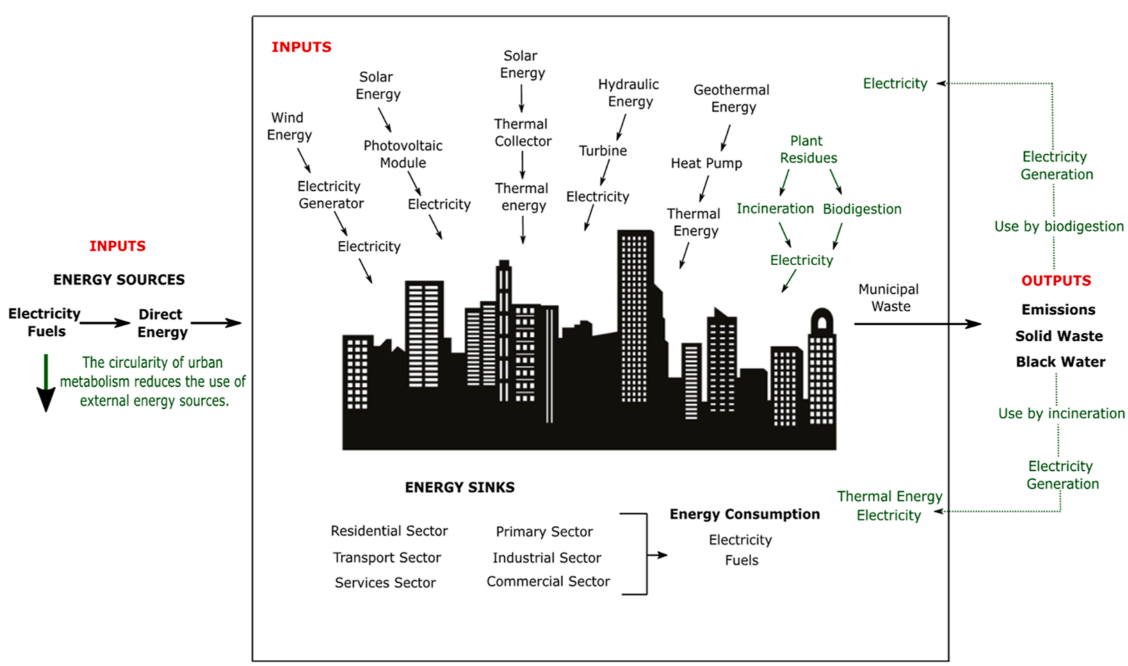

Fig. 7. Diagram of a city's energy metabolism. Source: Own elaboration.

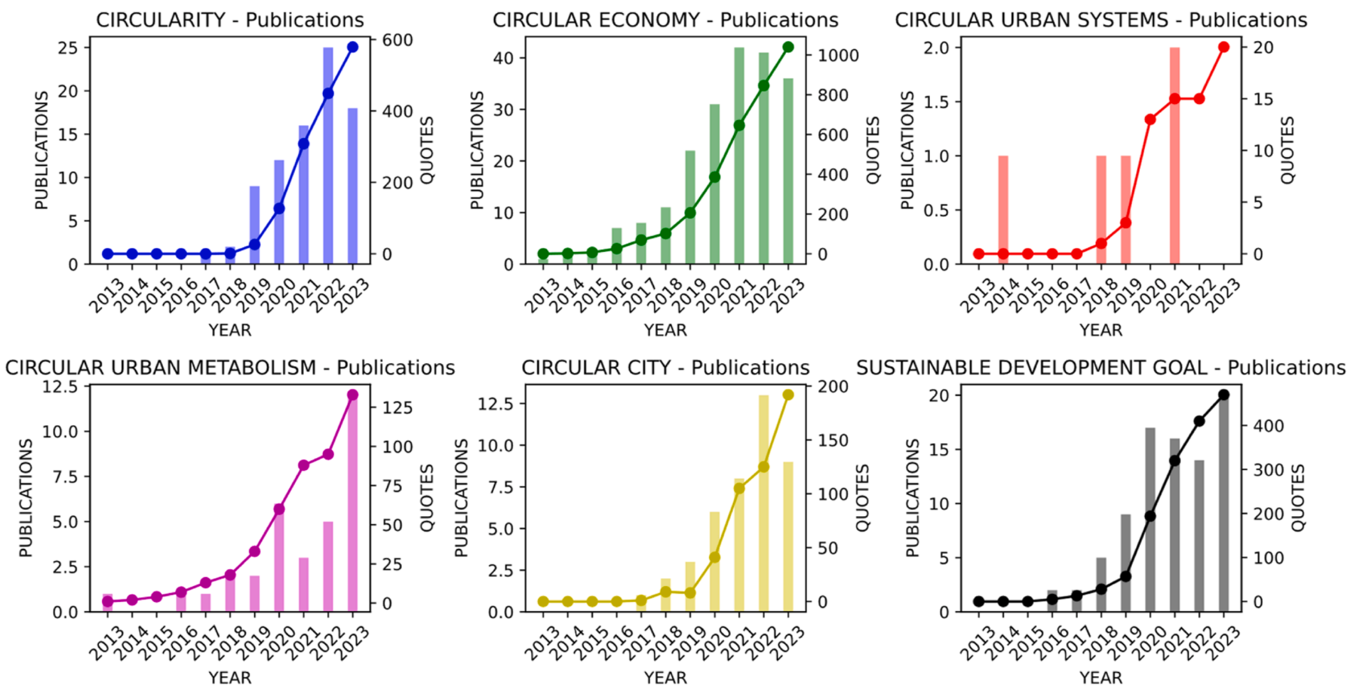

Fig. 8. Publications on circularity concepts and SDGs. Source: Own elaboration.

and their promotion on social and political agendas, such as those of the SDGs in the 2030 Agenda [236]. Both concepts give rise to circular urban metabolism, which aims to investigate how urban flows interact with the environment in order to redesign them in a more sustainable way.

4.2. Urban metabolism, circularity and sustainable development goals (SDGs)

Circular urban metabolism is closely linked to existing energy planning for the energy transition. The Sustainable Development Goals (SDGs), adopted by the UN in 2015 [237], also include solutions at the local level, as cities are vital centres for optimising the SDG agenda to achieve a transition in the policies, budgets, institutions, and regulatory frameworks of governments, cities, and local authorities. At the urban level, the most important SDGs are SDG 7, which seeks to ensure access to affordable, reliable, and sustainable energy by promoting access to electricity, the use of renewable energy, clean cooking solutions, energy efficiency, and financing; and SDG 11, which calls for safe, resilient, and sustainable cities through circularity-oriented urban planning and improvements in public transport.

If we filter for 'Sustainable Development Goal' in the search of the 1020 documents, we get a total of 85 documents that specifically start mentioning them from 2016 onwards. In 2020, the number of documents already exceeds 10, with a growth rate of 88 % compared to 2019 (Fig. 9).

However, one of the questions that arose and needed to be revisited was whether the entry of the SDGs had changed anything in the way urban metabolism was approached. The answer is yes, as most of the articles published up to May 2023 focused primarily on environmental protection and, to a lesser extent, on sustainable development [238]. Additionally, it is interesting to note that, since 2015, urban sustainability has become an increasingly important topic for researchers. This brief review of the SDGs not only provided insight into the growing interest in the topic, but it also highlighted that, in the context of urban metabolism, several SDGs are relevant, such as SDGs 11 to 15, which refer to targets for sustainable cities, consumption, climate, and biodiversity. This interaction increased the emphasis on environmental protection alongside human coexistence, with these SDGs outlining different analyses of energy consumption to regulate sectoral energy use and facilitate the understanding of sustainable energy practices [239, 240].

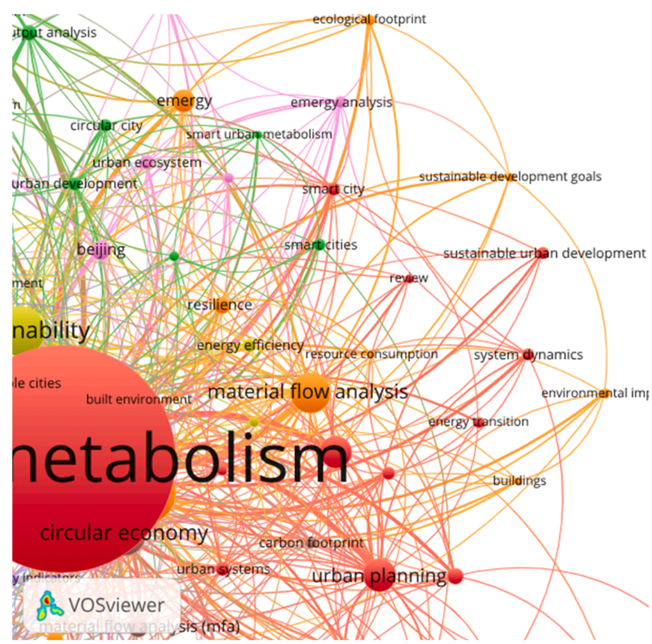

Fig. 9. ODS connections and urban metabolism (map of concurrence by keywords). Database: Scopus. Source: Own elaboration [VosViewer].

The study of urban metabolism is intrinsically related to all the SDGs, although SDGs 7 and 11 are the most closely linked. The following SDGs are also relevant:

- **SDG 8: 'Decent work and economic growth'.** This goal seeks sustained, inclusive, and sustainable economic growth by maintaining per capita economic growth and promoting resource-efficient

production. It is linked to the long-pursued goals of eco-efficiency and sustainable development [145].
- **SDG 9: 'Industry, innovation and infrastructure'.** This goal promotes industrialisation, including small industries in medium-sized cities.
- **SDG 12: 'Responsible production and consumption'.** The aim is to decouple economic growth from environmental degradation [146], which, when applied to cities, is achieved through efficient resource management and rational waste management.
- **SDG 13: 'Climate action'.** Pollution control in cities can be key to lowering the pollution rate of larger regions. For example, there are already plans that define city territories with Low Emission Zones that affect transport.
- **SDG 14: 'Life below water'.** Medium-sized cities with seaports have set targets to control excessive fishing, making sustainable use of the oceans and contributing to circular urban metabolism.
- **SDG 15: 'Life on land'.** As nature is the most obvious example of circular metabolism, it is necessary to set targets within cities with natural ecosystems to protect this way of life, which can be useful for developing an efficient circular model [241].

5. Future UM research

As noted in earlier sections of this review article, research on the concept of urban metabolism (UM) has evolved from basic models, such as the black box model—which considers only general input and output variables—to more sophisticated models that delve into the intricate functions of the cities or regions being studied.

Despite the advancements made, substantial limitations and gaps persist in the research surrounding this concept. For instance, the collection and accessibility of data related to the metabolism of cities pose significant challenges, hindering the ability to conduct comparative analyses across different regions or to track the evolution of a city over time [242].

Following several literature review studies on the concept of urban metabolism, it has been deemed essential to standardise methodology in order to simplify comparisons between studies, find methods to integrate analysis results, and encourage collaboration between disciplines. The standardisation of data quantification should be prioritised, as research is often hindered by issues related to data accuracy and availability.

After reviewing the literature, three main lines of research are identified. The first focuses on optimising urban metabolism networks using multi-objective methods to define feasible solutions, requiring clear definitions of system nodes and flow dynamics [243]. The second, as highlighted by Zhang, centres on the impact of carbon and energy metabolism on climate change, emphasising reducing emissions and expanding case studies in developing cities [244]. The third line aims to develop models that incorporate social factors to understand why certain urban flows are preferred and why some potential connections remain underutilised, impacting regulatory effectiveness.

In addition to these lines of research, another significant advancement in urban metabolism studies is the integration of Geographic Information Systems (GIS) with material flow analysis (MFA). Liu et al. developed a GIS-based framework that quantifies urban mass gains and losses, providing spatio-temporal maps of material stocks and flows during urbanisation. This approach is particularly relevant in rapidly urbanising regions, such as China, where significant material inputs and environmental impacts are observed [245]. Similarly, Peña et al. highlight the value of spatially explicit data in urban metabolism studies, arguing that such data can improve urban planning practices by increasing the efficiency of resource use at the city scale [246].

The application of ecological network analysis (ENA) has also gained ground in urban metabolism studies. Rosales et al. used ENA to quantify a virtual water metabolic network in Quito, Ecuador, demonstrating how this method can elucidate the connections between urban components and their external environment [247]. This holistic perspective is crucial for understanding urban sustainability and resource management. Furthermore, Feng et al. explored carbon metabolism within urban 'production-living-ecology' spaces, highlighting the dynamic interactions between different urban functions and their carbon fluxes [248].

Future lines of research in urban metabolism are likely to focus on the integration of digital twin technologies with urban metabolism analysis. Geremicca proposes a framework for applying these technologies to the monitoring and analysis of resource flows, which could foster circular economy strategies within urban environments. This approach aligns with the growing recognition of the need for sustainable urban practices that prioritise resource recovery and reuse [249].

Additionally, the concept of rural-urban metabolism is emerging as a critical area of study. Pianegonda et al. advocate for a methodological approach that considers the interdependencies between urban and rural areas, emphasising the importance of monitoring and assessing resource flows across these boundaries to promote sustainable development. This perspective is essential to address the complexities of urbanisation and its environmental impacts [250].

Another interesting point to mention within the potential future lines of urban metabolism (UM) research is the application of neural networks and artificial intelligence (AI) in urban modelling and simulation. This represents a promising frontier for understanding and predicting future urban states, especially in rapidly urbanising cities. Recent studies have highlighted the integration of neural networks with various modelling techniques to improve the accuracy and reliability of urban growth predictions.

Neural networks, particularly when combined with Markov models and cellular automata, have proven effective in simulating urban growth scenarios. For example, it has been discussed how a neural network-Markov model can simulate future exposure to urban coastal flooding, thus assisting in sustainable urban planning by evaluating different urban expansion scenarios [251]. Similarly, the work of Kamusoko and Gamba highlights the usefulness of neural networks in capturing complex non-linear relationships in urban systems, showing their potential in optimising urban growth modelling. This indicates that neural networks can not only forecast urban growth but also contribute to the efficient management of urban resources [252].

In addition, the integration of AI techniques with spatial prediction models has been recognised as a significant advance in urban planning. Ranagalage et al. illustrate the effectiveness of combining random forests with cellular automata to predict land use and land cover changes in urbanised areas, thus supporting sustainable urban development strategies [254]. This approach is reflected in the findings of Simwanda et al. [253], who used a neural-Markov network model to simulate intra-urban land use expansion in Lusaka, Zambia, highlighting the importance of using remote sensing and geographic information systems (GIS) to improve the accuracy of urban growth predictions. Such models are essential for developing urban planning frameworks that can adapt to changing environmental and social dynamics.

The application of neural networks also extends to specific case studies, such as the research by Rifat and Liu, which demonstrates the practical implications of these models for predicting urban growth scenarios and potential exposure to flooding in metropolitan areas such as Miami. This underscores the crucial role of AI in formulating urban resilience strategies [254].

In summary, urban metabolism continues to evolve towards an interdisciplinary approach, using advanced technologies and more accurate modelling to improve urban planning and sustainability. Future research should focus on standardising methods, incorporating AI, and integrating social and environmental dynamics to create more resilient and sustainable cities.

6. Conclusions

This literature review underlines the urgency of addressing urban metabolism in the current context of climate change, the consequences of human activity (resource depletion and global warming) and the uncontrolled growth of cities, which have come under the spotlight due to their significant energy consumption and contribution to greenhouse gas emissions. These factors underline the need for a comprehensive literature review to understand urban metabolism, especially circular metabolism in combination with a circular economy, not only as a response to environmental challenges, but also as a means to reduce waste, regenerate resources in cities and integrate the UN Sustainable Development Goals (SDGs), which are crucial for sustainable urban planning.

The uniqueness of this review lies in its focus on circular urban management as an integrative framework that promotes waste reduction and resource regeneration. The relationship between circular urban management and sustainable development provides a critical analysis of how cities can adapt to the demands of a low-carbon future. This approach requires redefining urban models, moving away from simple analyses towards more complex and dynamic frameworks that take into account the interactions of multiple factors affecting urban systems.

However, one of the most important challenges highlighted by the review is the lack of standardised and accessible data on urban metabolism, which limits the ability to make meaningful comparisons over time and across contexts. Interdisciplinary collaboration is needed to establish a solid foundation for future research, especially in urban network optimisation, integration of generic models and consideration of social factors, areas that require immediate attention.

Research on urban metabolism has progressed from basic models, such as the black box approach focusing on general input and output variables, to more detailed frameworks that delve deeper into urban functions. However, gaps remain in data collection and accessibility, making comparative analysis across regions and over time difficult. Standardisation of methodologies will facilitate such comparisons, integrate the results of analyses and foster interdisciplinary cooperation. Recent research from 2022 to 2024 reinforces the importance of integrating energy and food flows, as well as the transformative role of advanced technologies in improving urban metabolism. These perspectives offer clear directions for future research, especially in the transition towards a circular and resilient urban metabolism.

Future research should develop circular urban models that align with current policies, such as the SDGs, while measuring their tangible effects on climate change. This may involve exploring new energy dynamics at the local scale, the electrification of industry, the use of waste and innovative technologies such as AI and neural networks to model eco-efficient urban scenarios. The shift towards a more circular urban metabolism offers cities the opportunity to adopt advanced technologies, modify material and energy flows and adapt organisational and institutional practices. Cities that adopt a circular economy will not only manage resources more efficiently, but also mitigate environmental impacts.

Furthermore, it is crucial to develop generic models to better understand the influence of social factors on urban dynamics. While studies have quantified urban flows, the reasons behind specific patterns remain unclear. Enhancing connections between components of the urban system can further improve efficiency. Research should also focus on analysing urban metabolism in the context of climate change, in particular carbon and energy flows, to reduce consumption and emissions from a metabolic perspective. Broadening spatial analysis and extending case studies to developing cities will address unique sustainability challenges. Finally, incorporating technologies such as Geographic Information Systems (GIS) and Artificial Intelligence (AI) into the analysis of urban metabolism can advance urban planning, optimise resource management and develop precise strategies to create sustainable and resilient cities.

Funding

This research received external funding. This work is funded by The Spanish Government's state-wide research project entitled: Sustainability and resilience of medium sized cities and their contribution to the energy transition: circular urban metabolism, energy scenarios and indicator proposals. Acronym: METURBAN2030. Project type: Competitive $R + D + I$ project. Start date: 12/01/2022. End date: 11/30/2024. Funding entity: MINISTRY OF SCIENCE AND INNOVATION. GOVERNMENT OF SPAIN. Management center: Research Management Service. Code: 2022/00,407/001. Internal reference: MICIN_Transition_ECO_DIG_2021.

CRediT authorship contribution statement

Lucía Galán-Cano: Conceptualization, Methodology, Software, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Juan Cámara-Aceituno:** Writing – original draft, Software, Resources, Methodology, Investigation, Formal analysis, Conceptualization. **Manuel Jesús Hermoso-Orzáez:** Methodology, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – review & editing, Supervision, Project administration. **Ángel Mena-Nieto:** Writing – review & editing, Validation, Supervision, Project administration, Funding acquisition. **Julio Terrados-Cepeda:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Funding acquisition.

Declaration of competing interest

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

Appendix 1. Summary table of figures in the text

Item	Title or Description	Location	Purpose
Fig. 1	*Steps to follow in order to carry out the work methodology.*	Section 2	To illustrate the methodological process described in the manuscript.
Fig. 2	*WOS and SCOPUS publication and citation reports.*	Section 3. Section 3.1	To visualise the temporal evolution of publications and citations in two major scientific databases: Web of Science (WOS) and Scopus.
Fig. 3	*Most common research areas of search databases.*	Section 3. Section 3.1	To visualise the percentage distribution of research areas in the WOS (Web of Science) and Scopus databases.
Fig. 4	*Citation-country relationship. Database: Scopus.*	Section 3. Section 3.1	To represent a network of citation relationships between countries, generated from data in the Scopus database, using the VOSviewer tool.
Fig. 5	*Source-citation analysis. Database: Scopus Source:*	Section 3. Section 3.1	To show a co-citation network of academic journals, generated with the VOSviewer tool.

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Item	Title or Description	Location	Purpose
Fig. 6	*Timeline of the historical evolution of Urban Metabolism.*	Section 3. Section 3.2	To represent a timeline of the historical development of urban metabolism research (UM, Urban Metabolism).
Fig. 7	*Diagram of a city's energy metabolism*	Section 4	To represent a schematic model of urban metabolism, showing the input and output flows of energy and resources in the context of an urban environment.
Fig. 8	*Publications on circularity concepts and SDGs.*	Section 4. Section 4.1	To show the temporal evolution of scientific publications related to circularity concepts and the Sustainable Development Goals (SDGs).
Fig. 9	*ODS connections and urban metabolism (map of concurrence by keywords).*	Section 4. Section 4.2	To represent a map of keyword concurrence in urban metabolism research and its connection to the Sustainable Development Goals (SDGs), generated with VOSviewer.

Data availability

Data will be made available on request.

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