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Review

Integration of Circular Economy and Urban Metabolism for a Resilient Waste-Based Sustainable Urban Environment

Konstantina Ragazou [1,2,*], Georgia Zournatzidou [3], George Sklavos [4] and Nikolaos Sariannidis [5]

[1] Department of Management Science and Technology, University of Western Macedonia, GR50100 Kozani, Greece
[2] Department of Economics and Business, Neapolis University Pafos, Pafos 8042, Cyprus
[3] Department of Business Administration, University of Western Macedonia, GR51100 Grevena, Greece; gzournatzidou@uowm.gr
[4] Department of Business Administration, University of Thessaly, GR41500 Larissa, Greece; gesklavos@uth.gr
[5] Department of Accounting and Finance, University of Western Macedonia, GR50100 Kozani, Greece; nsariannidis@uowm.gr
* Correspondence: kragazou@uowm.gr

Abstract: An unsustainable rate of resource production and consumption is evident in urban environments. The absence of innovative approaches in conjunction with the exponential urbanization and expansion of the global population will inevitably result in substantial environmental consequences. There are two emerging alternatives: circular economy (CE) and urban metabolism (UM). The integration of these principles into novel methodology casts doubt on the linear model of contemporary economic and urban systems, which includes extraction, production, utilization, and disposal. In the development of a distinctive urban framework known as circular urban metabolism, the current study has illustrated the application of these principles. We design this study to motivate urban planners and decision-makers to investigate, develop, and supervise ecologically sustainable cities. Scholars from a variety of academic disciplines, intrigued by the intricacies of urban planning, design, and administration, can foster interdisciplinary collaboration in the circular urban metabolism (CUM) region. To address the research question, we implemented a bibliometric analysis, which involved the examination of 627 pertinent research papers, utilizing the R (R 3.6.0+) statistical programming language. The results emphasize the fundamental characteristics and significance of CUM in the management of refuse. In addition, the findings underscore the importance of creating a novel framework that incorporates the principles of urban political ecology, CUM, sustainability, and the novel dimension of waste metabolism. It is the goal of this framework to emphasize the significance of recycling in the informal sector as a waste management strategy in low- and medium-income countries (LMICs).

Keywords: circular urban metabolism; waste metabolism; R statistical programming language; efficiency; sustainability

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1. Introduction

The circular economy is a novel socio-economic paradigm that aims to minimize pollution and maximize the utilization of resources and products [1,2]. As stated in the European Green Deal, the primary goal of the European Union is to achieve a climate-neutral and circular economy [3]. This entails facilitating and providing direction for investment in many economic sectors. The newly published Circular Economy Action Plan (March 2020) encompasses a wide range of actions designed to accelerate the transition to a circular economy in Europe. Moreover, the circular economy has become a crucial element in achieving the Sustainable Development Goals (SDGs) and the Paris Agreement [4]. The circular economy signifies a substantial departure from a linear economic paradigm since it necessitates a fundamental transformation in our patterns of consumption and production

of products. This transformation is accomplished by eradicating inefficiency and contamination by deliberate planning, avoiding waste entirely, reintegrating resources into both the natural world and the economic system, and extending the durability of commodities and products through reuse. In recent times, there has been an increasing inclination towards embracing the circular economy idea at both the national and subnational levels. Several regions and cities are now initiating programs to convert their systems into sustainable circular models [5].

Regions and cities have a strategic advantage in promoting and leading the transition to a circular economy. They are responsible for implementing policies that directly relate to a circular economy model, such as waste management, zoning, and urban and regional planning. In addition, they can create markets for circular products and services via public procurement, provide favorable framework conditions for industrial symbiosis, encourage the formation of networks and hubs, and assist in local circular economy experiments and innovations [6]. At the same time, they may empower consumers to promote sustainable consumption and help reduce garbage. Public policies may support the implementation of a circular economy, which has the capacity to act as a driver for economic, social, and environmental sustainability in regions and cities. The use of novel circular business models, waste reduction techniques, recycling programs, and eco-design practices leads to cost savings, increased income, and the creation of local job prospects in many sectors. By 2036, the use of circular approaches in various sectors, such as the built environment, food, textiles, electrical appliances, and plastics, is projected to bring an estimated yearly benefit of GBP 7 billion to London. The Mairie de Paris (2017) predicts that the Île-de-France area will create more than 50,000 jobs in the circular economy sector by 2030 [5].

Moreover, the concept of circular economy in urban settings has transformed into the concept of circular urban metabolism. This notion characterizes cities as dynamic organisms that engage in processes of consumption, metabolism, excretion, respiration, distribution, and self-protection. Abel Wolman introduced the concept of a living organism in 1965 with his article "The Metabolism of Cities", published in Scientific American. According to Wolman, one way to enhance the efficiency of flows and minimize their negative impacts is by tracking the inputs, outputs, and stocks of cities. The concept has since been used to analyze the movement of people into and out of metropolitan regions. Hong Kong and Brussels were the first cities to be studied in 1970 and 1975, respectively. The objective was to measure the volume of materials and energy entering, leaving, and remaining in metropolitan areas to prioritize activities that encourage more efficient circular processes [7]. These cycles would resemble those seen in nature, where nothing is considered waste since everything serves a purpose for another creature. This is very imperative since cities now account for the bulk of resource use in the world, around 70%, including two-thirds of the energy.

However, one of the major concerns of urban metabolism is waste management of trash [8]. Waste significantly impacts both the environment and development, making it a substantial issue. Waste is an inevitable outcome of human activity that is difficult to prevent. At present, individuals are generating a greater quantity of refuse than they did in previous generations. The variable composition of solid waste, changes in consumption patterns, and the enormous growth in population over the last centuries have resulted in this outcome. Nevertheless, it is imperative that we shift our focus from the mere disposal of waste in landfills to the promotion of waste reduction. The per capita consumption of packaged products and consumer items has experienced a substantial increase since World War II. This may be associated with the extensive implementation of an economic development strategy that emphasizes economic expansion and consumption growth. This signals the beginning of a swift and comprehensive use of global resources. Waste is a common problem in urban areas, leading to a variety of negative consequences. Degradation of water quality leads to issues like inundation, as waste blocks water drainage systems. Additionally, it promotes the proliferation of disease-carrying organisms, which raises public health concerns [8–10]. Additionally, it has a negative impact on the perception

of public spaces, implying that they are neglected and devoid of civic responsibilities. Ultimately, it cultivates a sense of alienation among the local populace. Furthermore, waste encompasses additional social, economic, and environmental factors, which will be further investigated in the subsequent sections.

The objective of the present study is to highlight contemporary research trends in circular urban metabolism and waste management while proposing solutions to any challenges that urban areas may face when implementing the urban metabolism model. A bibliometric analysis has been conducted to address the research objective, utilizing the R statistical programming language and the bibliometric instruments of Biblioshiny and VOSviewer. Furthermore, this article comprises five sections, including the Introduction, which articulates the research question and the study's objective. The urban circular metabolism and waste management principles are the focus of the theoretical framework, which underscores the challenges and obstacles that are associated with them. In Section 3, the Materials and Methods are presented, as well as the specific procedures that the researchers employed to establish the criteria for the development of the research formula. The selection of the bibliometric data that are utilized in the analysis is facilitated by this formula. The results are depicted in Section 4 as graphs, maps, tables, and diagrams. In conclusion, Section 5 assesses the study's findings and explores the potential future research directions, repercussions, and limitations.

2. Literature Review

2.1. Exploring the Concept of Urban Mining and Its Relationship to the Circular Economy

There has been a considerable increase in population and a substantial acceleration in economic development since the conclusion of the Second World War. The consumption of natural resources to manufacture a variety of consumer necessities, such as food and gasoline for transportation, increased significantly because of the increased demand for products and services. The consumption of resources increased eightfold over the previous century, resulting in an annual consumption of 60 metric tons of basic materials [11]. Initially, Europe served as the primary provider, and this pattern persists because of the greater consumption rates in industrialized nations. Empirical data indicate a continuous and unabated rise in the use of materials, with no signs of a decline or deceleration. While consumerism may have positive effects on individual well-being, human activities have a long-lasting and rapidly increasing impact on ecosystems, especially in light of the growing awareness of environmental issues. The worldwide scope of pressure necessitates the transnational importation of commodities.

Furthermore, the use of natural resources has a broad spectrum of adverse consequences. Resources are depleting at a pace that is 50% higher than their usual rate of replenishment. Resource scarcity refers to a condition in which the availability of renewable resources, such as water, forests, and croplands, is inadequate to satisfy the demand for them. The exhaustion of resources and the costly nature of exploration have caused a rise in the cost of raw materials, leading to disruptions that are now affecting the whole production process. Resource efficiency and optimization are crucial methods for promoting sustainable economic growth in nations [6,7]. The circular economy is a transformative concept that addresses the challenge of achieving resource efficiency and productivity in industrial processes while also benefiting all stakeholders involved. Consequently, scientific scholars are still engaged in ongoing discussions to provide a precise and formal definition of the circular economy [12,13].

To ensure the preservation of resources and promote sustainable development for future generations, CE must prioritize the support of environmental, economic, and social objectives [1,14]. The concept "circular" refers to the antithesis of a linear economy, in which natural resources are extracted, transformed into consumer products through industrial processes, and subsequently disposed of after they have satisfied the customer's demand. In a linear economy (LE), products are intentionally designed with shortened lifespans, resulting in the waste of energy, labor, and value when they are disposed of in landfills [8].

On the other hand, the circular economy (CE) offers an alternative to conventional economic models that employ a linear strategy of "take–make–consume–dispose", which assumes that natural resources are limitless, readily accessible, and inexpensive to dispose of. This paradigm renders the concept of "end of life" obsolete, as the ultimate dispersal of materials should never occur. Consequently, materials are in a state of perpetual circulation within closed cycles throughout the production process. Closed loops employ the concept of "waste-as-food" or "reverse chain", reintegrating industrial residues into subsequent production cycles as raw materials. Reverse-cycle activities have the potential to substantially reduce material costs by converting waste into beneficial resources.

2.2. The Challenge of Waste Management in a Circular Urban Metabolic Model

The concept of urban metabolism (UM), like circular economy (CE), has been in existence for a considerable period. People widely acknowledge Abel Wolman as the progenitor of this notion. UM stands for the provision of resources such as material, energy, and food to a hypothetical metropolis, as well as the consequent production of waste products. As an additional point, the concept of urban metabolism (UM) draws on the analogy of cities as living, breathing entities that produce waste due to their transformational processes and require resources to sustain their functions. According to Christopher Kennedy, urban metabolism (UM) refers to the whole of technical and socio-economic activities occurring in cities, which contribute to development, energy production, and waste disposal [8]. The concept of UM involves the transportation of natural and industrial resources, energy, people, and information. It is important to mention that the notion of CE does not consider the consideration of individuals and information. Moreover, UM also represents the increase in population moving into the urban area [15].

UM consists of six main themes: (i) the city seen as an ecosystem; (ii) the flow of materials and energy within the city; (iii) the economic and social interactions within the city; (iv) the economic factors that influence rural–urban relationships; (v) the continuation of urban inequality; and (vi) attempts to redefine the city through new understandings of socio-ecological connections. In the context of UM, the city and its boundaries have importance. Flows are located inside a physical region referred to as "space". In order to understand and assess the various motions, it is essential to define the physical boundaries and spatial dimensions [16,17].

However, cyclic urban metabolism faces some notable challenges. One of the initiatives is the development of innovative environmental techniques and substitutes for fossil fuels. Shifting towards a cyclical and adaptive resource supply model, together with a change in lifestyle, might provide the foundation for an urban environment that requires fewer resources when resources are scarce [4,18]. To ensure public welfare and develop sound political decisions, it is critical to conduct a system-wide analysis of the environmental, economic, and social dimensions of sustainability in urban systems, which are intricately interconnected via numerous supply chains for production and consumption. Notwithstanding the evident advancements and efficacy exhibited by material recycling practices, energy efficiency initiatives, and the integration of renewable energy sources, a considerable degree of unfinished business persists.

Dynamic channels of trade and supply chain facilitate the operation of society as a complex and interconnected network of production and consumption. The application of circular economy principles, resource exchange, or recycling in order to improve energy efficiency at a single node of the network does not always result in a comprehensive improvement in system-wide efficiency. In the same vein, a reduction in a specific category of consequences, such as emissions, water depletion, energy depletion, or land demand, does not necessarily lead to a reduction in the system's overall consequences. As soon as feasible, it is imperative that research on urban metabolism commence efforts to develop sustainable solutions that address socio-ecological dynamics by elucidating the interrelationships and fluctuations between ecosystems and cities [11].

Waste management is an additional challenge in the implementation of urban circular metabolism. Challenges in waste management include the escalating production of waste due to rapid population growth and urbanization, insufficient infrastructure and resources, water and air pollution, disease transmission, high maintenance costs, political intervention, scarcity of collection vehicles, underdeveloped infrastructure, inadequate funding, and the presence of illegal dumping sites. These issues present substantial economic and environmental risks, which in turn lead to the transmission of infectious maladies and health hazards. Developing countries face additional challenges, such as the development of refuse that exceeds the rate of economic growth and population growth. However, there are opportunities to address these challenges by instituting effective waste management strategies, including the generation of energy from refuse, recycling, repurposing, and reducing waste [19]. The effective mitigation of waste-related issues can be achieved by providing substantial financial support, developing infrastructure, and efficiently executing cohesive policies. Nevertheless, the obstacles to waste management can be alleviated through the implementation of intelligent waste management. Smart waste management is a transformative strategy that seeks to enhance the efficiency, sustainability, and environmental awareness of waste management. It assists in resolving the problems associated with conventional waste management techniques. Additionally, Smart Waste Management suggests a transformative approach to waste management by integrating emerging technologies, including data analytics and community engagement.

3. Materials and Methods

This study used a bibliometric technique to carefully evaluate articles in order to find recurring themes, deficiencies, and developing areas. Bibliometric analysis enables the assessment of current research status and identification of prestigious academic journals, publishing corporations, or authors within a certain field. By using the bibliometric approach, one may gain a comprehensive awareness of the academic domain and enhance their understanding of the new concept of circular urban metabolism and its contribution to the waste management process. This research employs a systematic analysis of compiled literature data acquired from sources like Scopus, Web of Science (WoS), and Google Scholar. Quantitative and bibliometric methodologies have seen a notable surge in their use for assessing research output in recent years. A thorough assessment should be conducted to evaluate the effectiveness, accuracy, and consistency of an evaluation process [20,21].

3.1. Data Collection

The data used in the current investigation were obtained from Scopus in January 2024. Scopus, founded in 2004, is a well-regarded bibliographic database. The collection consists of abstracts and citations acquired from respected scientific publications. The database contains a total of 36,377 titles obtained from 11,678 publishers. Therefore, the data for this research specifically focus on four key concepts: circular urban metabolism, circular economy, waste management, and urban sustainability. The process of doing keyword searches is well explained and shown in Table 1.

In addition, the PRISMA flow diagram provides a visual representation of the important steps involved in a reliable selection of articles for bibliometric analysis (Figure 1). The search query resulted in a total of 1923 sources in the collection. However, limiting the selection to only articles reduced the total count to 1100. Afterwards, we conducted a thorough analysis of a total of 841 documents, eliminating those that lacked a clear connection or encompassed a broad scope unsuitable for our current investigation. The primary aim of this inquiry is to emphasize the importance of circular urban metabolism and its key obstacles, such as trash management. Upon thorough examination of the papers, we discovered that several selected sources do not explicitly indicate the dimensions and attributes of the investigated area in their title or keywords. We modified the search criteria to only include publications directly relevant to the current research issue, eliminating

any irrelevant references. After implementing this filtering methodology, we selected and included a cumulative sum of 627 scholarly papers in the bibliometric analysis.

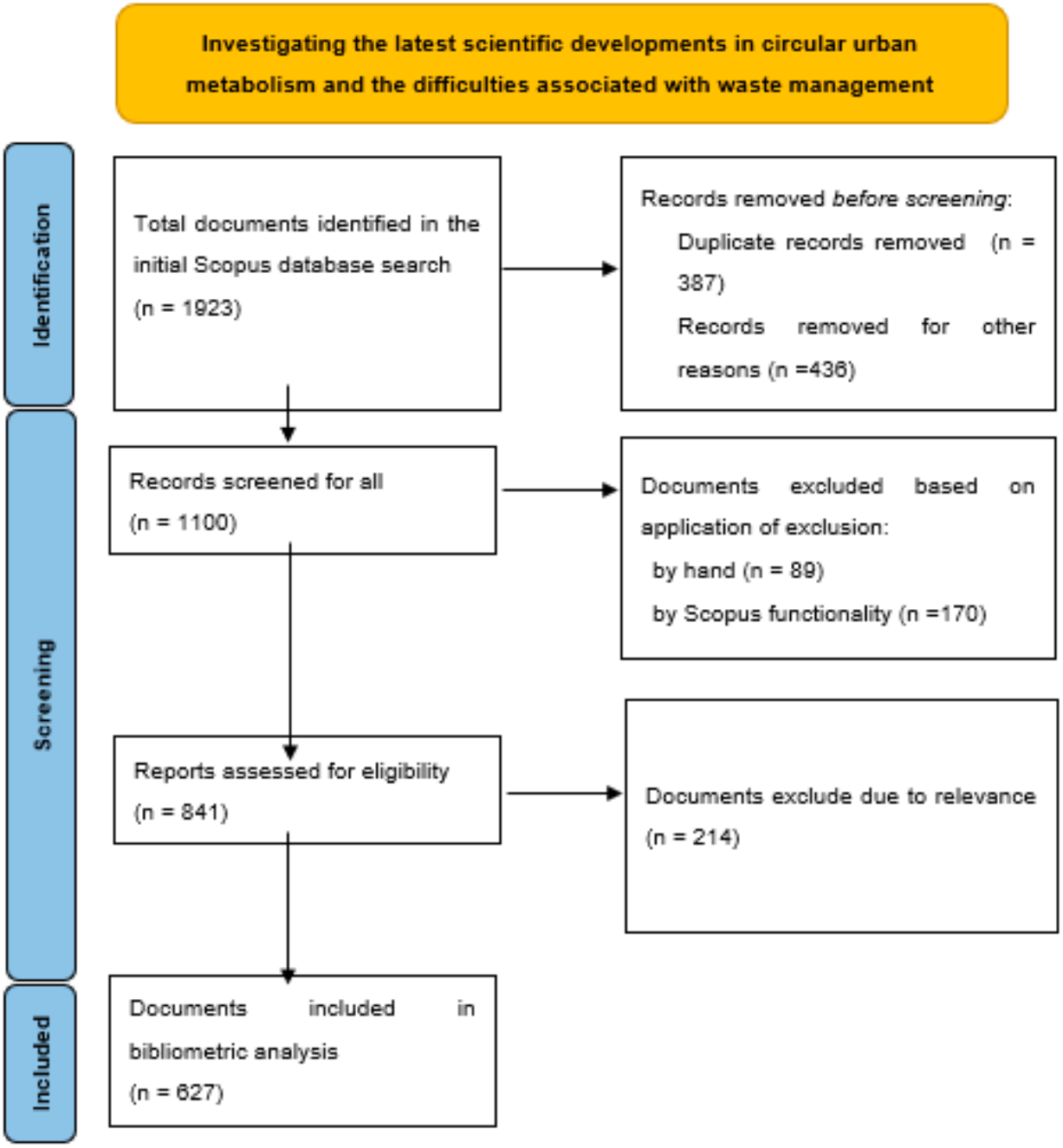

Figure 1. PRISMA flow diagram.

Table 1. Keyword search formula. Source: Own elaboration.

Step	Keyword Search
1	((“circular economy” AND “waste management”))
2	((“circular economy” OR “circularity”) AND “waste management”))
3	((“circular economy” OR “circularity” OR “circular model”) AND “waste management”))
4	((“circular economy” OR “circularity” OR “circular model”) AND “waste management”) AND “urban” OR “urban metabolism”))

Table 1. *Cont.*

Step	Keyword Search
5	(("circular economy" OR "circularity" OR "circular model") AND "waste management") AND "urban" OR "urban metabolism" OR "circular urban metabolism"))
6	(("circular economy" OR "circularity" OR "circular model") AND "waste management" OR "municipal solid waste management") AND "urban" OR "urban metabolism" OR "circular urban metabolism"))
7	(("circular economy" OR "circularity" OR "circular model") AND ("waste management" OR "municipal solid waste management") AND ("urban" OR "urban metabolism" OR "circular urban metabolism" OR "circular cities"))
8	(("circular economy" OR "circularity" OR "circular model") AND ("waste management" OR "municipal solid waste management") AND ("urban" OR "urban metabolism" OR "circular urban metabolism" OR "circular cities") AND "sustainability"))
9	(("circular economy" OR "circularity" OR "circular model") AND ("waste management" OR "municipal solid waste management") AND ("urban" OR "urban metabolism" OR "circular urban metabolism" OR "circular cities") AND ("sustainability" OR "sustainable development"))
10	(("circular economy" OR "circularity" OR "circular model") AND ("waste management" OR "municipal solid waste management") AND ("urban" OR "urban metabolism" OR "circular urban metabolism" OR "circular cities") AND ("sustainability" OR "sustainable development")) AND (LIMIT-TO (DOCTYPE, "ar")) AND (LIMIT-TO (PUBSTAGE, "final") OR LIMIT-TO (PUBSTAGE, "aip")) AND (LIMIT-TO (SRCTYPE, "j"))

3.2. Software for Bibliometric Visualization and Analysis

The authors used the R statistical programming language for data analysis with the bibliometric applications Biblioshiny 4.1 and VOSviewer version 1.6.20 [22,23]. The authors obtained the whole bibliographic dataset in CSV format from the Scopus database. Initially, we used R Studio to install and start the Bibliometrix R package. The authors then started the Biblioshiny program by entering Biblioshiny in the R terminal. Biblioshiny is a web application that enables anyone without programming skills to use the Bibliometrix tool for R. Bibliometrix provides an array of tools that provide comprehensive bibliometric analyses for researchers [24]. Biblioshiny, a statistical software application, enables data mining in bibliometrics. The aim is to determine the frequency of simultaneous keyword occurrences in two scientific contexts. The Biblioshiny interface has acquired an Excel file named "A.csv". We have sent PNG and Excel (.csv) files.

Furthermore, the authors obtained (.png) files and used them for data analysis in accordance with the study's objectives. We used VOSviewer to elucidate the complex characteristics of Omicron-based research and discern supplementary patterns. The global publishing landscape was analyzed with VOSViewer software, specifically intended for the aggregation and visualization of bibliometric maps [25]. It allows readers to establish and oversee a network or connection when referencing an article or subject. This application can map publications and articles that are much larger in size. VOSViewer may provide certain information on the bibliometric visual map. Numerous prior studies have used this tool for bibliometric analysis, allowing researchers to proficiently investigate relationships over an extensive bibliometric map [26].

4. Results

4.1. Bibliometric Analysis

Figure 2 depicts the yearly output of research publications on urban circular metabolism and its importance in trash management. The COVID-19 pandemic led to a significant surge in research activity within the business. The outbreak has been characterized as the most serious health calamity in a century, and it has led to the gloomiest economic projection since the Great Depression. This assumption suggests that sustainable urban

design often emerges because of a sequence of crises, whereby hygiene crises, health crises, and epidemics play a crucial role. The rise of the urban planning movement in the 21st century was a direct reaction to the detrimental consequences of urban growth in the 19th century, particularly its significant impact on public health [27]. Throughout the history of modern planning, concepts and ideas relating to urban planning, such as the cyclic urban metabolism, have been often repeated and used. The debates have primarily focused on the growing urban issues, including urban health emergencies and disparities, unsanitary housing and urban surroundings, inadequate public spaces, inefficient land use, and transportation, among other concerns. Public health has consistently been associated with the attributes of readily available and verdant communal places, along with the discourse on the growth of cities versus condensed urban development, the clustering of people, and the organization of urban spaces. Therefore, the main goal in urban planning was to prioritize public health by including both built-up and open areas in urban growth patterns, whether openly or implicitly.

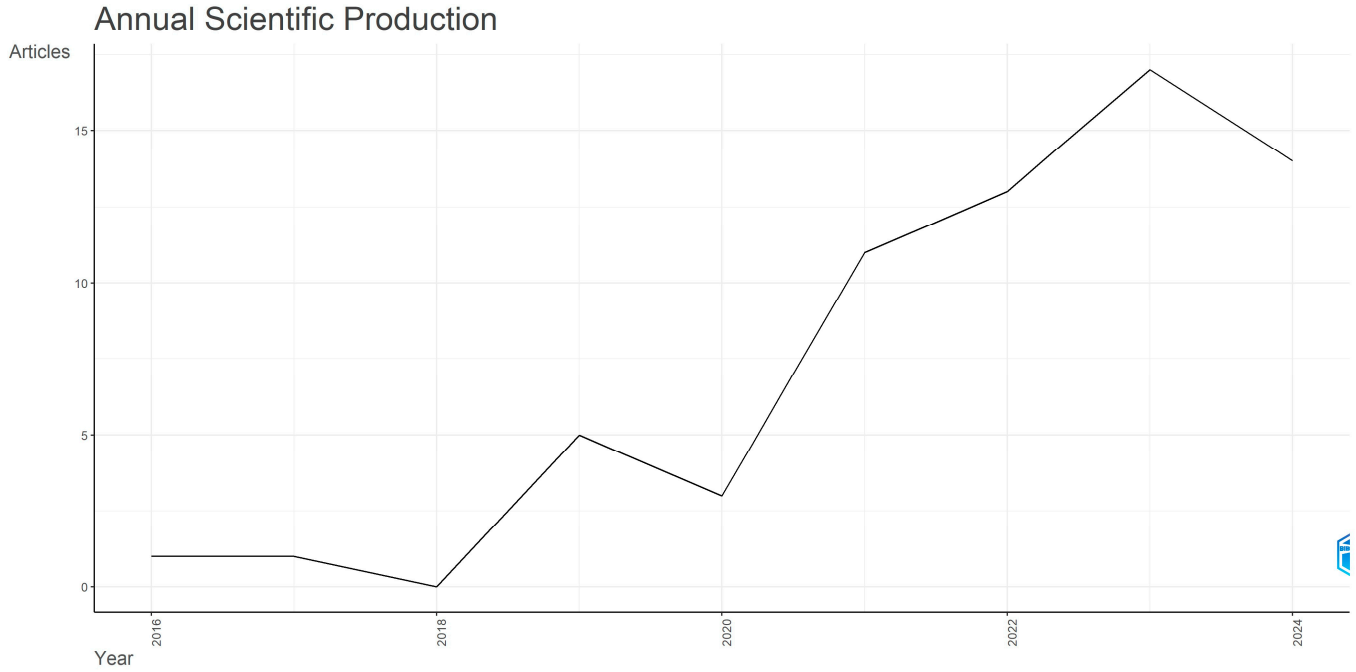

Figure 2. Annual research production. Source: Scopus/Biblioshiny.

Thus, in recent years, there has been a strong emphasis on planning models and techniques that harness the urban system's capacity to maintain itself over a long period of time to achieve urban sustainability. This study offered innovative perspectives on fundamental urban planning matters, including urban form, population density, and the integration of land use and transportation planning. It achieved this by establishing correlations with environmental and climate change concerns. Unlike previous decades, which witnessed a decrease in the inner-city core, the current trend is one of re-urbanization. This phenomenon is a consequence of cities adopting urban planning and policies that emphasize the improvement and rejuvenation of densely populated cities. Several European cities embraced Hall's introduction of "the lost art of urbanism" by implementing environmentally friendly and other sustainable measures. The transition to urbanization, and therefore the adoption of the compact city concept, aimed to stimulate urban revitalization and enhance the overall urban living standards. Urban policy largely acknowledges this as a remarkable accomplishment.

Figure 3 displays the journals with the highest volume of research submissions related to the study subject from 2012 to 2023. Therefore, the Journal of Cleaner Production holds the highest number of related publications in the field of circular urban metabolism

and waste management. Specifically, The Journal of Cleaner Production is a globally oriented, interdisciplinary journal that particularly focuses on the study and application of cleaner production, environmental sustainability, and sustainability. Its main objective is to promote sustainability in communities via its publications. Also, the main concept of the journal, which is cleaner production, strives to minimize waste output and enhance efficiency in the use of energy, water, resources, and human capital. Additionally, the Journal of Cleaner Production provides a forum for examining and debating both the theoretical and practical aspects of cleaner production, which include environmental and sustainability concerns in many sectors, such as enterprises, governments, educational institutions, regions, and society.

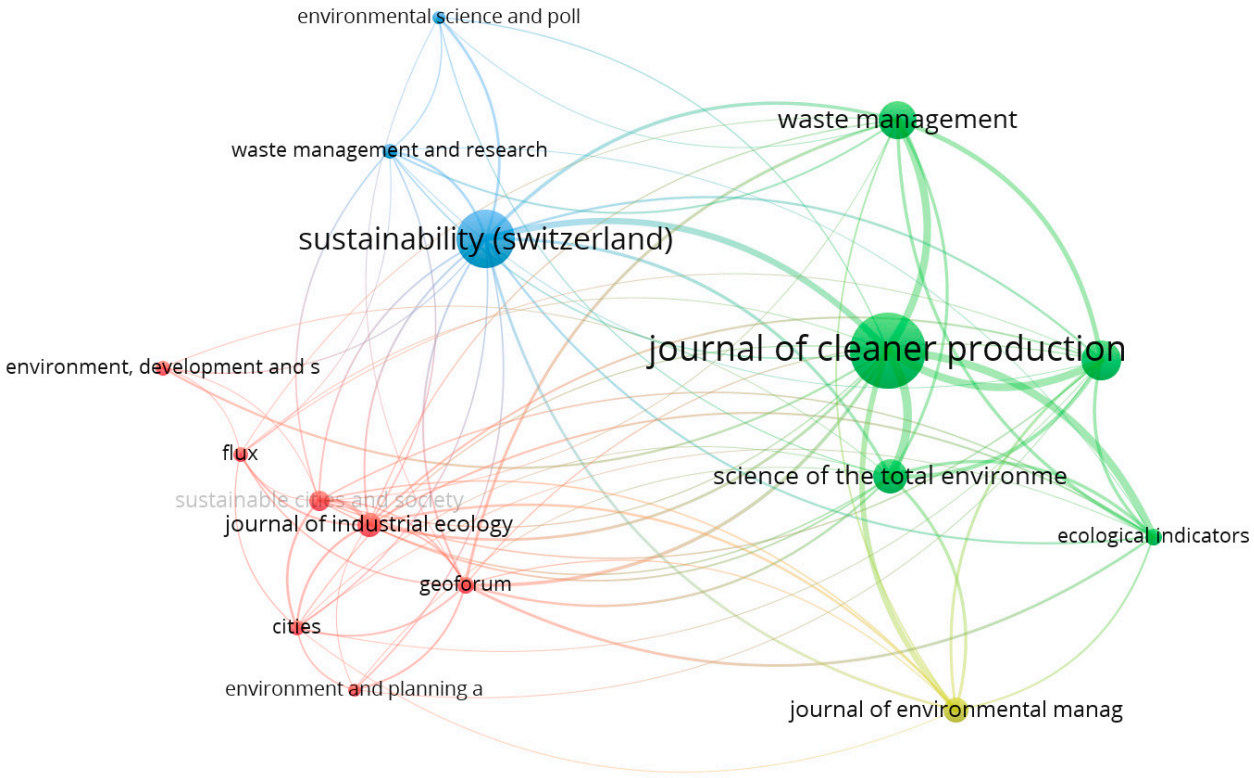

Figure 3. Most relevant sources. Source: Scopus/Biblioshiny.

Furthermore, sustainability holds the second position in the list of sources with the most publications in the field. Sustainability focuses on the technological, environmental, cultural, economic, and social aspects of human sustainability [28,29]. The primary goal of this initiative is to encourage academicians to publish their extensive experimental, computational, and theoretical research, particularly in the areas of circular economy and sustainability. This improves scientific comprehension and enables the prediction and assessment of global transformations and developments that are pertinent to the concepts. Furthermore, it supports the 2030 Agenda for Sustainable Development, which was ratified by the United Nations, thereby recognizing the significance of sustainability and the necessity of achieving sustainable development for the benefit of humanity. Finally, the third position belongs to the journal of waste management. The objective of this journal is to disseminate and engage in discussions regarding a variety of aspects of solid refuse in urban areas, such as its origination, characterization, minimization, collection, separation, treatment, and disposal. In addition, the journal publishes manuscripts that address economic and environmental assessments, education, and waste management policy. In addition, it encompasses a broad spectrum of solid waste, including municipal.

Furthermore, Table 2 provides a summary of the most frequently cited documents in the field of investigation. The research document "Circular economy practices in the

built environment" is the most prominent and contains most of the citations. The purpose of this literature review research is to provide structured information that will serve as the foundation for the organization of future cities through the circular economy. This article provides evidence that the constructed environment is the primary source of global greenhouse gases and raw material extraction. Replacing outdated structures with new ones cannot improve the climate in cities, as the construction and operation phases require substantial energy and resource consumption. Both academics and practitioners have recognized the circular economy as a critical strategy for sustainable urban development, particularly in China and Europe. The circular economy's primary goal is to prevent the use of virgin materials and waste outputs and to preserve the value of resources. Reducing resource consumption, along with recycling and repurpose, accomplishes this. As a result, the purpose of this review paper is to identify research gaps, clarify the general perspective, and guide future research by analyzing the current body of literature's perspective on the organization of cities in the transition to a low-carbon circular economy. Furthermore, this review includes 282 journal articles that collectively represent three methodologies for the implementation of circular economies in the constructed environment: (i) sustainable city management; (ii) urban services and consumer practices that are consistent with circular economies; and (iii) cleaner production and construction. The results of the consumer practices indicate the need for further research to explore strategies for reduction. These strategies could include product–service systems that encourage intensified use and an extended service life, as indicated by the requests for waste hierarchy. The review also suggests a novel concept of urban–rural symbiosis as a potential method for resource recovery in fully integrated urban refuse, water, and energy systems.

Table 2. Most related and cited documents in the field. Source: Scopus/Biblioshiny.

Research Document	Total Citations	TC per Year	Normalized TC
Circular economy practices in the built environment	160	32.00	2.45
Circular Economy Strategies in Eight Historic Port Cities: Criteria and Indicators Towards a Circular City Assessment Framework	132	22.00	1.78
Overcoming the Main Barriers of Circular Economy Implementation through a New Visualization Tool for Circular Business Models	114	19.00	1.54
Circular Cities: Challenges to Implementing Looping Actions	90	15.00	1.21
Eight energy and material flow characteristics of urban ecosystems	61	6.78	1.00
An overview of the end-of-life tire status in some Latin American countries: Proposing pyrolysis for a circular economy	52	13.00	2.58
Evaluation of urban metabolism assessment methods through SWOT analysis and analytical hierocracy processes	50	16.67	4.22
Circular Cities: A Revolution in Urban Sustainability	38	9.50	1.88
Comparing the convergence and divergence within industrial ecology, circular economy, and the energy–water–food nexus based on resource management objectives	37	9.25	1.83
The Role of Renewable Energy in the Promotion of Circular Urban Metabolism	35	4.38	1.00

Nevertheless, the circular urban metabolism concept is only mentioned in one of the most relevant and commonly cited papers in the field, "Evaluation of urban metabolism assessment

methods through SWOT analysis and the analytical hierocracy process". Particularly, the aim of this paper is to investigate the relationship between environmental pressures and urbanization trends, which are a consequence of the growing demand for resource consumption, refuse production, and greenhouse gas emissions. In light of the substantial decline in natural resources, the deterioration of life quality, and the consequences of climate change, the scientific community emphasizes the significance of understanding and accentuating the dynamic relationship between cities and the environment. As an outcome, cities are faced with the challenge of instituting alternative strategies to encourage the sustainable management of urban resources. Voukkali and Zorpas (2021) research contributes to the elucidation of the concept of urban metabolism, as previously mentioned. The current methodologies must be updated to meet the needs of the cities in the future, as indicated by the results. A new hybrid approach is required, which will entail the implementation of a new set of key performance indicators.

Figure 4 indicates the most relevant authors in the field of circular urban metabolism and the way that urban areas can mitigate the challenge of waste management. Among those, the one that concentrates most of the interest of the research community is "Lost in Transition? Drivers and Barriers in the Eco-innovation Road to the Circular Economy", written by de Jesus and Mendonça. This paper aims to add to the ongoing discussion by reviewing information pertaining to the many elements that facilitate or impede the development of a CE in urban areas. Specifically, it examines the eco-innovation route towards a CE and tries to consolidate existing but scattered research on how "transformative innovation" might promote this transition while overcoming sustainability barriers.

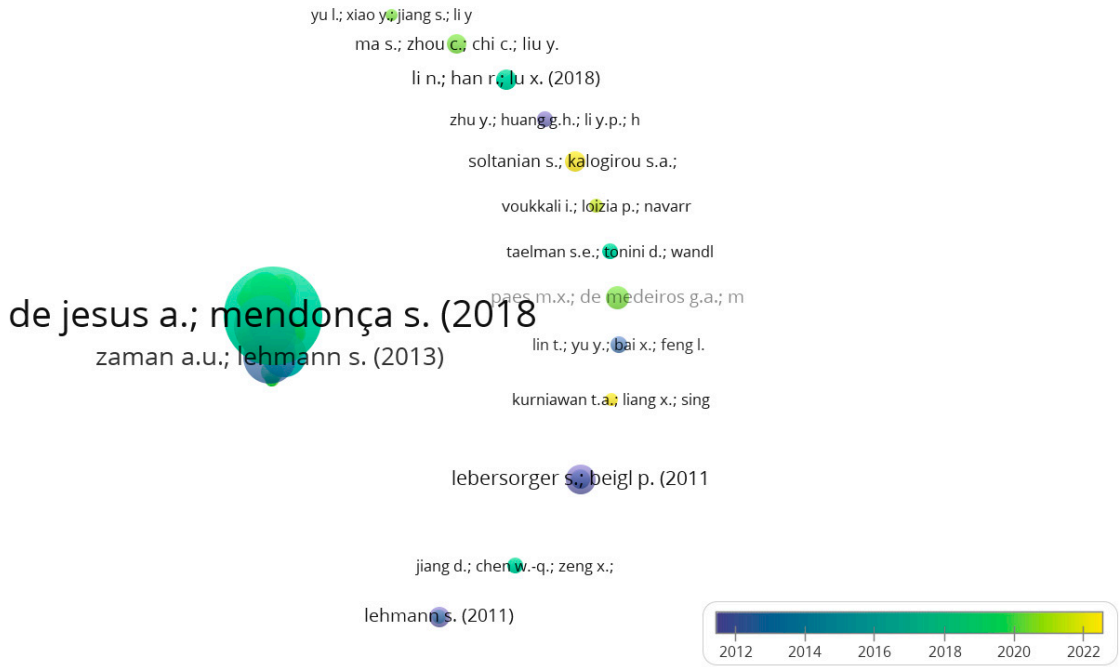

Figure 4. Most relevant publications.

Nevertheless, the challenge for cities in developing and employing circular systems persists, as emphasized by Williams (2019) in the research work "Circular Cities: Challenges to Implementing Looping Actions", published by *Sustainability* one year later. Through the utilization of a mixed methods approach, the author has effectively identified five common obstacles in the implementation of circular methods. By addressing these issues, it would be feasible to execute looping operations that encompass a variety of resources in urban areas. Additionally, this study demonstrates the influence of context on the challenges associated with the implementation of nexus solutions and looping activities in urban areas.

Finally, after a few years, urban areas have successfully tackled the significant challenges of implementing circular methods. However, a new issue has emerged: waste

management. Soltanian et al.'s 2022 research work, "Exergetic sustainability analysis of municipal solid waste treatment systems: A systematic critical review", specifically reveals that urban areas often dispose of waste through open dumping, landfilling, or uncontrolled burning. This can lead to the release of significant amounts of contaminants and pathogens in the soil, water, and air of urban areas. However, municipal solid waste can serve as a useful practice in managing the challenge of urban waste and achieving the development of a sustainable urban metabolism. Solid waste management (SWM) is a critical city administrator responsibility and a strong governance indicator. Effective SWM reduces health and environmental risks, conserves resources, and promotes city livability. However, it is advisable to include comprehensive and resilient sustainability evaluation methodologies throughout the planning, building, and functioning stages of SWM treatment systems.

Another critical component of bibliometrix is the analysis of the most influential countries in the global sphere of circular urban metabolism and the strategies that cities may implement to effectively manage their refuse. Figure 5 illustrates the nations, with China at the top of the list. The country's tranquil progress has been impeded by severe environmental issues, despite significant improvements in its quality of life and robust economic growth. China is presently grappling with the issue of excessive solid refuse production. Demolition detritus and excavation are the two primary sources of refuse [30]. Consequently, socio-economic advancement has been impeded by the substantial increase in environmental degradation. Organic waste constitutes over 80% of the urban areas in China. Furthermore, the escalation of population expansion and urbanization directly contributes to the excessive creation of municipal solid waste (MSW). Consequently, the current challenges in China are the reduction in consumption to alleviate waste management and the enhancement of recycling rates, as local populations produce significantly more refuse than non-industrial nations [31–33]. The environmental impact of their refuse cannot be effectively managed and reduced using conventional technical methods. In order to address this issue, Chinese cities have implemented circular urban metabolism and the emergence of cutting-edge technology in the era of Industry 4.0, which can provide a variety of digital solutions that can effectively manage waste [31].

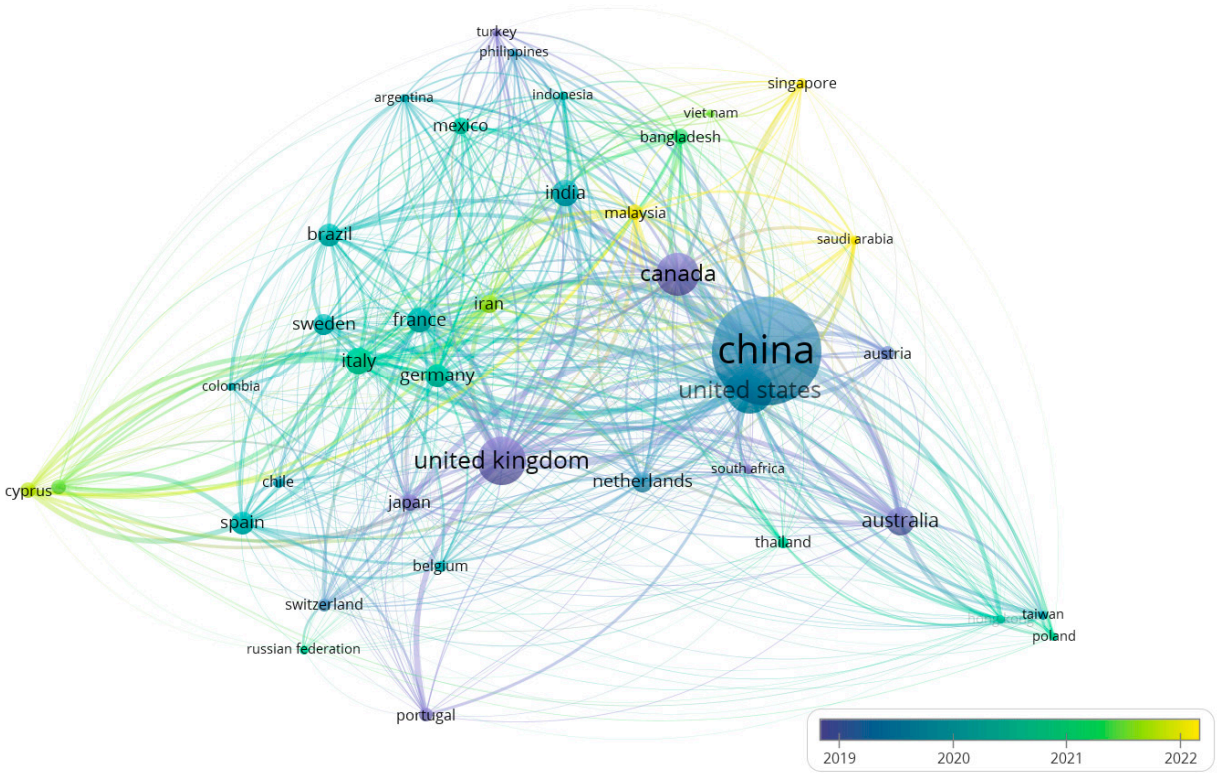

Figure 5. Countries with the most publications in the field.

4.2. Network Analysis

In recent times, scholars and practitioners have focused on the notion of the circular economy, which has been present since the beginning of industrialization. This attention has been particularly evident in the aftermath of the adoption of the Circular Economy Package and the Circular Economy Action Plan by European authorities. However, the idea of urban circular metabolism is quite new. The term "urban circular metabolism" can be used instead of "circular economy" to include six important elements: (i) viewing the city as an ecosystem; (ii) understanding how materials and energy flow within the city; (iii) considering the economic and social interactions within the city; (iv) recognizing the economic factors that affect the connections between rural and urban areas; (v) acknowledging the persistence of urban inequality; and (vi) aiming to redefine the city through innovative ecological and social ideas. The urban circular metabolism framework places great importance on the city and its limits [14,34]. Figure 6 depicts another facet of waste management in the context of circular urban metabolism. The picture illustrates the notion of circular urban metabolism, which aims to provide a holistic comprehension of various flows, including the transportation of garbage. Therefore, a new idea called waste metabolism might be proposed. Waste metabolism is a specialist investigation that specifically examines the mechanisms by which waste moves from its source to its treatment.

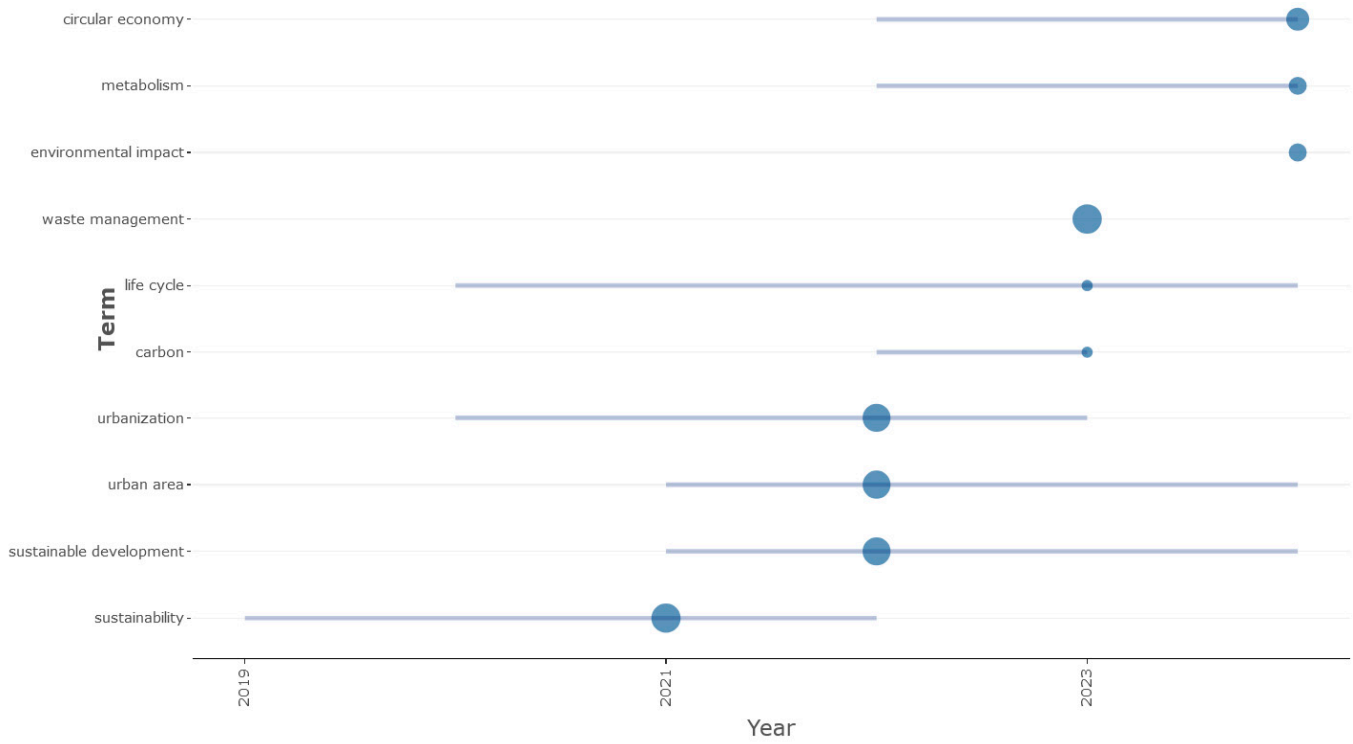

Figure 6. Research trend analysis. Source: Scopus/Biblioshiny.

The circular urban metabolism differs from the waste metabolism approach in its capacity to illustrate to stakeholders how cities can efficiently manage generated waste and utilize resources and products while adhering to the principles of the urban metabolism approach. New policy tools that are designed to enhance waste reduction and management may be developed and evaluated by urban centers in accordance with the outcomes of this methodology. Cities may benefit from the collaborative development of policy instruments that are consistent with the principles of waste metabolism. This can be achieved through the integration of diverse information, the expression of numerous opinions, the investigation of innovative solutions, and the development of new strategies. As a result, urban management will be approached with a more comprehensive and comprehensive approach.

Furthermore, the co-occurrence analysis of the authors' keywords underscores the research trends in the disciplines of CE, UM, and waste management (Figure 7). Circular urban metabolism (CUM) has been proposed as a synthesis of UM and CE, with an emphasis on the examination of their respective strengths and limitations. Within the CUM concept, circularity is defined as the utilization of renewable energy and the reduction, monitoring, and elimination of pollution through deliberate design. The CE concept has the potential to significantly contribute to the development of sustainable UM [10,35]. In addition, the integration of CE and UM has the potential to provide useful insights for urban decision-making, even though CE is mainly associated with the economic and production aspects. UM, or utilization management, may be used to examine and specify how resources are used within an economic framework that is influenced by changes in human behavior and technological progress. Moreover, the principles of "CE" provide instructions for efficiently altering patterns of resource consumption. Consequently, the local CUM enabled the evaluation and restructuring of resource flow in the urban environment in a cyclical fashion, including the reduction, reuse, and recovery of resources [8,9,36]. From this perspective, CUM provides a superior approach to investigating a cyclical and restorative model for a city.

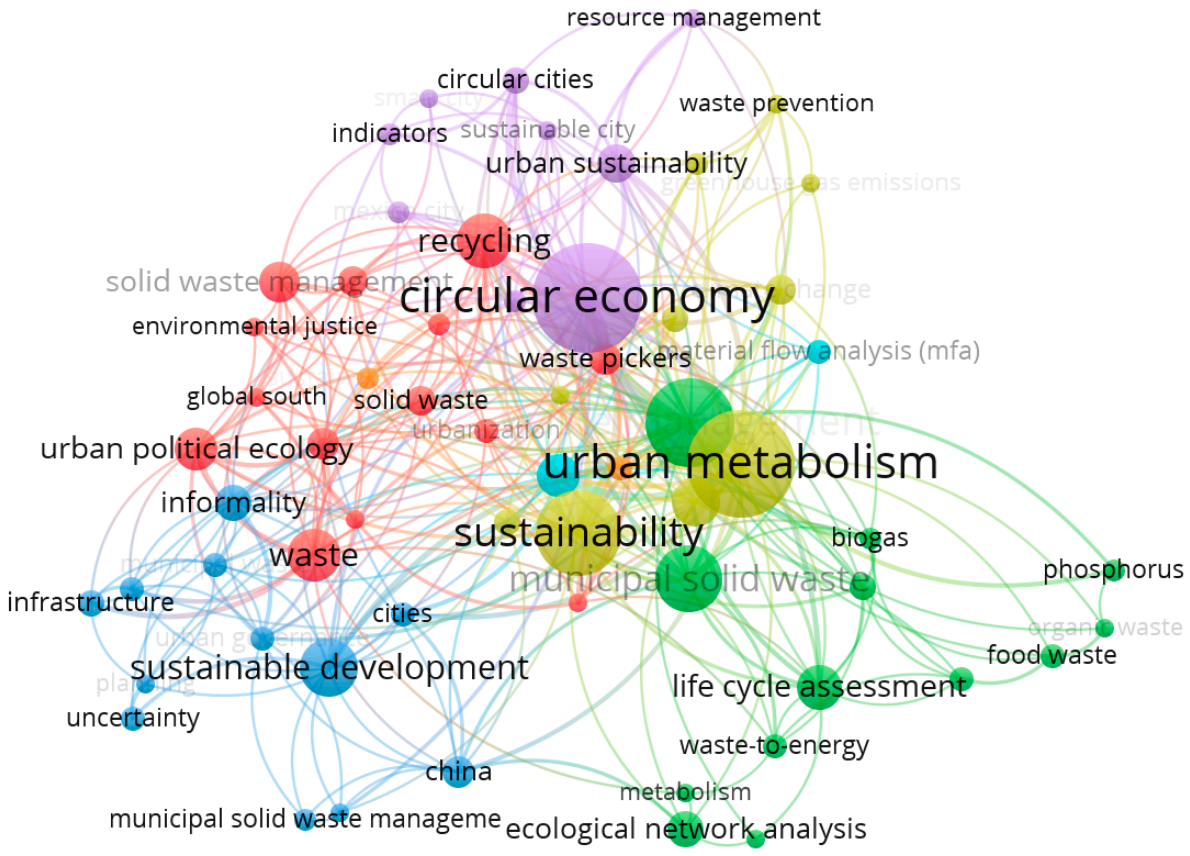

Figure 7. Co-occurrence analysis based on authors' keywords.

The resource use pattern can be enhanced by implementing a comprehensive CUM framework, even though the integration of the circularity concept with MFA has been investigated in the UM. Sustainable cities can be successfully established by optimizing intricate urban systems through significant changes in design, manufacturing, consumption, use, refuse management, and reuse methods. Geographical boundaries had an impact on urban design and planning at the city level, with the objective of offering metropolitan areas a variety of options to modify their production and consumption processes [37,38]. The concept of circularity may be employed to reconstruct urban areas after an examination of the way materials are transported between various regions of a city. The current CUM

framework, which has been recognized as having the potential to improve the ability to resolve resource depletion, is still in its infancy and necessitates further investigation. Consequently, it is imperative to understand and interpret CUM in a manner that offers policymakers at the local level valuable and insightful data [39].

In addition, co-occurrence research has emphasized the relationship between urban political ecology and the concepts of circular economy, urban metabolism, and sustainability. Metropolitan ecology is a specialized branch of ecology that specifically examines the interactions between organisms and their surroundings, with a particular emphasis on metropolitan environments. This habitat would include urbanized regions, including both the ecological aspects and the socio-economic factors of the environment [40]. The effectiveness of urban ecology relies on the implementation of sustainable urban planning. Ecological urban design incorporates green and blue features to rejuvenate nature within the ecosystem while also ensuring technical and infrastructure excellence. The concepts of green urban planning suggest that the city operates as a living thing with complex metabolic processes. To achieve maximum health, it is crucial to develop sustainable behaviors that provide a nutritious environment for the body's cells, often referred to as its occupants. Various concepts with similar connotations, such as new urbanism, green urbanism, bio-urbanism, organic urbanism, biophilic city, smart city, sustainable city, eco-city, and green city, are implemented [41,42].

The development of urban areas that have positive outcomes in terms of social, economic, and environmental aspects is the focus of green urbanism. Bio-urbanism, which is frequently referred to as organic urbanism, advocates for the harmonious integration of urban areas with their natural environments. Biophilic communities are distinguished by their commitment to the preservation, rejuvenation, and conservation of nature, as well as their abundance of natural elements. The environmental impact of eco-cities, which are also referred to as sustainable cities, is meticulously planned to minimize refuse generation, pollution, and the consumption of energy, water, and food. The foundational concepts of sustainable urban development are embodied by these objectives. A smart city is a concept that emphasizes investment in the development of human capital, urban infrastructure, and the efficient management of natural resources. The objective is to improve the quality of life and foster sustainable economic development through community involvement and commitment. Incorporating sustainable practices into urban environments is an effective method for improving the long-term sustainability of cities [42–44]. Green infrastructure is an urban design idea that is based on the ecosystem services given by natural elements. This idea effectively includes the characteristics of all the urban concepts stated before, such as a city that is in balance with nature, rejuvenating the urban environment, reducing the use of resources and energy, and taking advantage of the advantages of natural blue–green elements.

Finally, the co-occurrence analysis demonstrates the integration of informality, which can be beneficial for waste management. The informal sector is a significant contributor to the management of municipal solid refuse in numerous cities in developing countries. The aggregate cost of solid waste management for municipalities is reduced by the informal recovery of recyclables from the solid waste system [45,46]. This procedure results in annual savings of millions of euros. Additionally, municipalities can reduce the utilization of valuable landfill space and accomplish recycling objectives by participating in informal sector waste management activities. Moreover, Figure 7 suggests that the informal sector, which encompasses refuse pickers, salvage collectors, merchants, and recyclers, is indispensable for the management of waste in urban areas in a variety of developing nations. Laborers, as defined by the International Labor Organization (ILO), are individuals or small and micro-enterprises that participate in refuse management activities without being registered or formalized in the informal sector. These personnel are accountable for the provision of refuse management services [47,48]. This sector is frequently overlooked and does not receive government recognition. Nevertheless, the members of this organization are essential for the administration of refuse in urban areas. They are responsible for the collection,

sifting, processing, storage, and trading of refuse materials throughout the recycling value chain. The quantity of recovered materials that are obtained through informal routes in urban areas is significantly greater than that that is obtained through official channels.

Moreover, the informal recycling business in most poor nations is structured in a hierarchical manner, like a pyramid. At the lowest tier of the waste trade hierarchy, there are individuals known as trash pickers who engage in the unpaid collection of garbage from municipal garbage bins, streets, and landfills. The peripatetic scrap buyers collect small quantities of waste from residential residences. Households in several countries also participate in the practice of selling their recyclable waste to itinerant buyers at street cafés. In the waste management sector, many levels of traders exist, including merchants, stockists, and wholesalers, who function as intermediaries between garbage collectors and reprocessors. It is important to mention that a considerable proportion of these dealers are not formally established as businesses. As the pyramid rises, the trade becomes more specialized. As each phase progresses, trash is sorted with greater accuracy, leading to a gain in value as the segregation becomes more precise. The informal valuation sector sells the recovered materials to the industrial value chain. Non-government organizations and humanitarian agencies have helped informal sector workers in many countries establish garbage picker cooperatives. These workers are involved in formal contractual labor for a local organization while also engaging in informal recycling operations, which categorize their job as semi-formal.

5. Discussion

Urban areas are undergoing expansion, marked by the emergence of intricate urban systems, which is followed by a concomitant increase in production, consumption, and waste generation. As our understanding of the complexities of the urban system grows, it becomes clearer that traditional conceptions and procedures are no longer appropriate. Developing new urban frameworks is essential for policymakers and urban planners with the required tools and knowledge to address environmental constraints.

In this context, both the UM and CE approaches exhibit substantial potential. Although both concepts acknowledge the necessity of utilizing circularity to achieve sustainability, each approach is insufficient when considered in isolation [5,34]. Circular metabolism must be integrated into a supportive economic framework that encourages new business models, technological innovation, logistical enhancements, and behavioral changes in order to achieve sustainability in metropolitan settings. Consequently, both UM and CE may benefit from their collaboration. Both concepts can be implemented simultaneously and will provide mutually beneficial improvements. For instance, UM facilitates the mapping and measurement of energy and resource flows in urban environments. Once stakeholders have a comprehensive understanding of this concept, they will possess the requisite information to enhance the efficiency of their supply chains, minimize waste, and implement the circular economy framework's principles [49,50].

Nevertheless, the present research has demonstrated that the integration of the two methods CE and UM can facilitate the creation of a new urban framework that simplifies complexities and achieves the desired result of sustainable cities. The implementation of CE principles can contribute to the achievement of sustainable development when contextualized within the UM context, as many authors have emphasized. The CUM framework aims to establish a seamless integration between the CE and the UM concept of the urban ecosystem. This innovative approach to thinking can enable a reevaluation and re-design of spaces to be more environmentally sustainable by understanding the ways in which urban fluxes interact with them over time [42,51]. By redesigning social and urban infrastructures, employing measures to reduce, reuse, and recover resources, and establishing connections between flows (nexuses) to encourage a reevaluation of urban activities, the CE model can be implemented on a citywide scale. In particular, CE activities may be developed with the intention of functioning as tangible measures toward the goal of a more sustainable UM.

Additionally, the CUM framework was established by incorporating the CE concept into the context of UM. The CUM framework can aid policymakers and planners in reevaluating urban activities, such as food production and transportation, by considering the urban–rural space and time [42]. The approach may assess the practicality of implementing circular economy (CE) concepts, such as reducing, reusing, and recovering resources, by analyzing the geographical and temporal connections between material, energy, economic, and social flows. This graph specifically depicts the concepts of reduction, reuse, and recovery in the context of circular economy (CE). It aims to provide clarity on these principles while acknowledging that other components of the nine Rs, such as refurbishing and remanufacturing, are also deemed important. The ideas of CE, such as redesign and reconsideration, are clearly present in areas outside of metropolitan environments, hence strengthening the ties between rural and urban areas. Refuse and pollution may be effectively incorporated as secondary raw materials into the circular system under the CUM paradigm [51].

However, the CUM framework is still in its early stages and requires more investigation. The area lacks a cohesive and widely accepted scientific discipline and remains a fragmented amalgamation of concepts drawn from other fields, including the previously existing notion of CE. As a framework for the creation of resilient and sustainable cities, CUM will face several difficulties that are now representative of CE and UM [52,53]. The fundamental emphasis of future study should be on the dimension of space, including its capability as flow boundaries and places. Establishing clear borders is essential for enclosing and separating the urban structure. Furthermore, spatial planning accurately reflects reality by acknowledging that the urban system is intricately related to other systems and cannot be really regarded as separate. Considering the urban system in isolation is a simplification that, while necessary, may be misleading. To make informed urban choices, it is crucial to understand not just the quantity or mass of resource flows but also their geographical distribution, transportation routes, and relationships.

The temporal aspect is the secondary issue, intricately linked to the concept of space. Accurate information about the precise location of resource flows is essential for planners and policymakers. Planners and policymakers require current information, not data gathered years later, and they must have a deep understanding of how flows change and interact over time. Future scenarios and real-time data will be essential. Prioritizing these underexplored subjects and fields of study is crucial. This statement applies not only to policymakers and planners but also to scholars in various fields such as industrial ecology, natural capitalism, material-flow accounting, cleaner production, eco-efficiency, cradle-to-cradle design, biomimicry, social–ecological system resilience, the performance economy, and industrial ecosystems. By integrating these distinct disciplines into a more comprehensive research framework, there is the possibility of enhancing their combined application.

6. Conclusions

The primary consumers of global resources and the predominant producers of waste are urban regions. Over 55% of the global population resides in cities, which occupy approximately 3% of the Earth's terrestrial surface. By the year 2050, we expect that this percentage will increase to 70%. They are responsible for the generation of 50–80% of global greenhouse gas emissions, consume 75% of the world's resources, and account for half of all global detritus [51]. The unsustainable utilization of resources is a substantial issue in modern society. The Sustainable Development Goals (SDGs) emphasize the significance of this issue by striving to guarantee that human settlements and cities are sustainable, resilient, secure, and inclusive. It is imperative to take immediate action to ensure sustainable urbanization and prevent the overexploitation and degradation of natural resources [15,51].

In recent years, many measures have been enacted to address these issues. Two principal ideas that have gained prominence are the circular economy (CE) and urban circular metabolism (UCM). These policies are linked to resource efficiency, pollution mitigation, and zero land use. We forecast both models predict a paradigm change from an

unsustainable, wasteful linear approach to a more circular, closed-loop one. This research underscores the recent rise of the notion of urban circular metabolism. This notion is based on a worldview that perceives cities as living beings, necessitating resources for their functions (inputs) and disposing of trash throughout the transformation process. UCM is defined as "the total sum of the technical and socio-economic processes that occur in cities, resulting in growth, energy production, and waste elimination", as articulated by Christopher Kennedy. It is essential to acknowledge that the UM idea encompasses the flows of energy, individuals, information, and both natural and industrial materials, while CE fails to include people and information. Moreover, the urban management (UM) concept includes the dynamics that permeate the urban landscape [8,35].

This study indicates that CUM is now under development and requires more examination. The area is characterized by the absence of a cohesive and well-recognized scientific discipline, including a disjointed amalgamation of concepts from other fields, particularly CE. CUM will address CE- and UM-related concerns as a framework for resilient and sustainable urban environments. Future studies should prioritize the dynamics of spatial boundaries and places. Definitive borders are crucial for urban enclosure and segregation. Spatial planning recognizes the interdependence of the urban system and its autonomy. Although essential, concentrating just on the urban system may be misleading. To make informed urban choices, it is essential to understand the quantity, mass, geographical distribution, transit routes, and interrelations of resource flows [8].

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