Rahul Bhadouria ·
Sachchidanand Tripathi · Pardeep Singh ·
P. K. Joshi · Rishikesh Singh *Editors*

Urban Metabolism and Climate Change

Perspective for Sustainable Cities

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Foreword

Since cities are the first and foremost living spaces for people, enabling healthy living conditions is the top priority for the organization of cities. This means assuming very different living conditions for large parts of the urban population worldwide and improving them through planning and targeted measures. Urban elites around the world have mostly taken care of their needs optimally by spatially organizing their urban living conditions, without worrying about the rest of the urban population. This is not different, e.g., in America than in Africa.

Cities are striving for sustainable development using strategies and models that are often referred to as eco-city or smart city. Achieving these goals is only possible in different ways for different cities depending on their current situation, the actual challenges, and their development efficiently. This is all happening under the already actual stress test of climate change, which cities are facing first and foremost. The urban metabolism is challenged by this in a special way.

Cities are centers of cultural, social, and economic progress. Today, they generate about 90% of the global BIP. An ecologically oriented urban development currently faces three challenges:

1. Securing and promoting the quality of the environment and life for the growing urban population.
2. Reducing the consumption of limited natural resources (resource efficiency).
3. Promoting the ability to adapt to global climate change, but also to other change processes.

Environmental problems such as the supply of clean drinking water or the supply of food are certainly urgent in cities in the group of rapidly growing cities in countries with little capacity to act. In the cities that are hardly growing anymore and in states that can take action to compensate, such problems have been solved or at least significantly reduced, while questions of quality of life and healthy lifestyles are becoming increasingly important. Reducing stress and promoting physical activity in attractive open spaces and the experience of nature in cities are becoming important goals of urban development. In many cities, a major reduction in the need for natural resources and greenhouse gas emissions is an additional goal.

Urban nature in the form of green and blue infrastructure is, like technical infrastructure, infrastructure for the functioning of a livable city. This is being recognized more and more, and the appreciation for urban nature is growing with it. International projects for the development or restoration of different types of urban nature can be found everywhere.

Their driving questions are:

1. How can ecosystem services be determined and quantified more precisely and locally?
2. How can (new) urban nature bring benefits in urban areas with environmental and social problems?
3. How to determine optimally performing quality, quantity, and form for urban nature endowments in different urban structures?
4. How can the direct and indirect effects of the expected global climate change on concrete urban nature connections be determined with regard to urban quality of life?
5. How resistant is designed for urban nature (especially the tree population) to the effects of global climate change and how can this resilience be improved?
6. How can the supply (quantity and quality of ecosystem services) and the management of urban waters be improved by linking them to urban nature?

The expected global climate changes can already be felt in cities, which are "real laboratories" of climate change. On average, cities have a warmer and drier climate than the surrounding area. They are affected by more extreme climate events. Summer temperature extremes are the most stressful part of the urban climate for city dwellers. These will continue to take place in the future. Here, climate moderation to lower the temperature is a desirable goal to avert health hazards from particularly sensitive, vulnerable sections of the population. Cities can take medium- to long-term structural measures to avoid or reduce overheating effects and use urban nature to moderate or optimize the existing urban nature for this purpose.

Within the framework of urban development, technology is usually used to solve problems and reduce risks. Technology as a problem solver is familiar, predictable, well-established, and recognized outside the community of technicians. This is often the reason for preferring technical solutions over environmental engineering solutions. Environmental engineering, which integrates the debate about ecosystem services, has long offered the option of working with nature to solve problems. Solutions are offered outside of the technical domain or fostering the use of nature besides the use of technology. Financial considerations and a broader perspective of urban planners are indispensable/should be considered to make the use of "Nature-Based Solutions" (NbS) possible in cities using natural processes to support problem solutions.

The ideal as a concept on the way to the Green City needs to be adapted to every context. Green Cities should be the result of a transformation process in small steps of existent cities. This conversion process with many different requirements takes place in all areas. It depends on whether and what role urban nature can play.

Only a few societies are currently able to build new "eco-cities", above all China. The eco-city as a Green City can also be rebuilt. However, this remains the exception. In addition, even if several hundred cities worldwide, especially in China, already have this title, the actual realization of their ecological quality often remains incomplete.

The present book *Urban Metabolism and Climate Change—Perspective for Sustainable Cities* takes up exactly this current topic. It is becoming clear that precise analyses with large amounts of data are required for smart and ecological development targets of cities. A separate book section is devoted to this. Urban planning as a means of urban politics still appears to be the most suitable means of design, even if the efficiency of planning varies from region to region. Selected examples, representative of cities with traditional and efficient planning and those with less effective planning, are presented as examples.

It can be expected that this book will make a significant contribution to a better understanding of urban metabolism under the challenges of climate change. It is warmly recommended for reading by professionals and students.

Jürgen Breuste
SURE (Society for Urban Ecology)
President
Salzburg, Austria

Preface

Urbanization is accelerating flow of people, goods, and information across the world. This has a significant impact on flow of energy and materials in and around the cities. In the era of environmental degradation, resource scarcity, environmental pollution, and population growth, the sustainability of a city is of utmost interest and importance. With much wider interests and needs of Sustainable Development Goals, research in urban ecosystem sustainability has taken the central stage. An efficient analysis technique for studying urban ecosystems is urban metabolism (UM). Here, metabolism refers to physiological mechanisms that enable living things to continuously exchange matter and energy with their surroundings in order to function, grow, and reproduce. An urban settlement or a city can be defined as a "superorganism" that has distinct structure and function, with coexistence of biotic and abiotic elements, their interactions, and interrelations processes between society and the natural environment. Hence, UM is a useful concept for assessing and understanding the movements of material and energy within an urban ecosystem and might be discharging to other systems. This would provide a comprehensive insight to understand the prospective sustainable framework, the severity of problems within the same from local to global level, and making policies toward their sustainability.

With half of the world's population living in cities, knowing how cities run and keeping them healthy is crucial to their long-term sustainability. We have witnessed an increase in UM research in the recent years. Contemporary UM research is strongly influenced by biophysical sciences, system theory and thermodynamics, and political economy, while human activities are acknowledged to be essential component of UM analysis. In order to adapt UM to address future concerns, we need a deeper understanding of the connections between mass and energy flows (production and consumption) that form and sustain one another in society. It is crucial to comprehend the temporal and spatial characteristics of services flow and their linkages with material and energy flows in an urban ecosystem. A holistic approach addresses the need for urban sustainability transitions to urban metabolism. Further, cities are responsible for over 70% of global greenhouse gas (GHG) emissions. In a few decades, cities will house the great majority of world's inhabitants. Thus, cities can play a critical role in reducing CO_2 emissions and combating climate change, which is one of the most pressing issues confronting our modern way of life. Cities and urban systems are intricate, self-replicating organisms that require a range of material and energy inputs from outside their boundaries in order to sustain their own metabolism. In the recent years, there has been a growing interest in cities and their energy and material usage, fueled in part by concerns about climate change and in part by social issues resulting from massive migratory movements from rural to urban areas. Patterns of urban growth have an impact on material and energy fluxes within urban settlements, as well as exchanges with the surrounding environment.

Urban metabolism was previously thought of as a practical strategy required for the desired transition to sustainable urban development. But more recently, the growth of information and communication technology and, specifically the development of smart cities, has raised the idea of smart urban metabolism (SUM). SUM is regarded as a technology-driven evolution of the urban metabolism framework with the potential to get beyond some of its current drawbacks. The modeling framework has the potential to be utilized as a planning tool. Land use, transportation, soil-vegetation-atmosphere transfer, and meteorological models are all used to represent urban metabolism. Understanding self-sufficiency, efficiency, and resilience has been made possible by studies of resource stocks and flow exchanges in cities. These studies also offer a perspective for the study of urban systems. It is also possible to think of UM as a branch of an integrated earth system modeling approach with a spatial focus.

The use of a standardized interdisciplinary urban metabolism approach can be used to link the high-level policies of the new urban agenda, the SDGs, and the Paris Agreement across government scales (local, regional, national, and international). Linking urban metabolism to policy could be the missing piece in measuring and changing urban sustainability performance, but it will require development of a multidisciplinary urban metabolism practice. The present book encompasses various aspects of urban metabolism along with modeling and urban metabolism indicators in changing climate scenarios. The book contains a total of 17 chapters:

Chapter 1, by Rahul Bhadouria et al. from India, provides a brief introduction of the topics discussed in this book. Taking a lead from the systematic review from 1990 to 2023, the chapter provides research trend analysis on urban metabolism at the backdrop of changing climate. It discusses the sustainability in urban metabolism, sustainable urban planning, ecosystem services, and disaster resilience so as to provide an interdisciplinary understanding of urban metabolism. The chapter identifies an urgent need to develop new methodological approaches for real time and reliable evaluation of urban metabolism.

Chapter 2, by Riya Raina et al. from India, explores urban metabolism and sustainability and their interlinkages, which is a useful approach for the smart city development. The chapter comments upon the origin and evolution of urban metabolism, its relationship with sustainability of cities, and limitations of urban metabolism concerning urban sustainability.

Chapter 3, by Ariyaningsih et al. from Japan, Taiwan, and Indonesia, discusses the integration of resilience and urban metabolism framework while presenting some case studies that illustrate how such integration can be put into practice and its implications. The chapter emphasizes that the development of theoretical and practical approaches to urban metabolism requires interdisciplinary collaboration.

Chapter 4, by N. S. Nalini and Neesha Dutt from India, presents a case study of urban metabolism in an Indian city—Bengaluru. The chapters suggest that apart from economic processes, urban metabolisms include social, spatial, and environmental processes which should be considered together while developing blueprints for urban expansion.

Chapter 5, by Shivangi Singh Parmar et al. from India, focuses on the understanding of urban metabolism in the context of peri-urban development or urban sprawl with multiple case studies to develop recommendations for the sustainable development of an urban ecosystem.

Ayesha Agha Shah et al. from Bahrain, Italy, the United Arab Emirates, Sweden, and Saudi Arabia in Chap. 6 highlighted ecological aspect of a built environment concerning the sustainable supply of materials and energy required for a desired urban metabolism. The research also deals with a case for conservation and adaptive reuse to be employed as an important indicator for urban metabolism through the maintenance and management of historical urban built environments.

Chapter 7, by Mangalasseril Mohammad Anees and Bhartendu Pandey from the USA, presents a systematic understanding of how urban metabolism aligns with ecosystem concepts and how social dimensions, and associated multi-dimensional and multi-scalar inequalities, add novel characteristics, tradeoffs, and synergies. They provided an analytical framework that gives an outlook for sustainability goals relevant to urban areas including developing ecologically informed solutions and improving resource efficiency in urban areas.

In Chap. 8, Mushtaq Ahmad Dar et al. from India investigate the academic scope of urban metabolism, which includes its relationship with city sustainability and urban planning. They suggest for appropriate urban planning, particularly in developing economies, based on the principles of urban metabolism that can be a sustainable approach for reducing the carbon footprints of cities and mitigating climate change in the coming decades.

Chapter 9, on urban metabolism in the circular bio-economy of tomorrow by G. Venkatesh from Sweden, recommends that the social and economic dimensions of sustainability and thereby the related SDGs must not be overly compromised.

Chapter 10, by Bill Butterworth from the UK, provides a detailed overview of urban wastes and global warming. The chapter highlights the possibilities of reducing irrigation needs and reclaiming deserts along with waste management in urban settlements for financial sustainability.

Chapter 11, on "Transitioning Urban Agriculture to a Circular Metabolism at a Neighbourhood Level" authored by Sharmila Jagadisan and Joy Sen, explores integrated agriculture concepts. This chapter tries to provide an explanation on design and architectural changes that might enhance metabolic functions and restore urban sustainability through urban gardening.

Chapter 12, by G. Venkatesh from Sweden, proposes waste management (urban and otherwise) as both enablers and enabled in the context of SDGs. Readers will learn about the various facets of sustainable development and how effective waste management can create value in a circular economy or bio-economy.

Chapter 13 on emerging approaches for sustainable urban metabolism by G. Gupta et al. provides a detailed view of novel technologies for sustainable urban metabolism.

Chapter 14 by Ombir Singh emphasizes the selection of suitable plant species for plantation in urban areas. This chapter focuses on the species selection in urban forestry—toward urban metabolism.

Chapter 15, by Sunil Bhaskaran et al. from the USA, provides a detailed geospatial analysis for urban metabolism and climate change. It emphasizes that city planners and decision-makers can create new sustainable city design tactics to lessen the negative effects of GHGs and maintain urban metabolism.

Chapter 16 by Ruchira Ghosh and Dipankar Sengupta from the UK examines the application of big data and machine learning as an efficient technique to channelize and manage heterogeneous multi-dimensional datasets, adoption of practices, constructing self-learning machine learning models, and gaining fresh insights via predictive analytics in "smart urban metabolism".

Chapter 17 by Gladys Nkrumah et al. from Ghana provided a detailed overview of policies in Ghana that are related to urban metabolism.

Thus, the book provides a comprehensive understating of the contemporary practical and theoretical concepts along with the emerging issues of urban metabolism which will help readers to get a better insight and problem-solving approach. It highlights some of the major challenges faced by cities in terms of livelihood, agriculture, and other anthropogenic activities. This book will be equally beneficial for undergraduate, postgraduate, research scholars, teachers, environmental scientists, ecologists, agriculturists, urban policymakers, and early career researchers, especially those working in the areas of urban ecology and urban metabolism, non-governmental organizations (NGOs), and government institutions working on sustainable city, urban planning, and urban policymaking.

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Part I
Urban Metabolism and Climate Change: An Introduction

Chapter 1
Urban Metabolism and Global Climate Change: An Overview

Rahul Bhadouria, Sachchidanand Tripathi, Pardeep Singh, P. K. Joshi, and Rishikesh Singh

Abstract Urban centres are increasingly challenged by population increase and the resultant environmental concerns including the urban sprawl and climate change. Moreover, different patterns of urbanization contribute to the changing climate via differences in their urban metabolism represented by energy and matter. Urban metabolic studies in terms of energy and material inflows, outflows, and stocks can be associated with traditional evaluation techniques to help assess the magnitude and potential effects of variety of environmental challenges the world is facing today. Further, urban centres are critical real-time observatories that indicate the impact of anthropogenic activities on global biogeochemical cycles. For example, urban processes have significant and lasting impacts on the global carbon budget. It has also been observed that the technology and infrastructure advancements have fuelled increase in urban inputs and outputs of material and energy. Therefore, more sustainable approaches need to be adopted in changing scenarios for urban planning, particularly for sustainable resource utilization and better waste management practices. Taking a lead from the systematic review from 1990 to 2023, the chapter provides research trend analysis on urban metabolism in the backdrop of changing climate. It discusses the sustainability in urban metabolism, sustainable urban planning, ecosystem services, and disaster resilience so as to provide an interdisciplinary understanding of urban metabolism. The chapter identifies an urgent need to develop new methodological approaches for real-time and reliable evaluation of urban metabolism.

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Keywords Circular bio-economy · Climate change · Energy flow · Material flow · Sustainable development · Urban metabolism · Urbanization

1.1 Introduction

The term "urban metabolism" refers to "exchange processes that produce urban environment" (Kennedy et al. 2011). Urban metabolism indicates the processes by which cities convert raw material, energy, and freshwater into "built environment", "human biomass", and "waste" (Conke and Ferreira 2015). Cities are increasingly challenged by climate and other environmental concerns pertaining to ongoing rapid urbanization and population increase. Urban metabolic studies in terms of energy and material inflows, outflows, and stocks can be associated with traditional evaluation techniques to help assess the magnitude and potential effects of these environmental challenges. Further, urban settlements are critical real-time observatories that indicate the impact of anthropogenic activities on global biogeochemical cycles (Seto et al. 2012). Urban processes have significant and lasting impacts on the global carbon budget. It has been reported that cities contribute to approximately 70% of global greenhouse gas (GHG) emissions (Hendriksen et al. 2011). Hence, the estimation of the total C consumed and sequestered in a city metabolism may indicate its role in stabilizing the ongoing global climate change (Chen et al. 2020). It is anticipated that by 2050, up to 66% of global population would live in urban areas (United Nations 2015). Extensive urbanization with a rapidly increasing human population may lead to a change in the urban environment especially land use patterns, energy budget, overexploitation and depletion of natural resources, degradation of water, air and soil quality, and waste generation including wastewater and GHGs, causing more imbalances in the urban environment (Conke and Ferreira 2015). Therefore, more sustainable approaches are needed to be adopted in changing scenarios for the urban planning, particularly in developing smart cities with sustainable resource utilization and better waste management practices.

It has also been observed that technology and infrastructure advancements have fuelled increase in urban inputs and outputs of material and energy (Kennedy et al. 2007, 2014). Pressure is being placed on the land, housing stock, infrastructure, and environment of the cities due to exceptional urban growth and housing needs (Tainter 2000; Ford et al. 2019; Clark et al. 2022). Under such a scenario, sustainable urban development is a crucial challenge in a world of cities and may be the most important present and future environmental concerns (Kacyira 2012). It is therefore critical to know how urban metabolic systems work towards meeting the sustainability measures of a city (Kacyira 2012; Conke and Ferreira 2015).

This chapter provides a brief insight on different aspects of urban metabolism and sustainable cities against the backdrop of changing climate. The beginning of the chapter outlines different analytical approaches for the metabolism of cities, which is followed by climate change and sustainability, sustainable urban planning, ecosystem services of urban systems and their interlinkages with the urban metabolism, circular economy and its potential role in urban metabolism, digitalization approaches for smart urban metabolism, policies governing urban metabolism, and interdisciplinary understanding of urban metabolism. An up-to-date literature survey was performed using bibliometric analysis tools for the keywords "urban metabolism and climate change". This chapter is a concise account of the information related to different dimensions of urban metabolism and sustainable cities which are described and elaborated later in different chapters of the book.

1.2 Changing Climate and Urban Metabolism: Research Trend Analysis

A literature survey was performed on the first week of February 2023 using a set of keywords, viz. ("urban metabolism" and "climate change") in the "Web of Science Core Collection" database. The search query provided a total of 95 published documents between 1990 and 2023. Out of total 95 documents, 83 articles, 11 review articles, 3 proceeding papers, and 1 book chapter were published in 49 sources. The documents were contributed by 355 authors, with 356 keywords, and received 34.15 average citations per document. Though the literature search was performed from 1990 onwards, only one document was found in 1997 and then continuous publication on the topic was observed from 2010 (2) onwards, and in 2023, already two documents have been published. A maximum of 18 documents have been published in a single year in 2020. The annual production rate observed was 2.7% (Fig. 1.1). For clearly visualizing the research trend on this topic, bibliometric analysis was performed with the R program (ver. R 4.2.1, R Core Team 2022) using *bibliometrix* package (Aria and Cuccurullo 2017) based on the keywords plus database of "Web of Science Core Collection" (Singh et al. 2023). On the basis of the bibliometric analysis, a list of the top 10 countries, 10 leading affiliations, 10 most relevant sources/journals, and 20 leading authors publishing and/or carrying out research on the topic "urban metabolism and climate change" is given in Tables 1.1 and 1.2. Among leading countries (Table 1.1), 50 documents are published from China, followed by USA (29), Australia (26), the Netherlands (19), and UK (19). Among leading institutions/affiliations, the maximum number of documents (8) has been originated from the University of Queensland, 6 from Beijing Normal University, and 4 each from the University of Denmark, the University of Lisbon, and the University of Natural Resources and Life Sciences Vienna (Table 1.1). Elliot T. (4), Kenway S. J. (4), Zhang Y. (4), Kennedy C. (3), and Rugani B. (3) were identified as leading researchers publishing research on urban metabolism and climate change (Table 1.2). Results for country-wise, affiliation-wise, and author-wise analyses showed the predominance of China and European countries in urban metabolism research in the light of changing climate. Among different sources/journals publishing and promoting research on the topic "urban metabolism and climate change", Journal of

Cleaner Production (9), Resources Conservation and Recycling (8), Journal of Industrial Ecology (7), Science of the Total Environment (5), and Landscape and Urban Planning (4) were the leading ones (Table 1.2). The results further showed a considerably higher proportion of journals published by Elsevier with the core theme of sustainable development, and resource management was mainly publishing research articles on the book's theme.

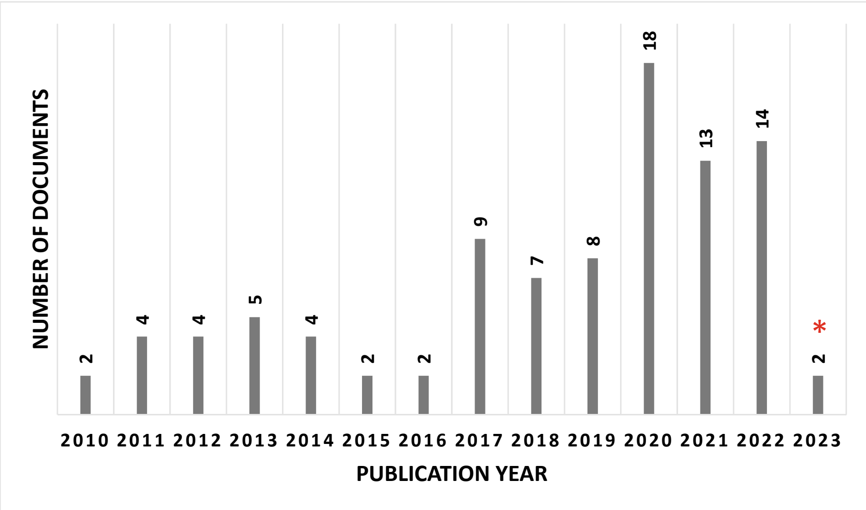

Fig. 1.1 Year-wise publication scenario on the topic "urban metabolism and climate change". *Source* Web of Science Core Collection 2023. *Represents incomplete dataset for the year 2023

Table 1.1 List of top 20 counties and affiliations/universities/institutions supporting/publishing research on the topic "urban metabolism and climate change"

Country/affiliation	No. of articles	Country/affiliation	No. of articles
Top 20 countries			
China	50	Norway	10
The USA	29	Denmark	6
Australia	26	France	6
Netherlands	19	Portugal	6
The UK	19	Sweden	5
Canada	15	Japan	4
Italy	15	Singapore	4
Spain	13	India	3
Austria	11	Luxembourg	3

(continued)

Table 1.1 (continued)

Country/affiliation	No. of articles	Country/affiliation	No. of articles
Germany	11	Peru	3
Top 20 affiliations/universities/institutions			
The University of Queensland, Australia	8	Norwegian University of Life Sciences: NMBU	3
Beijing Normal University, China	6	NTNU: Norwegian University of Science and Technology	3
Technical University of Denmark, Denmark	4	Qingdao University of Science and Technology, China	3
University of Lisbon, Portugal	4	Singapore University of Technology and Design	3
University of Natural Resources and Life Sciences, Vienna, Austria	4	Autonomous University of Barcelona, Spain	3
Griffith University, Australia	3	The University of British Columbia, Canada	3
Humboldt University of Berlin, Germany	3	University of California, Los Angeles, the USA	3
Monash University, Australia	3	University of Toronto, Canada	3
The University of Newcastle, Australia	3	Wageningen University and Research—WUR, the Netherlands	3
North China Electric Power University, China	3	Chalmers University of Technology, Sweden	2

Source Web of Science Core Collection 2023

Table 1.2 List of top 20 authors and sources/journals publishing research on the topic "urban metabolism and climate change"

Authors	No. of articles	Country/affiliation	No. of articles
Top 20 authors			
Elliot T.	4	Dalla Fontana M.	2
Kenway S. J.	4	Facchini A.	2
Zhang Y.	4	Feng K. S.	2
Kennedy C.	3	Goldstein B.	2
Rugani B.	3	Hayat T.	2
Almenar J. B.	2	Holtslag A. A. M.	2
Alsaedi A.	2	Islam K. M. N.	2

(continued)

Table 1.2 (continued)

Authors	No. of articles	Country/affiliation	No. of articles
Brattebo H.	2	Jiang D. L.	2
Chen B.	2	Krausmann F.	2
Choy D. L.	2	Li Y. M.	2
Top 20 sources/journals			
Journal of Cleaner Production	9	Applied Energy	2
Resources Conservation and Recycling	8	Bioresource Technology	2
Journal of Industrial Ecology	7	Cities	2
Science of the Total Environment	5	Renewable and Sustainable Energy Reviews	2
Landscape and Urban Planning	4	Water Research	2
Sustainability	4	Water Science and Technology	2
Sustainable Cities and Society	4	Annual Review of Environment and Resources, Vol 39	1
Ecological Modelling	3	Anthropocene	1
Energy Policy	3	Applied Ecology and Environmental Research	1
Journal of Water and Climate Change	3	Applied Geography	1

Source Web of Science Core Collection 2023

For clear visualization of research themes and patterns on the topic "urban metabolism and climate change" in the last few years, a word cloud diagram, keyword co-occurrence network analysis, and thematic evolution map were formulated with the help of "*bibliometrix*" package in the R program. A detailed description of the above-mentioned features is given in Verma et al. (2021) and Singh et al. (2022). Among the most frequent keywords excluding climate change (25) and urban metabolism (24), the results presented in Fig. 1.2 revealed energy (19), cities (18), sustainability (14), consumption (13), GHG emissions (10), systems (9), water (9), China (8), and metabolism (8) as the top 10 keywords having a higher frequency of occurrence in the literature. Keyword co-occurrence network analysis (Fig. 1.3) results revealed the formation of two separate but interlinked clusters identified as urban metabolism clusters (red) associated with the city, consumption, GHG emissions, system, material flow analysis, life cycle assessment, footprint, CO_2 emissions, model, etc. as one cluster whereas climate change (blue) cluster as the second one which was mainly comprised of cities, sustainability, energy, water, management, systems, metabolism, governance, ecosystem services, mass balance, flow analysis,

Fig. 1.2 Word cloud diagram based on the keyword plus database on the topic "urban metabolism and climate change". Size of the word depicts the frequency of occurrence in the literature. *Source* Web of Science Core Collection 2023

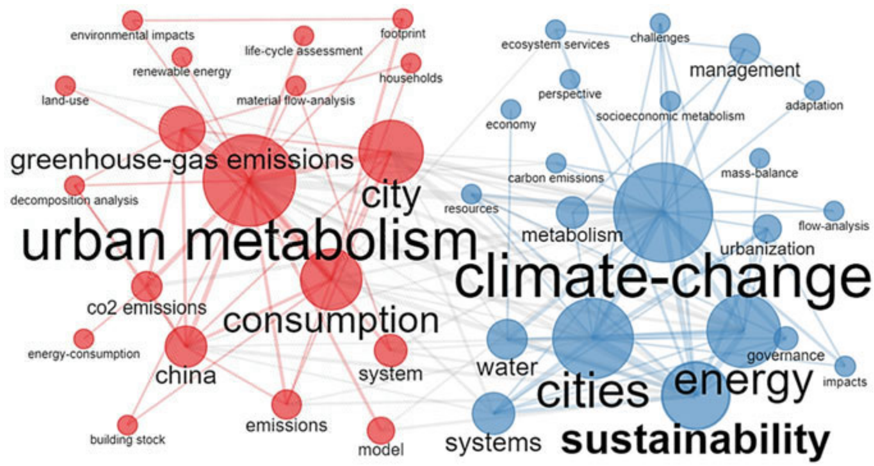

Fig. 1.3 Keywords co-occurrence network plot based on the keyword plus database on the topic "urban metabolism and climate change". Size of bubble represent the frequency of occurrence in the literature. *Source* Web of Science Core Collection 2023

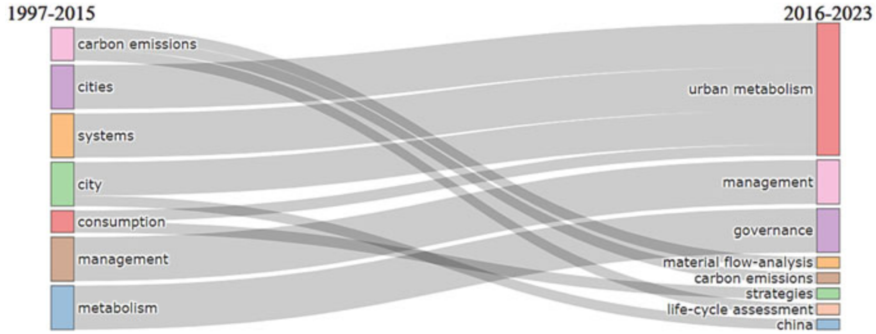

Fig. 1.4 Thematic evolution map based on the keyword plus database on the topic "urban metabolism and climate change". *Source* Web of Science Core Collection 2023

etc. The first red cluster revealed the role of within city performance, whereas the blue cluster provides a broad understanding of the impacts and measures for mitigating climate change through proper resource utilization, management, and governance approaches. Further, the thematic evolution map for the topic "urban metabolism and climate change" for two different time periods, i.e. 1997 to 2015 and 2016 to 2023 revealed two different approaches where the first one is linked with basic approaches for identification and management, whereas the second one is showing more implicative approaches for climate change mitigation. The convergence of different themes of 1997–2015 such as cities, systems, and consumption to a holistic theme of urban metabolism; metabolism to governance; and consumption to strategies themes of the 2016–2023 time period (Fig. 1.4) is observed. Moreover, the emergence of different new themes cum analytical approaches for understanding urban metabolism, i.e. material flow analysis and life cycle analysis is observed for 2016–2023 period where the convergence of carbon emissions is observed for 1997–2015 period. The management theme showed consistency throughout the study period. China emerged in majority of the research during the 2016–2023 period which further revealed the role of the Chinese government in developing research facilities and approaches for urban metabolism and climate change mitigation. Overall, the results of the bibliometric analysis revealed the trend of ongoing research on the themes of the book. Moreover, these observations are further detailed in the following sections and other chapters of the book.

1.3 Metabolism in Cities: Analytical Approaches

Analysing Urban Metabolism

The studies in urban metabolism help in quantifying material and energy flow in the urban ecosystem, thereby contributing to the planning of a sustainable city in future (Kennedy et al. 2007). Also, it indicates that how the sustainability of a city is assessed and reflected by its design and planning (Li and Kwan 2018). The conceptual frameworks adopted to describe physical and social processes in urban centres employ urban climate, governance, and human health-related information in studies and modelling. The urban metabolism analysis is conventionally based on two major approaches—material and energy flow.

1.3.1 Material Flow-Based Approaches

There are three types of material-based analysis: “material flow analysis (MFA)”, “life cycle assessment (LCA)”, and “ecological footprint assessment (EFA)”. The basic principle behind all three methods is that “matter can neither be created nor destroyed but merely transformed”. Hence, the input of material and resources in an urban ecosystem should be equal to the output in the form of waste generated, emissions of gases, and produces (Kennedy et al. 2007; Li and Kwan 2018).

Material flow analysis (MFA) has a wider application in urban metabolism studies (Zhang 2013; Thomson and Newman 2018; Bahers et al. 2019). According to Kennedy et al. (2007), the MFA includes three major components: defining the system, quantifying material stock and flow, and analysing the result generated. Therefore, MFA provides a quantitative assessment method for limited urban resources needed to maintain a sustainable urban metabolism. In other words, MFA provides a tool to analyse the flux of resources and their transformation in an urban centre (Thomson and Newman 2018).

The LCA gives a detailed account of a production process, and evaluation of supply chain impacts of resource conversion and its applicability (Chau et al. 2015). According to Chau et al. (2015), various stages of LCA are *goal and scope definition, inventory analysis, impact assessment, interpretation, and applications*. All the stages are interlinked and impact each other. Furthermore, the environmental impact of urban metabolism and urban products can be assessed by applying LCA (Solli et al. 2009; Heijungs et al. 2010). LCA can be applied in two ways, first the process-based LCA which involves input and output processes, sub-processes involved via the supply chain, and assessment of principal components included in the whole process (Li and Kwan 2018). However, the economic input–output LCA (EIO-LCA) emphasizes more on “*calculating, evaluating and predicting the urban inputs and outputs associated with the economic activities in various sectors of the economy*” (Li and Kwan 2018). Often, both the methods are applied in combination to conduct any urban metabolism study, which further helps in the comprehensiveness of the data required for urban modelling of the economic supply chain.

Ecological footprint assessment (EFA) assesses the extent of the land cover of a country, or a city needs to attain its input and output metabolic requirements. According to the urban ecological footprint, there is always a requirement of an optimum land area of biologically productive land to meet the demand for natural resources for urban consumption and the removal of waste generated therein.

According to Kennedy et al. (2007), the actual area required to sustain an urban settlement is twice in magnitude than the relevant urban area, particularly in terms of the consumption of natural resources and to manage the waste generated. Moore et al. (2013) in their study integrated EFA with urban metabolism to assess the actual land required to manage the input and output fluxes of an urban system. The study also compared metabolic load of a city and its overall biophysical carrying capacity, thereby trying to comprehend the sustainability of urban metabolism through EFA.

1.3.2 Energy Flow-Based Approaches

Emergy indices have been designed to evaluate urban metabolism of cities across the globe; however, their measurement depends upon the status of the ecosystem processes and its health and availability of solar energy (Huang and Chen 2009; Carréon and Worrell 2018; Li and Kwan 2018). The ability of nature and humans in providing resources and services is measured in terms of solar in joules. Emergy indices can be commonly utilized to measure socio-economic and environmental values of an urban system and therefore "*seeks to provide a common value basis to study the material and energy flows in urban metabolism*" (Li and Kwan 2018).

The above-mentioned conventional methods to analyse urban metabolism, though are descriptive and largely being in use, may face challenges in the spatio-temporal analysis of urban metabolism of cities in developing countries that are facing great environmental and demographic challenges in the contemporary scenario of changing climate. Similarly, in developed countries which are currently facing a decline in population growth, the conventional analysis methods may have certain limitations in the actual evaluation of urban metabolism. Hence, novel and upgraded methodological approaches are warranted for real-time and reliable evaluation of urban metabolism. For instance, Rosado and his team (Niza et al. 2009; Rosado et al. 2014) provided Urban Metabolism Analyst (UMAn) model to tackle the shortcomings of MFA method. Several new approaches like Integrated Urban Metabolism Analysis Tool (IUMAT) (Mostafavi et al. 2014) and 3D geo-visualization in urban metabolism studies tried to cater the current methodological need; however, they may have their limitation in the application.

1.4 Climate Change and Sustainability in Urban Metabolism

Along with the increase in the size of the city and the high rate of urbanization, unsustainable urban development can cause severe ecological and environmental issues because cities are essential points of interaction between natural and socio-economic setups and places where human activity is concentrated (Kapoor et al. 2020; Singh et al. 2022). In addition, urban areas are becoming extremely vulnerable to risks caused by a wide range of sources, including climate change and urban disasters (Satterthwaite et al. 2009). Furthermore, it is not clear how the urban system relates to one another across different scales within a city or how cities compare to one another in terms of their capacity to survive, recover from, and adapt to various sources of stress (Carter et al. 2015; Verma et al. 2020). In the meantime, the concept of resilience has been around for a long time, and it has seen great benefits in the implementation in urban planning and disaster preparedness (Bush and Doyon 2019). Further, in the recent years, urban metabolism has been extensively adopted as a valuable framework for assessing urban system energy efficiency, material recycling, waste management, and infrastructure (Pincetl et al. 2012; González et al. 2013). The amalgamation of principle of urban resilience and urban metabolism can be of tremendous value to the development of strategies for sustainability (Broto et al. 2012; Dijst et al. 2018). Further, the development of theoretical and practical approaches to urban metabolism requires interdisciplinary collaboration. However, there is a downside to this growth pattern where rapid urbanization coincides with deteriorating livelihood, air pollution, climate change, and many man-made and natural disasters (Revi et al. 2014). Therefore, while promoting such regional and urban development, it is important to manage the impending risk to our ecological environment stemming from rapid urbanization (Kacyira 2012).

Cities are the biggest consumer of global resources (Glaeser et al. 2001; Westphal et al. 2017). Unsustainable consumption of global resources often leads to environmental degradation and ecological imbalance (UNEP 2011; Kandil et al. 2020; Bhadouria et al. 2022). Therefore, to alleviate environmental pressures, sustainable usage of natural resources is imperative to support city development (Freedman 2018; Liu et al. 2022). This intent leads to emergence of concepts like, “safe”, “resilient”, and “sustainable” metropolises and inclusion of strategies pushing to build such sustainable cities to reduce over-extraction of and address the consequent degradation of environmental resources. Two Sustainable Development Goals (SDGs), SDG-11 (to make urban systems inclusive, safe, resilient, and sustainable) and SDG-12 (to ensure sustainable consumption and production patterns), explicitly place emphasis on this direction (Musango et al. 2020).

Following through on these, city planning objectives serve as a powerful reminder of the significance of environmentally responsible development and disaster preparedness (Lucertini and Musco 2020). Urban metabolism has, thus, been extensively adopted as a useful method for evaluating an urban system’s infrastructure, material recycling, waste management, energy efficiency, and contribution to the GHG emission having direct connotation for changing climate. The concept of urban metabolism positively impacts strategizing sustainability and ensuring urban resilience, thus correcting the feedback process within the metabolism of the urban system. This may have direct implications on urban sustainability and well-being, under the current scenario of rapid urbanization across the globe (Van Kamp et al. 2003; McPhearson et al. 2016a, b). Further, it is critical to comprehend how urban communities self-organize and make decisions to manage better resources and understanding the life cycle of resources and how to best repurpose them to benefit the local community (Ulgiati and Zucaro 2019).

The boom in the transportation sector has on the one hand made life more efficient in a household, while the increase in fossil fuel consumption and air pollution on the other (McMichael 2000). Furthermore, the urban design on the mode of transportation may have space demands, air quality impacts, and health effects in the coming days (Cervero 2001). The urban metabolism analysis may be applied efficiently to understand the role of urban GHG emissions in global warming (Conke and Ferreira 2015; Chen et al. 2020). Further, enhancing awareness towards developing urban resilience in the perspective of climate change adaptation must be considered in future policy planning (Demuzere et al. 2014).

1.5 Urban Metabolism and Disaster Resilience

Under the current scenario of changing climate, rampant urbanization, and increasing population, cities across the globe are facing two major challenges to be met: resilience and sustainability in their ecosystem. The occurrence of extreme natural events has increased in the last decade which makes the concept of resilience and sustainability more significant. Therefore, it seems that only a resilient urban system can be sustainable in future (Verma et al. 2020). Further, extreme natural events have many negative consequences pertaining to environmental and socio-economic perspectives which make resilience and sustainability more relevant. The erratic disaster events related to climate change pose great uncertainty and challenge towards risk understanding and management (Singh et al. 2022). In the recent years, it is comparatively difficult to forecast the nature and frequency of hydrometeorological disasters; hence, disaster management authorities and planners find uncertainties to assess and managing these disasters in cities across the world. Unmanaged and ill-planned urbanization, migratory influxes, and related unsustainable exploitation of natural resources particularly in developing nations have worsened the situation (Verma et al. 2020). Furthermore, extreme levels of pollutants in almost all the components of the biosphere have disturbed biogeochemical cycles in urban ecosystems and invited various water-borne and vector-borne diseases and epidemics in the recent years. Under the above-mentioned scenario, urban metabolism can be an important utensil to provide parameters which can be used to measure and analyse the role of urban centres in creating environmental concerns (Kennedy et al. 2011). Furthermore, urban metabolism aids in the formulation of efficacious policies in sustainable urban planning which eventually assist in the development of a resilient urban ecosystem. Moreover, the parameters generated through urban metabolism provide satisfactory criteria of sustainability indicators in terms of scientifically valid data which are comprehendible, non-ambiguous, and comparative over time (Kennedy et al. 2011; Pincetl et al. 2012; Yang et al. 2014). The data generated, therefore, can be utilized by policy planners to develop sustainable plans that may assist constructively in resource conservation, management of waste, and GHG emissions (Álvarez and Julián 2014).

1.6 Urban Metabolism and Sustainable Urban Planning

There are two widely accepted schools of thoughts, the first propagated by Odum (1975), which involves urban metabolism based on of energy equivalents, and the second, which is based on material flow in terms of mass fluxes, can be utilized to develop sustainability indicators for a city and, hence, the measures of overall energy consumption pattern, water flow, material dynamics, and waste output from city's metabolism. This assessment can also be applicable to the quantification of GHG emission from urban centres. The use of urban metabolism studies in urban planning and urban designing is a comparatively juvenile area, and researches are going on across the globe to understand this concept (Kennedy et al. 2011).

Contemporary studies have been emphasizing on implementation of urban metabolism in developing sustainable urban designs (Kennedy et al. 2011). The data obtained from the urban metabolism studies have been utilized to mathematical models having its significance for policy analysis and development. The group focused on MFA has developed many such mathematical models. For instance, modelling platforms like SIMBOX (Baccini and Bader 1996) and STAN (Cencic and Rechberger 2008) include sub-processes like stocks and material flow and outputs. These models may also be applicable to forecast future alterations in urban metabolism arising out of technological and policy innovations. Further, a sustainable urban design must strive to reduce GHG emissions, and urban metabolism matrices being useful in the quantification of GHG emissions may have implications for sustainable urban design. Moreover, studies have been conducted to track material and energy flow to mitigate environmental impacts in an urban design. In the master plans for Dongtan and the Thames Gateway, for instance, Arup's Integrated Resource Modelling (IRM), which is basically a model of urban metabolism, has been used (Kennedy et al. 2011).

In the multidisciplinary researches of cities, urban metabolism is an interesting topic of study. It is suggested that different metabolic components be evaluated at various scales and that urban metabolism be monitored as part of planning practice. In order to identify research gaps and needs in the field of urban metabolism, the constraints of the same must be carefully examined in the light of urban sustainability (Cui 2018; Leal Filho et al. 2020).

1.7 Ecosystem Services and Urban Metabolism

In an urban system, ecosystem services are critical in resource cycling and GHG emission abatement and, therefore, provide a range of techniques and strategies for the optimization of urban metabolism (Perrotti 2020; Cárdenas-Mamani and Perrotti 2022). However, it has been observed that this range of techniques based on the ecosystem services concept is by and large underexploited in urban metabolism studies, even after the considerable progress in research analysing and classifying the ecosystem services (Cárdenas-Mamani and Perrotti 2022). Urban policy decisions have been benefited from the use of the notion of ecosystem services, such as the adoption of nature-based solutions (Almenar et al. 2021). Further, it suggests that integration of the concept of ecosystem services with urban metabolism research may help in mitigating the methodological lagging and strengthen the modelling of the urban system (Newell et al. 2019; Winker et al. 2019; Cárdenas-Mamani and Perrotti 2022).

1.8 Urban Metabolism and Circular Bio-economy

A bio-economy is focused on generating biological resources renewable in nature on land and water, and a value addition to be given to transformation of these resources and waste produced, in terms of bio-based products and bioenergy (Venkatesh 2022). While resource conservation is the driving force behind a circular economy and renewable is the essential term in a bio-economy, a circular bio-economy combines the "best of these two worlds" (D'Amato et al. 2017; Venkatesh 2022). Urban metabolism in a circular bio-economy will undoubtedly turn into something quite powerful for addressing a variety of difficulties, including tackling climate change and its effects and achieving numerous SDGs in the process. Needless to state, as all know, challenges lurk where opportunities abound to replace the take-make-use-dispose paradigm of a linear economy with a grow-make-use-share-partake-restore paradigm of a circular bio-economy. These approaches pave the way for sustainable as well as smart urban metabolism.

1.9 Smart Urban Metabolism (SUM)

Smart urban metabolism (SUM) is a contemporary conception of urban metabolism which includes modern-day technologies dealing with the complex challenges of growing smart cities (Allam 2020a, b, c). Traditionally, urban metabolism deals with the influx-efflux of energy and the flow of materials through urban space. However, with the growing needs of smart cities, these flow patterns are transiting as a complex network and are subject to interdisciplinary understanding. Furthermore, data availability is a major challenge faced by city planners due to the lack of data inventories and appropriate data management solutions to handle massive datasets, arising from these complex flow patterns. This is ensuing to the inefficient adaptation of urban metabolism approaches, especially in developing economies. Thus, the situation remains grave when it comes to resource management of a smart city, and how urban areas may additionally deal with intricate issues like climate change when they are striving to understand their own material and energy cycling. SUM can potentially be an effective approach for identifying complex issues in the flow patterns of energy and material in an urban space (Allam 2020a, b, c).

1.10 Digitalization: An Approach to Circular and Smart Urban Metabolism

The adverse consequences of the linear and traditional urban approach have now been realized by policymakers and city planners (European Commission 2020a, b; D'Amico et al. 2022). Therefore, digitization of circularity has been recommended to take urban metabolism towards automation and sustainability (Ingrao et al. 2018; D'Amico et al. 2022). Furthermore, United Nations has recognized that digitalization may be a potent tool to drive the circularity in urban metabolism and will be instrumental in achieving SDGs by 2030 (United Nations 2015; De Pascale et al. 2021). Further, circularity in urban metabolism strives to achieve a holistic connection among the natural, built, and digital environments (Mikalef et al. 2020; D'Amico et al. 2022).

1.11 Governing the Urban Metabolism: Policy Approaches

The promotion of responsible and balanced use of resources is the focus of an increasing number of policies being enacted at the international level. International political instruments, such as the SDGs and the New Urban Agenda, direct cities to focus towards an environmentally sustainable urban ecosystem. This mandate has provided the impetus to research, particularly in the area of urban climate governance (Heidrich et al. 2016; Bansard et al. 2017; Reckien et al. 2018; Heikkinen et al. 2020). Urban sustainability and resilience can be aided by the centrality of urban metabolism and its ability to influence city policies and designs directly (Bristow and Kennedy 2013; Bristow and Mohareb 2020). It has been realized that most of the challenges in governing environmental flows are due to gaps in accountability and loopholes in strategic planning and its implementation. The urban metabolism approaches integrated to environmental governance may strengthen accountability in terms of responsibility, transparency, assessment and participation, and augment urban policy planning and implementation.

1.12 Interdisciplinary Understanding of Urban Metabolism

Urban metabolism indicates the exchange processes that give rise to an urban environment and gave impetus to find out ways to make cities more sustainable. However, it has invited criticism for some specific types of social and economic systems that have prioritized or marginalized some peculiar type of flow patterns with urban systems. The current scenario of changing climate and increased urbanization with an increase in urban population has compelled to develop an alternative understanding of the functioning of an urban system. For instance, analysis of urban ecology and material flow (MFA) may be instrumental in the formulation of social and environmental policies (Dijst et al. 2018). Furthermore, analysis focused on the metabolism of the urban economy suggests the role of environmental and social resources in running the growth of the urban economy, along with their spatial manifestation pattern.

1.13 Conclusion and Future Perspectives

Currently, more than half of the global population is residing in cities. The majority of cities in the globe are seeing significant growth, particularly those that are located near large urban centres. Therefore, it is crucial that efforts are made to make cities and other human settlements safer and more resilient. There is also a perceived need to find, test, and adopt policies that could improve the physical environment and the harmony between urban residents and ecosystems. To create more sustainable cities and human settlements, the SDGs, particularly SDG-11, provide novel opportunities and thrust. With aspects such as life cycle analysis, input–output analysis, and ecological network analysis, studies have been focused on understanding interrelationship between the components of the urban system and direct and indirect resource consumption and assess how the human system affects the environment. It will be important to strengthen the theoretical underpinnings of this field of study, standardize and unify the methodology to enable comparisons between studies, examine and combine the outcomes of analyses at various sizes, and promote collaboration across a wide range of disciplines. A systems engineering approach may be adopted to standardize and bring conformity in the methods for categorizing and quantifying data to develop databases, to strengthen research, analysis, and evaluation, hence providing multiscale data needed for such analysis databases thereby augmenting our understanding towards scale effect and principles of urban metabolism, that will be instrumental in development of sustainable policies and designs for urban systems. Discussions of this nature will be more fruitful if experts from fields not typically represented in resource management decision-making can participate. For instance, it would be fascinating to explore the literature in future research to find out how psychologists and sociologists try to address the human aspects of urban issues. Then, we may apply these ideas to the current technological and ecological paradigms. This may offer more consistent, unbiased, and useful direction for