Chapter 2
Interlinkages Between Urban Metabolism and Sustainability: An Overview

Riya Raina, Mushtaq Ahmad Dar, Rishikesh Singh, Daizy R. Batish, and Harminder Pal Singh

Abstract Urban metabolism is a concept in which the city is examined using biological principles that relate to the internal mechanisms by which living creatures maintain a constant interchange of matter and energy with their surroundings to permit their growth and development. In multidisciplinary studies of cities, urban metabolism is one of the potential fields of study. Urban sustainability refers to the urban planning measures implemented to enhance and build urban areas without depleting their resources indefinitely. To understand the in-depth features of urban metabolism and its potential for examining the sustainability of cities, the concept's historical development as well as its theoretical underpinnings are required. In order to address and identify the various research gaps and needs in the metabolism of cities, this chapter is intended to discuss the origin and evolution of urban metabolism, its relationship with the sustainability of cities, and the limitations of urban metabolism in relation to urban sustainability. There exists an interlinkage between the urban metabolism and sustainability within a city with respect to judicious resource utilization, energy flow, waste management, and social and economic development. The assessment of the urban metabolism and sustainability of a city can be a useful approach for smart city development. Moreover, there is a dire need to promote the circular urban metabolism for developing sustainable cities.

Keywords Agenda 21 · Circular urban metabolism (CUM) · Cities-4-People project · Climate change · Greenhouse gases · Linear metabolism · Material flow analysis (MFA) · People-Oriented Transport and Mobility (POTM) · Sustainability indicators

Riya Raina and Mushtaq Ahmad Dar contributed equally.

R. Raina · H. P. Singh (✉)
Department of Environment Studies, Panjab University, Chandigarh 160014, India
e-mail: hpsingh_01@yahoo.com

M. A. Dar · R. Singh · D. R. Batish
Department of Botany, Panjab University, Chandigarh 160014, India

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2.1 Introduction

The pace of population growth and simultaneous urbanization revealed that by the end of 2050, two-thirds of the world's human population (approximately 6.5 billion) will be inhabiting urban areas (Verma et al. 2020). The decisions made at the municipal, metropolitan, regional/sub-national, and national levels for urban expansion and related activities have a substantial impact on sustainable urbanization. For example, the effects of different processes and functions in cities on social and economic outcomes, human health and welfare, and both global and local natural surroundings will have considerable impacts on planetary boundaries and sustainable development (Webb et al. 2018). It is widely known that cities contribute to climate change and that potential mitigation and adaptation measures are required for attaining sustainability in the cities (Verma and Raghubanshi 2018; Sharifi 2021). However, because cities are complicated and dynamic systems, it is vital to identify flexible options and pathways when making decisions. Urbanization is the catalyst for economic development because it makes better use of resources like surplus labor and land. One of the key components of structural changes that take place when countries start down the path of improvement is the relocation of people (from rural to urban regions) in quest of better employment options as well as other opportunities (Roy and Thangaraj 2022). The workers' movement raises their income and standard of living while still assisting them in joining the "consuming class". This large consumer class is better able to make large purchases because of their increasing purchasing power, which in turn fuels the industrialization and urbanization processes (Joshi 2021). Thus, urbanization has improved people's living standards in addition to contributing to their increased incomes; hence, many developing nations like India may actively encourage urbanization. However, India presently faces a wide range of difficulties as a consequence of its large urban dweller population. Two major challenges include: (i) acceleration of the rate of urbanization; and (ii) implementation of the effective or planned urbanization in order to reap the most benefits (Tripathi 2021). This necessitates a greater involvement of researchers in urban planning, and management methods for the development of a city (Kennedy et al. 2011; McPhearson et al. 2016). Researchers may assist innovation, evolutionary co-design, and adaptive management of our cities by cooperating with the urban stakeholders to generate knowledge, carefully documenting and communicating learning to decision-makers.

It is important to understand how urban environments influence local climates and how climatic variability could have a big impact on urban settings as the population moves from rural to urban areas. Rapid urbanization has led to rising resource needs and pollutant flows throughout the planet. Urban economic networks extract, transform, and transport more than 40 billion tons of materials annually (as of 2010), accounting for an estimated 80% of world energy use. Cities are also accountable for 65% of the world's environmental emissions as a result of this mobilization of both energy and matter (Swilling et al. 2018). Additionally, the intricacy of the metropolitan system is increased by natural catastrophes. This is particularly important in cities that are experiencing fast development characterized by inadequate planning and a lack of basic urban public services (Bahers et al. 2022). Sustainability and resilience are thought to be powerful tools for dealing with hazards and supporting urban planning processes (Pirlone et al. 2020). Sustainability is a "complex and contentious" issue in terms of "interpretation and application", and when the words "sustainable" and "development" are combined, the emphasis is on economic development rather than comprehensive sustainability (Purvis et al. 2019; Toli and Murtagh 2020). Fair, livable, and financially viable are the three pillars of sustainable development (Pissourios 2013). Since its beginnings in the economic and ecological philosophies, sustainability has indeed been extensively included in urban development (Zeng et al. 2022). On the other hand, resilience is the ability of a system to 'bounce back' or revert to a pre-stressed, stable state. The capacity of the urban community to rebound from hazards is another way to define resilience (Sarker et al. 2020). A community's or city's potential to alter in response to numerous internal and external risks is known as resilience. Urban sustainability is concerned with an urban environment's ability to maintain the desired result over time. Given the consequences of climate change, the urban community ought to be able to think resiliently in order to help address environmental problems (Zeng et al. 2022).

Urban metabolism (UM) is a concept that studies how cities interact with the environment, particularly how they use resources and produce pollutant fluxes, as well as the associated sociological, economic, and environmental challenges related to these flows (Kapoor et al. 2020; Bahers et al. 2022). Although the idea of urban metabolism has its roots in the eighteenth century, it has gained considerable importance in the research community over the past few years (Barles 2010). Theodor Schwann first proposed the idea of urban metabolism in the nineteenth century, and Karl Marx's economic theory outlines its historical antecedents (Restrepo and Morales-Pinzón 2018). However, Abe Wolman's work was the first to introduce the idea of urban metabolism (Wolman 1965). In broader aspects, urban metabolism is the study of energy storage, its outputs and inputs into the urban region, as well as the quantification of the removal of wastes and nutrients from an urban area (Brunner and Rechberger 2016). The study of urban metabolism gives the parameters and indicators that enable researchers to assess and measure the environmental impacts caused by urban systems, i.e., cities, and therefore helps to generate certain effective policies that could be helpful in urban planning and development (Pincetl et al. 2012). The idea of urban metabolism has been correlated to the metabolism of living organisms and their interaction with the ecosystem. Similarly, the cities in urban metabolism are considered living organisms that consume resources from their surroundings and expel wastes to their nearby areas (Cui 2018). However, cities themselves constitute a whole ecosystem as they are home to a huge number of organisms (Savard et al. 2000). Therefore, the idea that cities are similar to ecosystems would be more appropriate. Moreover, this comparison of cities with natural ecosystems can be used for developing sustainable urban ecosystems because these are usually energy self-sufficient and can conserve mass and energy through recycling by decomposers (Moscovici et al. 2015). If cities attain such qualities, they would be more supportable and sustainable (Pincetl 2012).

The information and guidance obtained from the studies on urban metabolism have ensured the sustainability of cities. This would optimistically influence the representatives to develop strategies that are helpful in the preservation of resources, and the reduction of waste production and greenhouse gases (GHGs). For instance, the European Union's Seventh Framework Programme (FP7) project BRIDGE (sustainable urban planning and decision support accounting for urban metabolism) has established a decision support system (DSS) for sustainable urban planning (Chrysoulakis et al. 2013). DSS helps to evaluate the potential impacts of urban metabolism components, *viz.*, carbon, energy, and pollutant changes, and can offer a quantifiable assessment of their sustainability performances (González et al. 2013). In this way, it is helpful to formulate various policy recommendations that could further promote the effective usage of resources and augment the ecological quality of the cities. Moreover, studies related to urban metabolism are contemplated as an important requisite for planning projects that target urban sustainability in cities (Perrotti 2020). The present chapter encompasses the theoretical foundations of urban metabolism, its origin and evolution, processes in the urban metabolism concept for urban sustainability, interlinkages between urban metabolism and sustainability, as well as limitations of the concept and challenges for urban sustainability.

2.2 Concept of Urban Metabolism: Origin and Evolution

Researchers have compared urban areas to biological organisms (Wolman 1965). As we know, organisms in the natural environment need energy and resource inputs, and they then utilize this energy in doing work and excreting waste, the same as cities do (Barrera et al. 2018). Urban metabolism can be defined as *"the sum total of the technical and socioeconomic processes that occur in cities, resulting in growth, the production of energy, and the elimination of waste"* (Kennedy et al. 2007; Lucertini and Musco 2020). The concept basically appeared in the late twentieth century as an organized method to understand urban pathways of resource utilization, production of waste, and their influence on the surroundings (Lanau et al. 2021). Some ecologists neglected the comparison made between the metabolism of cities and that of an organism, as they believed that only living organisms can have metabolisms, and declared the urban metabolism concept an inappropriate biological analogy (Pincetl et al. 2012; Webb et al. 2018). However, some have recommended that cities be more similar to ecosystems (Ko and Chiu 2020). Yet urban metabolism is an integrated and multidisciplinary platform that studies the matter and energy flows in urban areas (cities) as complicated systems as different societal, economic, and environmental factors shape them. Therefore, urban metabolism gives us a figurative outline to observe the exchanges of human and natural systems (EsmaeilpourZanjani et al. 2020).

The concept of urban metabolism is well known in the theories of the socio-economic distribution of neo-Marxist (Özdemir 2021). Marx used the term metabolism to define the processes between man and nature in which man regulates, contemplates, and controls the metabolism among him and the environment (Wang 2020). Various other theorists on urban metabolism, *viz*., Kaika, Heynen, and Sywngedeou, have also approached this concept of urban metabolism from a neo-Marxist perspective (Ko and Chiu 2020; Ulgiati et al. 2021). They have used Marx's approach to understand and analyze the dynamic relationship between human beings and nature. Earlier to the petroleum age, humans used to exert physical and animal labor for their survival (in terms of food and shelter) on the Earth. In this process, they altered the various physical forces in order to supply the metabolism of human activities. Marx explained that man is a natural being itself and is dependent on nature for his material needs. In this process, he alters and transforms nature and eventually changes the Earth's systems, of which 'climate change' is possibly the most vivid example (Pincetl et al. 2012). Further developments in the concept of urban metabolism are outlined in the following sub-section.

2.2.1 Urban Metabolism in the Twentieth Century

The first precise application of this concept was given by Wolman in 1965 in his book "*The Metabolism of Cities*", in which he represented the metabolism of an imaginary city, i.e., the United States (Wolman 1965). The Wolman study was promulgated at a time when uncertainties about the impact of anthropogenic activities on the surroundings were increasing rapidly. The study gained massive importance among environmental activists who were concerned with the growing human population and its effect on the ecosystem's ability to provide resources. Wolman's key innovation was that he presented the city as an ecosystem, and therefore, he focused more on the "ecology of cities" than the "ecology in cities", i.e., he emphasized more on urban areas' (cities) processes and exchange of energy or matter relative to their surroundings (Oliveira and Vaz 2021). He established a model of an imaginary American city with one million people, calculated the actual inputs and outputs of materials and waste from that hypothetical urban system, and therefore, showed urban metabolism as a quantitative entity. He advanced the idea that urban metabolism was no longer controlled by political or geographic limits. He explained that cities have affected the environment on broad as well as local scales by using resources and producing waste and pollution (Paul et al. 2018). He was concerned about the growing population and its effects on natural systems and resources. Published in *Science*, Wolman was able to connect with a large audience by emphasizing the need for freshwater supplies for cities and demonstrating how urban systems (cities) draw their inputs from the environment and leave behind a trail of effects outside of their immediate physical bounds (Kingsland 2019).

2.2.2 Measurement Methods of Urban Metabolism

After the ground-breaking effort by Wolman, urban metabolism progressed into two different approaches: mass balance accounting and Odum's emergy method (Pincetl et al. 2012). The first one discusses industrial ecology and is also associated with engineering fields. Mass balancing is an approach that accounts for materials entering and leaving the system and uses tools such as material flow analysis (MFA) to keep track of the flow of materials as well as energy through the urban system (Cui et al. 2019). It also keeps track of the energy required to convert raw materials into material goods to fulfil the demands and needs of people. A new approach that has largely influenced the urban metabolism concept is the introduction of energy flows by Odum (1983). He quantified the available solar energy that was used directly or indirectly to produce a product, and used that figure to define the metabolism in terms of solar energy equivalents and account for metabolic fluxes. He called this concept *emergy*, which is quantified in terms of solar emergy joules (SEJ). This method highlights standard units for both material and waste flows in any biophysical system. Though theoretically feasible, it would be difficult to characterize all urban processes in common units. The energy-material flux method was therefore accepted as a more typical urban metabolism approach due to the complexity of this methodology and its limited use as a result of the conversion of flows to SEJ metric. It emphasizes calculating an urban system's materials and energy flows, irrespective of units.

Due to the surge in the global impacts of urban areas (cities), they have become the main centers for metabolism studies. A study of urban metabolism includes the measurement and quantification of energy, material, and water flows into the city as well as stocks and flows outside of the urban area. Therefore, we can develop an environmental outline of an urban area as these flows cause degradation of the environment as well as the scarcity of some resources (Wei et al. 2015). Once the metabolic profile of a city is established, it enables us to identify key elements and, thus, helps to formulate effective policies related to some major urban issues, such as waste production due to higher resource demands and scarcity of water supply due to increased water demand. Some other issues are energy and climate change due to the increased emission of GHGs and air pollution instigated by the release of nitrogen, phosphorous, metals, SOx, NOx, and particulate matter (Lv et al. 2020). Changes in landscapes due to the relocation of huge amounts of building materials and impaired environmental quality because of the emissions of the above-mentioned pollutants have an extremely negative influence on the quality of natural ecosystems and human health. For that reason, urban metabolism analysis is necessary to tackle such environmental issues, particularly in areas where fast urbanization is taking place, such as in developing nations (Wei et al. 2015).

The urban metabolism studies include quantification approaches such as MFA, mass balance, and life-cycle assessment (LCA). MFA includes the principle of mass conservation and measures the total materials entering a system, such as material flows inside a system, and the material flows in the form of pollution or waste that are leaving the system (González-García et al. 2021). The materials that enter the urban system are consumed, and biophysical structures such as human bodies, buildings, machines, roads, artefacts, agricultural and livestock products, and export products such as waste are formed. Mass balance is grounded on the belief that substances can neither be created nor destroyed but can only be transformed (Voukkali and Zorpas 2022). Therefore, according to this principle, the total input into a system equals the total output from the system. As explained by Einstein, energy is the transformation of mass, and therefore, standard units such as kilograms, joules, or tons are used to describe the energy flows in the mass balance approach. A cradle-to-grave approach is used in LCA, which includes a regular analysis of the possible environmental impacts of goods or services throughout their life cycle and is recorded (Akizu-Gardoki et al. 2022). By modelling, the energy fluxes entering and leaving the urban system, quantification of urban metabolism in integration with the LCA enhances the ability to compute the environmental impacts of cities (Elliot et al. 2018). LCA provides a hands-on set of methods and tools for measuring the material flows within the urban system. All these methodologies, whether alone or in conjunction, involve the quantification of energy flow, that is, nutrients, raw materials, and food that enter the urban system, as well as the wastes that leave the system, in standard units such as kilograms, tons, and joules. The LCA method has been brought into the ISO 14044 standards and accepted by various LCA practitioners (Talwar and Holden 2022). There are various softwares such as GaBI (PE International, Germany) and SimaPro (PRé Consultants, The Netherlands), that were developed for conducting LCA (Tintelecan et al. 2019). An urban area's physical metabolism may be attained by measuring energy flows. It includes the measurement of energy, materials, nutrients, water, and wastes, and therefore helps researchers to understand various phenomena in cities all over the globe.

2.3 Urban Sustainability

Some of the important events in sustainability research include the 1972 United Nations Conference on the Human Environment, where the international communities met and discussed the challenges related to the environment and its development. Further, the 1987 Brundtland Report gave the definition of sustainable development (Brundtland 1987). The Earth Summit or Rio Declaration that took place in Rio de Janeiro, Brazil (1992), introduced the concept of sustainable human development and posed vital goals for its measurement. During the 1992 Earth Summit, Agenda 21, which calls for developing sustainability indicators, was adopted. Further, in 2002, the implementation of Agenda 21 was reaffirmed at the Johannesburg Earth Summit, which emphasized hands-on methods for executing sustainable development. Sustainable development addresses human needs and increases the quality of life. Concurrently, natural resources must be exploited at a rate that can be sustained by the regenerative ability of the ecosystem. Overall, sustainability is based on the three major pillars of economic, social, and environmental sustainability (Tsalis et al. 2022). The health of an ecosystem is a prerequisite for its sustainable development (Carréon and Worrel 2018). Considering these facts, Sustainable Development Goals (SDGs) with 17 broad goals and 169 interrelated objectives were established on national precedence (Salvia et al. 2019). The SDGs were approved in 2015 and the specific aim of this approach was to attain sustainability in both developing and developed nations for the next 15 years. The SDGs are accompanied by indicators that are supposedly meant to be universal, but basically, they are not relevant to every nation (Vandemoortele 2017). For example, SDG-11 talks about the safe and sustainable development of cities and communities, which also includes human settlement planning and its management as well as affordable housing and sustainable transport. Sustainable development can only be attained by effectively renovating the ways that shape our urban spaces (Sarbu et al. 2021).

The idea of urban metabolism is strongly associated with sustainable development because both emphasize persistent ecosystem facilities to support humans by supplying materials and goods. In other words, sustainable development in an urban area must be viable, equitable, and liveable (Vidal et al. 2020). Over the last few decades, urbanization has turned out to be one of the most imperative subjects that describe the human association with ecosystems (Huang et al. 2015). Cities and the urban population play a vital role in developing urban sustainability. Cities are defined as super organisms that have a spatial structure and dimensions where both living and non-living organisms interact and coexist (Wolfram et al. 2016). This coexistence produces some inter-relational processes, such as involvement in the biogeochemical cycles and the flow of material, energy, and waste within the urban system. Therefore, evaluating the growth of a city towards sustainable or unsustainable urban development has become an important area of research and needs quantification with the help of appropriate sustainability indicators (Verma and Raghubanshi 2018). Due to the increased complexity and difficulty in an energy system's elements such as transportation, delivery systems, utilization of food, supply of freshwater, utilization of goods and services, and waste generation and handling, cities are accountable for about 60% of energy consumption and 70% of anthropogenic GHG emissions (Maranghi et al. 2020). All these exchanges and emissions contribute strongly to climate change. With the increased urbanization, cities would need to develop more sustainable methods, and the increased population would need some novel ways to handle urban living. Thus, some new solutions are required to identify problems such as inefficient resource management, social exclusion, high energy consumption, declining human well-being, overcrowding, and environmental degradation (Perrotti 2020). In this regard, urban sustainability is defined as the urban planning actions and principles that build and improve urban areas without aggressively consuming the resources endlessly (Restrepo and Morales-Pinzón 2018). A sustainable city would, therefore, be one that could minimize the expenditure of fossil energy and waste generation through recycling and recirculation (Broekhoven and Vernay 2018).

2.4 Inter-Linkages Between Urban Metabolism and Sustainability

A city cannot stand alone, and its sustainability largely depends on the quality of surrounding urban systems, agricultural areas, and other countries (Girardet 2017). The urban metabolism can be of two types, *viz.*, linear and circular metabolism. A linear metabolism is defined as a situation where there is no link between the inputs of resources and the outputs of waste. On the other hand, circular metabolism refers to a state where the outputs of the city's metabolism are utilized as inputs in the production system (Girardet 1996). The sustainability of capitals in urban metabolism is grounded on the effectiveness of some processes and the elimination of linear urban metabolism in favour of circular urban metabolism (CUM). Thus, it becomes critical to account for the circuitous utilization of resources and discharge of contaminants outside the city. Keeping track of urban inputs and outputs due to domestic consumption helps us recognize the dependency of a city on other areas, but this consumption-based method is not always helpful, and thus, consumption- and production-based quantifications are needed for the development of suitable urban policies (Maranghi et al. 2020). In a circular metabolism, the cities encompass balance with the ecosystem and therefore face fewer environmental impacts. CUM involves an initiative that incorporates energy and material inputs and outputs used in different functions such as cooking, food consumption, and production to generate other local cycles of energy and material so as to reduce the ecological burden of the existing city areas. A simple illustration of CUM is the utilization of organic waste to yield biogas and compost through anaerobic digestion. However, the lack of suitable data is another major obstacle in developing the metabolic profile for an urban area (Verma et al. 2021). To attain sustainability, cities have to put some serious efforts into collecting data related to urban metabolism. Also, research is required to build up some methodologies for evaluating gaps based on existing data (Cui et al. 2019). Since cities are intricate urban systems, tracking the data of flows, inputs, and outputs of the cities would require some efficient policies and strategies, so in this regard, the integrated models are predominantly helpful for detecting trade-offs and suitable answers to numerous ecological problems beyond "end of pipe" approaches (Wei et al. 2015). The interlinkage between urban metabolism and the sustainability of a city has been represented in Fig. 2.1. For the sustainability of a city, there should be some mechanisms through which the outputs generated after the metabolism of raw materials can be re-utilized, either directly in the city system or indirectly through the input system for re-circulation to the city.

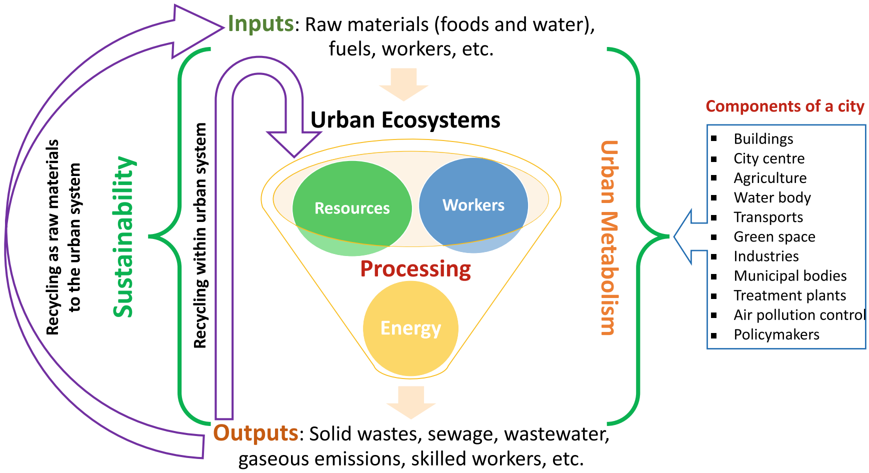

Fig. 2.1 Interlinkages between urban metabolism and the sustainability of a city

2.5 Phases of Urban Metabolism Leading Towards Sustainability

Urban metabolism offers a thorough framework, concepts, methodologies, and policy-making to help investigate the material and energy transitions in cities (Cui 2018). If we desire that a city's development occur without increasing the amount of matter and energy beyond the biosphere's capability, then research related to urban metabolism has a liability to expose how urban areas could achieve sustainability (Cui 2018). The geological transport of matter and energy among different cities led to their interdependence on each other. This, therefore, serves as a threat to upcoming generations. Accordingly, it is tough to recognize whether an urban area is sustainable, particularly for developed cities. Understanding the involvement of an urban area to sustainability is, however, convenient and depends largely on the city's consumption and production patterns, health and welfare levels, and disposal amounts (Bengtsson et al. 2018; Bibri and Krogstie 2020; Perrotti 2020). Determining the city's contribution to sustainability involves the following efforts:

1. Studies of the metabolism of a city help find sustainable development solutions through resource and flow modeling, and network translation (Wang 2023). The patterns in urban metabolism modify with time, and the chief drivers of these alterations in the city's metabolism have been considered from time to time in many studies. These studies assess how urban metabolism affects the environment and surroundings, as well as its effects in the present and the future (Dijst et al. 2018). These studies on urban metabolism are required as the flows of material and energy may vary markedly with time. For instance, material needs, production and consumption patterns, technologies, and underlying economic activities can vary and modify at a temporal scale (Cui 2018). Environmental

impacts on a city with a large number of construction projects compared to a city with a lesser number of construction projects can vary because of the increased demands for landscapes and aesthetics. These studies then help the policymakers to propose solutions for sustainable development and the modeling of energy flows and network translation. The time series methods help the policymakers understand the urban consumption and production trends and, therefore, elucidate sustainable urban planning alternatives from an ecological or environmental perspective (Wu et al. 2018). Furthermore, these trends facilitate the effective investigation of the progression and evolution of urban metabolism, which therefore gives sensible and practical information for studying its role in sustainability.

2. Because anthropogenic activities have an important influence on the sustainability of cities by interfering with the metabolisms of materials, energy, and elements like nitrogen, carbon, and phosphorous, the biogeochemical cycle of these metabolic elements was described, and the related environmental pollution problems were discussed in various studies (Gu et al. 2012). Metabolic elements are more dynamic than the materials used in construction activities, such as steel, cement, gravel, and sand, and therefore, these metabolic elements flow more rapidly within complex urban systems (Huang et al. 2018). For instance, the studies of water metabolism in an urban area are complex and more dynamic as the accessibility of water is largely constrained by wastewater discharge, water table fall, groundwater depletion, and seawater intrusion. Carbon metabolism can also massively affect the urban metabolism of cities as it is very much interrelated with human activities (Xia et al. 2018). About 70–80% of carbon is emitted by an urban area; therefore, accounting of carbon-flow modeling and studies on carbon footprinting essential in attaining sustainability in cities (Verma et al. 2021). Also, cities typically have a high dependence on energy; thus, studies on carbon metabolism help to evaluate the environmental quality and policymaking. In addition, nitrogen and phosphorous flows are also significant for the sustainability of the city's metabolism, as a major chunk of these elements are being released from agricultural run-offs, solid waste landfills, and fossil fuel combustion (Guan et al. 2021). Phosphorous is being released in cities via waste generation, ore extraction, and resource use, which leads to different ecological problems. Air pollution monitoring in the cities, such as organic pollution load, and concentrations of fine and coarse particulate matter, has also been studied in urban metabolism. All these studies and research give us a general view of the impacts relating to air, water, and soil in a combined system.
3. In a city, various urban metabolism mechanisms are linked together and therefore have a complex structure. Simplifying these complex components of urban metabolism components is essential to achieving sustainability. This, therefore, demands a need to describe the inner workings of urban metabolism, which involves the internal mechanisms of urban metabolism as well as flow of matter and energy that are produced and circulated (Fróes and Lasthein 2020). The transportation components in urban metabolism emit a huge amount of GHGs; thus, a sustainable revolution of the substructure in urban areas is essential to

changing the present trend of increasing GHG emissions. The urban substructure on a large scale consists of budget, volume, and timelines. Its intricacy could appear daunting to local people; nevertheless, both citizens and infrastructure are directly and closely related and mutually dependent (Puerari et al. 2018). Urban Transition Labs, Urban Living Labs, and Learning Alliance concepts define the transformation of cities' infrastructure via local stakeholder co-creation processes, and this may lead to some of the key benefits such as encouraging creative and innovative ideas, intensifying social inclusivity, increasing engagement, increasing ownership, etc. Also, co-creating with various stakeholders helps to promote a sturdy flow of resources throughout the urban metabolism (Nevens et al. 2013; Khan et al. 2017). In this aspect, it also supports the typical healthy urban environment for the residents. The formation of healthy cities involves a well-operated technical urban sub-structure, which eventually is the outcome of human activity and design. Involvement of co-creation techniques as well as a co-production approach in urban planning and metabolism can also lead to sustainable cities.

4. The Cities-4-People project is a new method of attaining healthier cities and urban metabolism. It focuses on some new, innovative methods for locally and regionally supported, sustainable, and supportable mobility solutions (Fróes and Lasthein 2020). As reported by the World Health Organization (WHO), people from several disciplines can efficiently work on a way to build sustainable, vital, and healthy cities. This goal can be achieved by transforming urban infrastructure and altering the modes of transportation, thereby enhancing the livability of inhabitants by transforming their ways of transportability from private cars to biking, public transportation, and walking (Noring et al. 2018). This is the exact principle behind the Cities-4-People project, in which stakeholders from five urban areas have been engaged to alter the top-down process approach to transportation and mobility into a more inclusive and dynamic bottom-up approach. These stakeholder groups, more precisely from academia, government, and industry, work together via several interventions to tackle cities' main mobility problems that were recognized earlier through quantitative and qualitative study. The main notion in this mission was People-Oriented Transport and Mobility (POTM), which offered novel ways to get targeted and sustainable answers to the needs of the public (Fróes and Lasthein 2020). POTM included the combination of the latest digital and communal technologies under a comprehensive approach to get answers that had a little environmental footprint, a sharing mindset, and the potential to resolve actual urban mobility problems. Cities-4-People was spread-out in European regions and established by bringing together authorities, citizens, and innovation experts (Liu et al. 2015).
5. The use and reuse of resources for societal welfare and their impacts on a city's health have been mentioned in some key studies. Evaluating source consumption, waste production, and human livability and welfare in different cities allows us to conclude if urban areas have helped policymakers on sustainability (Newman 1999). As a result of this perception, cities have to compute their contributions in terms of reducing metabolic flows while upgrading human livability (Cui

2018). Researchers have designed a model connecting socio-economic activities and underlying environmental circulation processes to the intricate and complex city's landscape pattern (Zhou et al. 2021). This model provides the details of matter and energy inputs, helps to recognize the important infrastructures in urban metabolism, and improves urban metabolic efficiency. During a water shortage in a city, these models promote the concept of regenerative use, which includes rainwater and groundwater collection and recycling wastewater. Studies have confirmed that these techniques are accessible with present methods and can help in habitat water utilization as well as aquifer recharge (Thomson and Newman 2018). Also, elements such as nitrogen, carbon, and phosphorus can be recycled and can supply an adequate growing medium for agriculture. Cities are supposed to be capable of making contributions to sustainability through local solutions that tackle numerous challenges such as resource insufficiency through material use, lesser biodiversity loss, and climate change through reduced energy use (Cui 2018).

2.6 Challenges for Urban Sustainability

The environmental footprint of urban areas expands much ahead of their administrative boundaries by means of the assimilative and productive services of the ecosystem, facilitating the flow of energy and material (Verma and Raghubanshi 2018). Urbanization is a large section of human residents living in cities. As cities grow, anthropogenic activities increase, which, therefore, causes a decrease in natural resources and ultimately causes a threat to urban sustainability (He et al. 2018). Mori and Christodoulou (2012) have stated that cities encompass both economic and social collisions on sustainability as their environmental externalities are not limited to their specific areas. Therefore, this concept becomes very important in understanding the sustainability of cities as they expand outside of their administrative boundaries. Urban sustainability indicators are suitable ways for evaluating urban sustainability because of their huge acceptance and several options in combination with software (Kaur and Garg 2019). There is a broad range of sustainability indicators and indices that are in use; however, these indicators vary with respect to the goals and needs of different cities and regions. Indicators are variables that are used to assess a predetermined phenomenon, whereas an index is comprised of a mixture of different indicators. Indices help in simplifying the intricacy of an indicator; however, indices are more intricate and complex to calculate. For that reason, indices require an assemblage of various indicators to be assessed (Mori and Christodoulou 2012). For example, if we want to evaluate the carbon dioxide production of a particular urban area, it is important to assess the emissions coming from different sources. The sources could be buildings, industries, and transportation, which form different sub-indices. A sub-index may have different sub-indices until a simpler indicator is achieved. In this way, the carbon dioxide emission from a private car can be considered an indicator for the entire carbon dioxide emission;

however, several other indicators may also be important to assess all the emissions in an urban area, which, therefore, makes it tricky to get a valid figure (Corredor-Ochoa et al. 2020).

In order to reduce and simplify the issues during the implementation of indicators, Verma and Raghubanshi (2018) classified the urban sustainability challenges into two broad categories: external and internal challenges, through which sustainable development indicators can be studied. Internal challenges focus more on the problems in the methodologies used for developing indicators. External challenges include problems that resist the execution of these sustainability indicators and are usually characterized by policy lethargy, a lack of sufficient data, and the unwillingness of higher authorities to implement suitable indicators. The steps required during the framework of sustainability indicators are: Preliminary assessment (A), Setting goals (B), Indicator selection (C), Setting baseline (D), Selecting targets (E), External challenges (F), Application (F), Evaluation (G), Reporting findings (G), and Sustaining the indicators (J). Unclear methodologies may produce sustainability indices with unsustainable issues. Also, the development of indicators must involve scientific and technical solutions and should be unaffected by social challenges, which comprise moral and ethical dimensions. Furthermore, the sustainability indicators should focus on simple criteria such as easy calculations, appropriate methodologies, data availability, methodological commensurability, easy reach into policy decisions, and scientifically determined thresholds. Also, owing to the abundance of sustainability indicators, there is a requirement to establish the relevant and important ones. And in order to obtain a basic and relevant indicator system, the obstacles and challenges encountered during the development and application of these indicators need to be resolved.

2.7 Conclusions and Future Directions

The basic assumptions of urban metabolism, its genesis and development, the processes underlying the concept of urban sustainability, the interlinkages between urban metabolism and sustainability, and the limitations of urban sustainability are all covered in this chapter. We also discussed how cities contribute to sustainability, how urbanization has changed people's consumption habits, how pollution from the biogeochemical cycle of materials affects cities, and how to more effectively use the components of urban metabolism in policy-making to advance urban development. The study of urban metabolism is crucial to creating sustainability in the cities. These investigations might also open up fresh insights on how urban areas can grow without contributing to environmental concerns more quickly. Despite the enormous difficulties in reconciling the equally important issues of eco-environmental preservation and urban expansion, cities should always be aware of their inputs to sustainability from the point of view of urban metabolism. Despite an increase in research on urban metabolism over the last two decades, there continue to be numerous unanswered questions, such as:

1. Large cities must first establish a comprehensive and all-encompassing structure that makes the collection and sharing of data possible. If we are to consider sustainability seriously, then the significance of a single city and its worldwide influence is expanding, and there is an increasing need to record the corresponding material flows. As a result, the framework should be necessarily practical and standardized to enable the measurement of metabolism and to enable comparisons between other cities, particularly those in developing nations.
2. Urban metabolism studies should investigate the specifics inside an urban system to assist urban planners. Research must be combined at many scales, chiefly with specific geographic areas, human activities, and economic circumstances, in order to gain insight into the issues that arise throughout urban growth. This depends not just on attempts to close the data gap but also on the integration and use of cutting-edge technologies like geographic information systems, remote sensing, and information networks.
3. To effectively serve all of the stakeholders in a city, urban metabolism research with a more interdisciplinary component may be established. Urban metabolism encompasses a variety of viewpoints on biology, technology, sociology, and economics. By combining these viewpoints, it is feasible to perform additional studies utilizing more comprehensive methodological options. By incorporating policymakers and various local stakeholders in problem-solving, for instance, sociological and psychological approaches should be taken into consideration, which is in line with the initiatives now being made by some cities.

Overall, there is still more work to be done, and these suggestions can aid in coordinating data and methodological decisions in the next studies on sustainable cities.

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