HUNGARIAN UNIVERSITY OF AGRICULTURE AND LIFE SCIENCES

THE ROLE OF GREEN INFRASTRUCTURE FOR URBAN METABOLISM IN AMMAN

SPATIALIZING URBAN METABOLISM: FRAMEWORK FOR RESILIENCE AND SPATIAL JUSTICE

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CHAPTER 1. INTRODUCTION

1.1 Overview and Background

Cities are not static piles of buildings but complex, dynamic systems that consume, transform, and expel energy, water, and materials. Understanding these metabolic flows is critical for urban sustainability, the relationship between the metabolic flows, spatial justice and our complex human experience is an important element discussed in the upcoming subchapters.

1.1.1 Urban Metabolism: Context and Relevance

Cities today function as highly complex socio-ecological system-dense organisms that continually exchange energy, water, materials, information, and human activity. Urban Metabolism (UM) emerged historically from this recognition. Beginning with Wolman's (1965) metabolic model and later expanded by systems ecologists such as Odum, Baccini, and Brunner, UM became one of the earliest frameworks attempting to understand cities not only as built environments, but as living metabolic systems whose sustainability depends on the balance between inputs, outputs, accumulation, and circulation of resources.

While first developed as a largely quantitative tool, focused on measuring energy use, water consumption, waste flows, and emissions. UM has progressively evolved into a broader conceptual lens. Today, UM allows researchers and planners to trace how environmental burdens are produced, where resource pressures accumulate, and how material and ecological flows shape urban form, climate, and human wellbeing. Its relevance lies in its ability to reveal patterns that remain invisible through traditional planning approaches: hotspots of vulnerability, infrastructural inefficiencies, inequities in environmental quality, and the hidden costs of the daily functioning of the city.

Within the complex urban systems and planning of the cities, in a metabolic perspective, green infrastructure (GI) occupies a unique position. Although GI constitutes only a small component of the wider biotic flow (as outlined by Tillie in the IABR Rotterdam study, and Kennedy in his flow analysis), it is just one element within ecosystems, but it intersects with nearly every major urban metabolic flow. Unlike other single flows (Based on metabolic system studies beginning with Kennedy, IABR, and MoC datasets the least cross-connected flows are mobility, materials, solid wastes and energy), GI simultaneously influences multiple dimensions of urban performance: it cools microclimates, mitigates energy demand, improves air quality, stormwater, enhances walkability, supports biodiversity, and improves the lived experience of residents. This multi-scalar, crossflow influence gives GI a distinctive metabolic relevance. It is not the central "controller" of metabolism, but it operates as one of the few urban components capable of directly modifying several flows at once, thereby offering planners and landscape architects an accessible and effective entry point into metabolic thinking.

For this reason, this dissertation examines the potential of GI as an applied diagnostic instrument within UM. Rather than seeking to redefine GI as a core metabolic flow, the study argues that its spatial distribution, quality, and performance can reveal deeper metabolic conditions like inefficiencies, inequities, and environmental vulnerabilities. By focusing on GI, this research develops a multi-method diagnostic toolkit capable of analyzing flows at material, climatic, ecological, and experiential scales. This includes microclimatic simulation, species-level metabolic assessment, street-level profiling, policy and governance analysis, and spatial-equity mapping. Each tool is positioned not to simplify the complexity of UM, but to translate it into operational knowledge available to planners and decision-makers.

The study's relevance is further strengthened by its focus on Amman, a rapidly expanding city in the Global South facing acute challenges: arid climate, chronic water scarcity, severe spatial inequity, fragmented governance, and limited green infrastructure. The metabolic pressures in Amman are intensified by socio-economic disparities and uneven spatial development, conditions that make the city an ideal prototype for testing how GI-based diagnostics can reveal both environmental and social metabolic imbalances. Because UM is deeply context-dependent and shaped by political, economic, and cultural conditions, this dissertation does not pursue universal generalizations. Instead, it argues that Amman's metabolic characteristics provide a critical lens for understanding how inequitable distributions of GI, climate burdens, and resource flows influence the resilience and wellbeing of communities in similar arid, resource-stressed cities.

A final layer of this research is the integration of social and spatial equity into the metabolic framework. Although people are an essential component of every city's metabolism, prior UM literature has largely overlooked the lived experience of residents and the socio-spatial structures that determine their access to environmental benefits. Spatial justice, understood as the fair distribution of environmental qualities, risks, and opportunities, interacts strongly with metabolic flows but remains insufficiently studied. This dissertation therefore bridges UM with spatial-equity analysis, through analysis of GI, microclimate, land value, infrastructure, and neighborhood form contribute to unequal metabolic exposure among different social groups. In doing so, it extends UM beyond efficiency toward a more holistic understanding of environmental justice, resilience, and human wellbeing.

Together, these perspectives position UM as a conceptual and diagnostic framework, capable of analyzing the material functioning of cities, revealing the inequities embedded in their spatial structures, and guiding more resilient, just, and climate-responsive urban design, emphasizing it as a unique urban sustainability tool, that connects different flows all together. The relevance of UM today lies not only in measuring flows, but in interpreting what these flows mean for people, how they shape daily life, vulnerability, opportunity, and the evolving relationship between urban form, GIand society.

Because GI intersects with multiple metabolic flows (climatic, biotic, social, experiential, and regulatory) this dissertation adopts a multi-method approach in which each method examines GI within one specific flow. Rather than being separate case studies, the microclimate simulations, species assessments, street-scale profiling, spatial justice analysis, and governance review collectively form one metabolic inquiry: testing how GI behaves across different layers of UM and what this reveals about Amman's metabolic imbalances.

1.1.2 GI & Socio-Spatial Dimensions

This dissertation places and tests the role of Green Infrastructure (GI) within the field of urban metabolism. Technically, GI can operate as a sub flow in UM while from a spatial aspect it is also a tool we use to develop our surroundings. In urban systems, metabolic incomes and outcomes are rarely distributed evenly, instead, they follow complex spatial, socio-economic, and infrastructural patterns. Identifying how and why these patterns diverge across the city is a challenging task. Because GI is connected to several major urban metabolic flows, it holds significant potential to examine these inequities (particularly those associated with spatial justice) and to evaluate where disparities in environmental quality and metabolic performance emerge.

In this dissertation, GI functions as a probe, an element inserted into different flows (climate, carbon, water, people, policy) to diagnose how urban metabolism flows are affected in Amman. The close relationship between GI and socio-spatial dimensions is not new, many studies have demonstrated that vegetation cover, access to shade, thermal comfort, and ecological amenities tend to reflect broader patterns of spatial inequality. One well-known example is the research in Los Angeles (Jesdale, Morello-Frosch & Cushing (2013), where the distribution of urban tree canopy was shown to correlate strongly with neighborhood income levels and historic land-use decisions finding widely cited across environmental justice literature. Such cases illustrate how metabolic flows tied to climate, water, air quality, and carbon are expressed unevenly across different parts of the city, and how their spatial distribution is rarely neutral. Since GI interacts with several of these flows simultaneously, its spatial pattern becomes an effective lens for uncovering where metabolic burdens accumulate and where environmental benefits are lacking. In short, as seen in the Figure 2. Below, The interrelated cycle, where both flows of UM, have a direct cycle of implications upon each other that is under study.

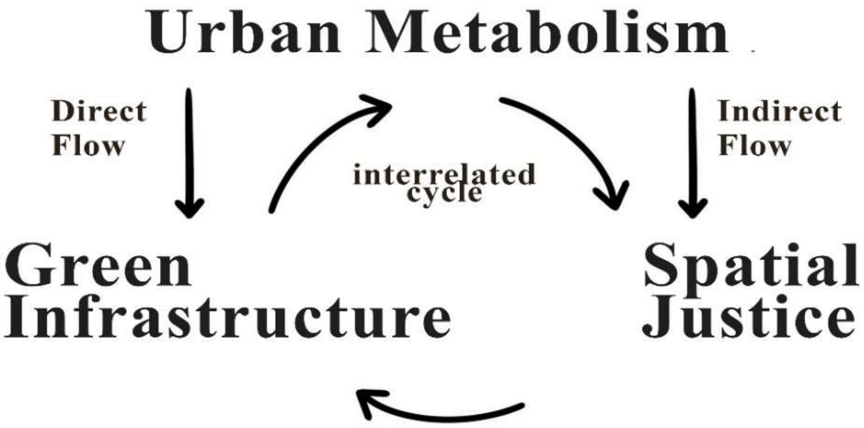


Figure 1. Cyclical relationship between UM, GI and Spatial justice. *(Source: Anas Tuffaha, 2025)*

This interconnected relationship is examined throughout the dissertation by studying how GI links to a range of urban metabolic processes but also looks the other way around where UM gives us insight on how to design and process GI, using its flows, like climate and water usage. The goal is not simply to assess GI by conventional metrics, such as tree species composition, NDVI levels, or green space per capita, although these remain relevant. Rather, the aim is to explore how GI connects with other flows: GI and water usage, GI and carbon sequestration, GI and temperature reduction, GI and spatial injustice, GI and policy-driven disparities in access, and GI within adaptive reuse or design-based applications. The study therefore investigates GI through multiple interrelated methods, each tied to a distinct metabolic process, to reveal how these different flows overlap, interact, and shape conditions of equity and resilience in the city. Finally to reveal how these different flows overlap, interact, and shape conditions of equity and resilience in the city in the study, as seen in Figure 2. where the chosen flows and the rest of UM, have a direct implications upon each other.

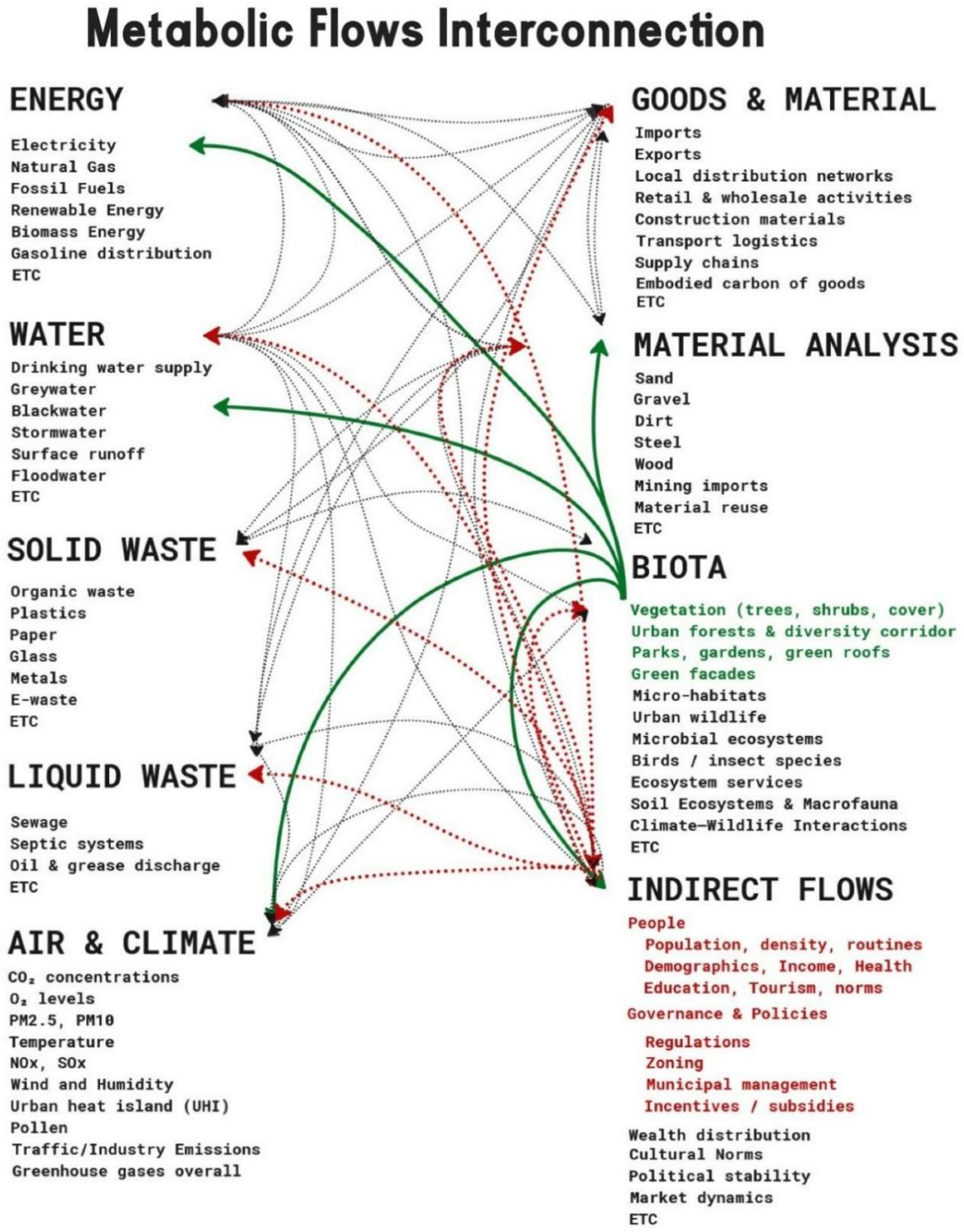


Figure 2. Metabolic flows interconnection diagram. *(Source: Anas Tuffaha, 2025)*

This relationship between flows leaves an implication upon each other, where Indirect flows like people and governance are interconnected with each flow, and GI have a very well connection with the rest, advances the position of importance within the studied flows.

At the end the focal point is also on two parallel imperatives: a diagnostic one, which examines whether GI-based indicators and methods can effectively detect metabolic disparities across

Amman, and a prescriptive aspect, which considers how these insights can inform targeted strategies for improving metabolic performance, reducing environmental burdens, and addressing inequities. Together, these sides reflect the broader ambition of the study: to understand how GI, socio-spatial conditions, and metabolic flows intersect.

1.1.3 Amman as a Case Study, Context, Urgency and Novelty

Amman provides the principal empirical context for this dissertation. As a rapidly expanding Middle Eastern capital, Amman has undergone unprecedented demographic and spatial transformation over the past four decades. With a population exceeding 4.5 million residents and continuing to grow at one of the fastest rates in the region, the city faces mounting pressure on its land, infrastructure, and environmental systems. Despite this rapid growth, there remains a notable scarcity of research addressing its environmental performance, spatial disparities, and metabolic structure. Urban metabolism studies are exceptionally rare in both Amman and the Global South, leaving critical gaps in understanding how resource flows function in arid and socially stratified environments.

Historic Growth

Amman's urban form is a shown by its rapid, often unplanned growth. From a small settlement in the late 19th century with Circassian, Palestinian and Jordanian Bedouin origins, it transformed into a capital city, absorbing multiple waves of refugees, which profoundly shaped its demographic and physical landscape (Daher, 2008). This history has resulted in a fragmented and sprawling metropolitan area, with the population of the Greater Amman Municipality growing from 1.8 million in 2004 to over 4 million by 2015, placing immense pressure on land and infrastructure (GAM, 2015, Alnsour, 2016). A central feature of Amman's urban geography is the well-documented East-West divide, a socio-spatial schism that is fundamentally metabolic in nature (Ababsa, 2011).

Metabolic Assessment and Urgency

In this context, the condition of GI in Amman is extremely limited. Multiple assessments have shown that the city suffers from low vegetation cover, low NDVI levels, and highly uneven green-space distribution (Fzaydat, 2020). This scarcity is not only ecological, it has profound implications for public health, thermal stress, mobility, and social wellbeing. An extensive body of research has demonstrated that access to greenery improves mental health, reduces heat exposure, enhances walkability, and supports both physiological and psychological comfort (Ulrich, 1984, Tzoulas et al., 2007, Gascon et al., 2016). In cities where GI is abundant, such as many European and South American contexts, these benefits are widely documented. In contrast, in arid cities like Amman, where vegetation is severely limited, the absence of GI amplifies metabolic burdens. The city is also among the top 10 most water-scarce countries in the world, exacerbating its vulnerability and limiting the expansion of ecologically functional landscapes. These conditions make the study of metabolic flows, particularly those linked to microclimate, water, and carbon, not only relevant but urgent. In short, these factors in Amman present a clear and critical metabolic profile:

- **Energy Flow:** Dominated by high demand for cooling, exacerbated by a pronounced UHI effect, particularly in asphalt-rich, GI-deprived areas (Al-Shawabkeh et al., 2023).

- **Water Flow:** Deeply unsustainable, characterized by extreme scarcity, a linear "consume-and-discharge" model, and high embodied energy (World Bank, 2022).
- **Biota Flow:** Highly uneven and often treated as an aesthetic amenity rather than critical infrastructure, leading to a systemic "biotic deficit" that compromises climate regulation and spatial justice (Myers & Saadeh, 2020).
- **People Flow:** Shaped by car-dependency in newer western areas and congested, mixed-use streets in the denser east, reflecting and reinforcing the socio-spatial divide (GAM, 2015).
- **Governance & Policy:** A constitutive force that actively shapes the above flows, often entrenching existing inequalities (Ababsa, 2011).

Therefore, Amman is not merely a passive site for data collection but an active collaborator in developing a more responsive UM science. Its struggles provide a powerful lens through which to interrogate the core questions of this dissertation: how GI can serve as a diagnostic and corrective instrument, how spatial justice is a measurable indicator of metabolic health, and how UM insights can be translated into actionable planning in resource-constrained, data-scarce contexts. The insights generated here are intended to provide a replicable model for the countless arid and rapidly growing cities worldwide navigating a path toward sustainable and just urban futures.

Socio Economic and Spatial Justice Situation

The urgency is intensified by Amman's socio-economic landscape. Research by Myriam Ababsa (2011) documents significant spatial disparities between the western/north-western districts and the eastern/southern sectors of the city. According to her analysis: "After 30 years of urban renewal, Amman remains characterized by strong contrast between poor, highly populated neighborhoods and areas with significantly higher education levels, building quality, and infrastructure investment".

This spatial segregation is not merely a matter of income, which is still seen in the maps and demographic studies as in the figure below. It highlights how the city developed into two contrasting halves (West Amman and East) each with distinct physical, social, and economic characteristics.

Her findings describe a city where the western districts exhibit higher land values, better public services, and stronger private investment, while the eastern and southern areas suffer from overcrowding, limited access to social services, and chronic unemployment. This divide is reproduced in land-use patterns, infrastructure provision, and environmental quality.

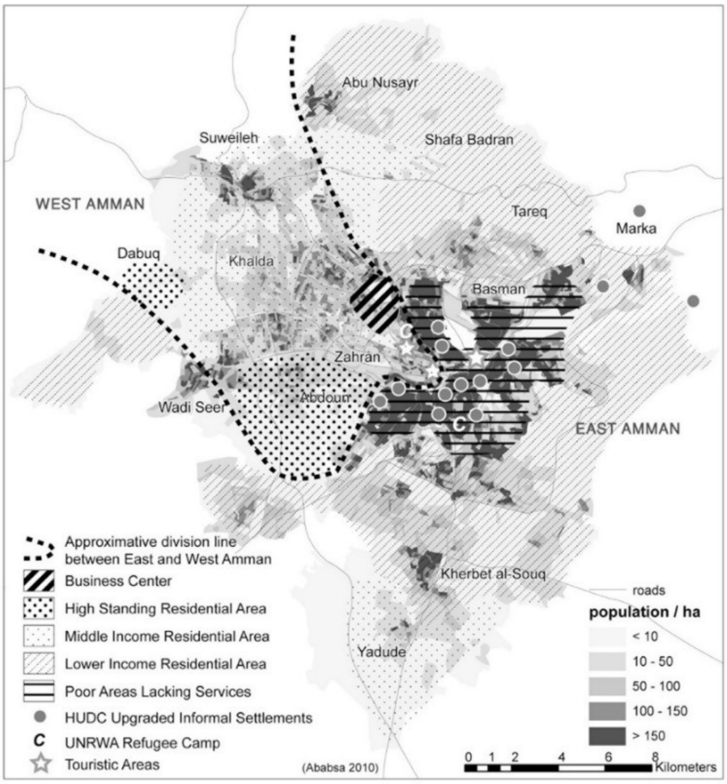


Figure 3. Showcasing an analytical map of Amman's urban morphology, showing the socio-spatial division between East and West Amman. (*Source: originally derived from Abbasa 2010).*

Similar conclusions are echoed in Zaid Fzaydat's study, "Urban GI in Jordan: A Perspective of Hurdles and Challenges" (2020), which highlights the systemic lack of coordination between municipal departments, fragmented governance mechanisms, and the absence of strategic green-infrastructure planning at the metropolitan scale. Such fragmentation reinforces inequities in access to shade, parks, ecological amenities, and climate resilience, conditions that directly affect different flows which ultimately change the metabolic performance.

These socio-spatial disparities, combined with Amman's aridity, water scarcity, and limited vegetation, create a setting in which urban metabolism, GI, and spatial justice are not abstract concepts but living, intertwined realities. Unlike in temperate cities, where high vegetation cover, strong environmental governance, and established planning systems often mitigate inequities (complex as it is), Amman presents a context in which all three dimensions (UM, GI, and SJ) perform at medium to low levels differently. The intersection of these conditions makes the city particularly suited for a metabolic investigation: in summary, GI is scarce, some metabolic flows are stressed, and inequalities are deeply spatialized.

For these reasons, Amman provides not only the empirical basis for the dissertation but also the justification for analyzing UM and using GI as a metabolic diagnostic framework capable of operating within arid, unequal, and rapidly changing urban environments. The city's challenges highlight the need to understand how metabolic flows and spatial justice intersect, and how GI, despite its scarcity, can serve as a tool or pathway for revealing, interpreting, and potentially addressing the environmental inequities embedded in the urban fabric.

1.2 Research Aim, Significance, and Contributions

To move from the contextual foundation laid in the previous section, the research aims are presented in addition to their significance, focusing mainly on GI relation with UM within Amman in addition to theoretical and practical contributions.

1.2.1 Aim of the Study

The aim of this study is to examine GI as an analytical instrument within the framework of Urban Metabolism (UM), and to investigate how its multiple capabilities can be used to understand and interpret the distribution of both direct and indirect metabolic flows, particularly those associated with socio-economic conditions and spatial justice. By positioning GI as a tool familiar to landscape architects, urban planners, and designers, the study seeks to explore how this element of the biotic flow can reveal broader patterns of metabolic performance in cities, especially where vegetation is scarce and environmental burdens are unevenly distributed.

The research aims to analyze how GI interacts with various metabolic processes and to test whether these interrelated dimensions can collectively expose areas of metabolic imbalance. In particular, the study focuses on socio economic and spatial related flows which are understudied as indicated in the literature review later, or what is described by Kennedy as indirect metabolic flows, linked to social, spatial, and economic conditions, to investigate how GI can serve to understand inequities in environmental quality, access, and resilience.

By integrating analysis of tree species selection, microclimatic behavior, GI-related policy frameworks, neighborhood-level spatial disparities, and residents' perceptions of greenery and walkability, the study aims to construct a comprehensive GI-centered metabolic assessment. The overarching goal is to evaluate whether these interconnected layers, when examined together, can illuminate the metabolic challenges of a city like Amman, characterized by extremely low vegetation cover, high climatic stress, and pronounced socio-spatial disparities, and demonstrate the value of GI as a diagnostic and interpretive tool within urban metabolism.

1.2.2 Research Significance

The significance of the study lies in examining this overlapping relationship: metabolic analysis can guide the placement and design of GI, while GI performance is also connected to metabolic flows, this research examines how can GI help correct the imbalances UM reveals but also tries to analyze the relationship between them. This analysis is essential at a time when cities face simultaneous climate, resources, and spatial equity crises, and when socio-economic activities increasingly shape environmental outcomes. This research also sheds a light on the relationship of GI, UM and other metabolic flows, especially non direct ones like equity. The results have abilities to affect design decisions and placement of GI, in addition to understanding more their overlapping relationship in addition to spatial equity as a factor.

This significance is particularly acute for Amman as mentioned in 1.1.3, in which even small shifts in GI distribution or performance can have major impacts on heat exposure, walkability, public health, and neighborhood resilience. In such a context, understanding how GI interacts with metabolic flows is not only academically important, but also crucial for addressing Amman's most pressing environmental and social challenges. This study therefore provides an approach capable of diagnosing metabolic vulnerabilities and guiding more just and climate-responsive planning in a city where these insights are urgently needed.

1.2.3 Expected Theoretical and Practical Contributions:

Theoretical Contributions: The study advances the theoretical landscape of UM in three keyways:

1. **Integrating socio-spatial equity into UM analysis:** The research extends Kennedy's, and the literature review emphasizes the qualitative and quantitative sides of UM, in which the relation between UM and indirect flows posits as essential components of urban performance. While
2. **Positioning GI as an analytical instrument within UM:** The dissertation reframes GI not as a crossflow indicator, capable of revealing thermal burdens, environmental stresses, and inequalities across the city. This conceptual refinement shows how GI performance can reflect metabolic health and expose systemic imbalances.
3. **Proposing a multi-method metabolic diagnostic framework:** By combining microclimatic simulation, species-level metabolic assessment, street-scale imagery, spatial-equity indicators, and policy analysis, the study offers different methodologies for examining metabolism at human and neighborhood scales.

Practical Contributions: The research also provides several practical contributions relevant to designers, planners, and policymakers:

1. **A GI-guided approach for metabolic diagnosis and intervention:** The study demonstrates another opposite direction, how UM directs GI to be used to identify heat stress hotspots, stormwater vulnerabilities, spatial inequities, and environmental burdens, providing actionable insights for targeted interventions in Amman.
2. **Evidence-based guidance for GI placement and species selection:** Through ENVI-met simulations and species-level metabolic profiling, the research offers practical recommendations for maximizing microclimatic benefits, improving cooling efficiency, and enhancing ecological performance in arid environments, a way planners and landscape architects can propose GI in relation with some UM flows.
3. **A framework for integrating metabolic insights into urban policy:** By analyzing zoning, land value, governance fragmentation, and spatial disparities, the study proposes ways in which metabolic findings can inform planning regulations, shading policies, public-space priorities, and resource allocation.
4. **A replicable approach for other cities:** Although focused on Amman, the diagnostic workflow, linking GI, UM, and spatial justice, provides a methodological template that can be adapted, and when repeated can serve guidelines or understandable approaches within nearby cities and neighborhoods.

1.3 Research Objectives and Research Questions

Guiding this investigation there are five interconnected questions. These move from critiquing the historical blind spots in metabolism literature to examining the specific, actionable relationships between infrastructure, environmental flows, and inequality in Amman.

1.3.1 Research Questions: They progress from diagnosing a foundational gap in the field, to proposing GI as a diagnostic lens, and finally to testing its application. RQ1 and RQ2 establish the theoretical gap, while RQ3–RQ5 operationalize this gap within Amman's urban context. Showcasing my brainstorming process to construct a logical pathway from critique to applied knowledge in Amman.

RQ1 — What gaps or limitations within the historical and contemporary evolution of Urban Metabolism literature have surfaced? What has led to the neglect of socio-spatial and socio-economic dimensions? Through a critical review of UM literature, the study examines how the efficiency-oriented origins of UM produced blind spots focusing mostly on qualitative aspects, while spatial equity, neighborhood disparities, and the lived experience of people as an indirect metabolic flow isn't often addressed which this dissertation seeks to address.

RQ2 — What is the relationship between Urban Metabolism and GI, and how do their interactions shape metabolic performance in cities? UM is a complex multi-flow system, with Gi being part of it. Investigating their relationship at a global scale requires massive datasets. Therefore, this research focuses on Amman, where aridity, low vegetation, and spatial inequity make GI–UM interactions particularly visible and critical.

RQ3 — How can GI-enabled diagnostic tools (e.g., microclimatic simulation, street-level imagery, species-level metabolic assessment) and UM flow analysis inform each other in evaluating metabolic performance? This question investigates the **bidirectional relationship**, like how Metabolic analysis reveals where GI is needed, GI interventions modify metabolic outcomes or even how Improvements in GI affect microclimate, carbon, walkability, and equity, and in general the ability to use UM findings to refine GI placement and design priorities.

RQ4 — What is the relationship between socio-economic conditions, spatial justice, governance patterns, and metabolic flows in Amman, and how do these factors influence GI distribution and performance? This question examines how zoning, land value disparities, income-based separation, and neighborhood form shape metabolic inequities, patterns that are strongly visible in Amman's east–west divide, water scarcity, and environmental burdens.

RQ5 — How can the multi-method GI-based metabolic toolkit developed in this thesis support evidence-based planning and decision-making in Amman?

1.3.2 Research Objectives: Each Objective is a result of the research questions asked and analyzed within this dissertation.

Objective 1, Critical literature diagnosis: The aim in this objective is to Conduct a systematic, critical review of UM literature to identify historical and methodological gaps, with particular emphasis on the neglect of socio-spatial and socio-economic (indirect) flows.

Objective 2, Conceptual integration: The next step is to Clarify and operationalize the conceptual relationship between UM and GI, developing a concise theoretical framing that positions GI as an analytically useful, crossflow instrument.

Objective 3, multi-method toolkit development: This objective focuses on Design and to validate a multi-method diagnostic toolkit that integrates street-scale profiling (SVI), NDVI/remote-sensing metrics, species-level metabolic assessment, and microclimatic simulation (ENVI-met) together with spatial-equity indicators.

Objective 4, Empirical diagnosis in Amman: Here the aim is to apply the toolkit to multiple neighborhoods in Amman to map metabolic performance, identify hotspots of environmental burden (heat, water stress, low GI access) and document socio-spatial correlations.

Objective 5, Interpretation of governance and socioeconomic drivers: By analyzing how zoning, land value, governance fragmentation, and socio-economic patterns shape metabolic inequalities and GI distribution, using policy and spatial analysis to link causal mechanisms to observed disparities.

Objective 6, Prescriptive synthesis and policy translation: Finally, to Synthesize diagnostic results into practical, evidence-based recommendations for GI placement, species selection, design interventions, and policy amendments (including zoning and shading guidelines), and assess diminishing returns / metabolic ROI to prioritize interventions.

1.3.3 Alignment Between Objectives, Questions, and Methods:

The questions researched are linked with the objectives formulating important aims and outputs.

Table 1.

Represents the alignment between research questions, objectives and methods

Research Question (RQ)	Corresponding Objective(s)	Expected Output
RQ1 Historical and contemporary gaps in UM literature.	Objective 1 – literature analysis.	Identification of gaps, missing dimensions, need for integration.
RQ2 – Relationship between UM & GI, overlap and metabolic relevance.	Objective 2 – Conceptual integration.	UM–GI framework and suggested tools, definition of GI as instrument and its role in UM.
RQ3 – How GI-based tools and UM flow analysis inform each other.	Objective 3 – Methods toolkit development, Objective 4 – Empirical diagnosis.	A developed diagnostic toolkit, flow assessment, GI–UM bidirectionality.
RQ4 – Relationship between socio-economy, spatial justice, policy, and metabolic flows.	Objective 4 – Empirical diagnosis, Objective 5 – Governance & socio-economic interpretation.	Understanding of socio-spatial metabolic inequalities & governance interconnections in Amman.
RQ5 – How the toolkit supports evidence-based planning and priority-setting in Amman.	Objective 6 – Prescriptive synthesis & policy translation.	Recommendations for GI placement and design in relation to UM study, species choice, zoning updates, shading guidelines, metabolic ROI in Amman.

1.4 Structure of the Dissertation

The argument unfolds across seven chapters. Following this introduction, the literature review establishes the theoretical gap, leading to the methodology, results, and a synthesis that culminates in prescriptive findings for more equitable metabolic planning.

Chapter 1 establishes the conceptual and contextual foundation of the dissertation. It introduces UM, identifies the neglect of dimensions within UM, and presents Amman as the case-study

Chapter 2 traces the historical and theoretical development of UM. It examines the quantitative–qualitative divide in UM, and analyses UM, GI, policies and Urban sustainability concepts.

Chapter 3 outlines research design and methodological logic. Introduces the proposed framework used like policy analysis, street-scale profiling (SVI), microclimatic simulation (ENVI met), species-level assessment etc.

Chapter 4 presents the empirical findings generated by applying the diagnostic toolkit. Reporting the results and applications mostly focused on Amman.

Chapter 5 synthesizes the results into broader interpretations, discussions and applicability.

Chapter 6 consolidates the dissertation’s original contributions into a series of scientific findings. These findings articulate how the dissertation advances UM theory, methodological approaches, and provides insights into GI’s role.

The final chapter offers concise synthesis of the dissertation’s arguments, results, and contributions bringing conceptual, empirical, and prescriptive threads.

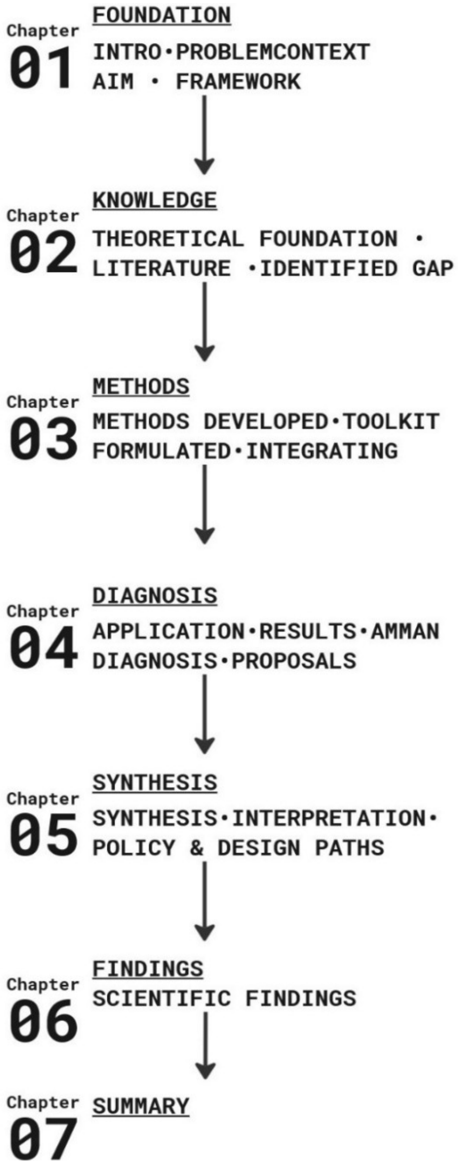


Figure 4. Chapters sequence *(Source: Anas Tuffaha)*.

1.5 Key Concepts and Definitions

This chapter includes a short list of essential definitions required to follow the introduction provided. A more comprehensive glossary and methodological terms are collected in Appendix B at the end of this dissertation.

Urban Metabolism (Wolman, 1965): Cities as socio-ecological organisms that ingest, transform and expel resources: a framework for quantifying material and energy inputs and outputs (Wolman, 1965).

Urban Metabolism (Kennedy et al., 2007): A broader definition that includes both technical and socio-economic processes, i.e., the sum of material, energy and social processes occurring in cities that produce growth, services and waste. Use this when linking flows and policy.

Crucially, it extends beyond biophysical accounting to reveal how these flows reflect power relations (Swyngedouw, 2006), inequalities, and political struggles over resource control (Heynen et al., 2006). Like living organisms, cities depend on these inflows to function and generate outflows (emissions, waste) that strain ecosystems (Baccini & Brunner, 1991). This makes metabolism both a diagnostic lens for urban sustainability and a design imperative for equitable resource circulation.

Metabolic Flows: Circulating streams of energy, water, materials, air/climate effects, biota, people and information that enter, move through, are stored in, and exit urban systems. Flows may be direct (e.g., water) or indirect (e.g., socio-economic activities). They encompass both tangible flows and intangible flows and they function across multiple spatial scales. "Cities are open systems dependent on the inflow of energy and materials, and the outflow of waste and emissions" (Baccini & Brunner, 1991).

GI: is "a strategically planned network of natural and semi-natural areas designed and managed to deliver a wide range of ecosystem services." (European Environment Agency (2011))

Spatial Justice: is the fair and equitable distribution of environmental benefits, burdens, and opportunities across space (Soja, 2010).

Urban Metabolic Health, or Urban Metabolic Stability: The term Urban Metabolic health is not used in UM literature and was introduced and used in some of the previous publications for its connection with the city as an "organism", as a substitute in this dissertation, Urban Metabolic stability will be used, a term used by Pickett et al. (2013) which state that Urban ecosystems have metabolic processes (energy and material fluxes and flows) and their stability depends on maintaining balance among flow, avoiding extreme burdens or inefficiencies, reducing outcomes and finally maintaining ecosystem services and incomes within the planned city.

CHAPTER 2. LITERATURE OVERVIEW

2.1 Historical and Theoretical Foundations of Urban Metabolism

The idea of UM did not emerge fully formed, it evolved through a century of interdisciplinary thought. This evolution began with a powerful metaphor of the city as an organism and progressed into material flows, each stage expanding the framework's analytical scope.

2.1.1 Wolman, Odum, Baccini & Brunner

Early references to the "metabolism" of cities can be traced to the urban thinker Patrick Geddes, who, in Cities in Evolution (1915), described the city as a living organism with circulatory processes and ecological interdependencies. Geddes' contribution, however, remained metaphorical and descriptive, he did not quantify flows, propose a metabolic model, or develop analytical methods. His work provided an early ecological imagination, but it did not constitute UM as a scientific field.

The scientific foundation of UM was established later by Abel Wolman in his landmark 1965 article, The Metabolism of Cities. Wolman operationalized the city-as-organism metaphor by quantifying its inputs and outputs, water, food, materials, and waste, thereby creating the first rigorous metabolic accounting framework. Working with a hypothetical city of one million inhabitants, Wolman demonstrated how urban sustainability could be measured through the balance and efficiency of these flows. His work marked a major conceptual shift: cities could now be examined as measurable metabolic systems with identifiable pressures, inefficiencies, and environmental burdens.

Building on Wolman's foundation, Howard T. Odum extended UM through the lens of ecological energetics. Odum viewed cities as complex energy-transforming systems defined by feedback loops, system boundaries, and energy hierarchies. His work emphasized that urban flows are not linear but cyclical and reactive to external pressures, introducing concepts that remain central to UM: resilience, regulation, and energetic efficiency. Odum's integration of urban and ecological systems helped position UM within broader systems ecology, bridging natural and built environments.

Contributions from Baccini & Brunner in the 1980s and 1990s transformed UM from a conceptual metaphor into a structured analytical method within industrial ecology. Their work on the "metabolism of the anthroposphere" formalized Material Flow Analysis (MFA) and tools for quantifying urban stocks and flows.

Together, Geddes' ecological imagination, Wolman's quantification of flows, Odum's energetic systems thinking, and Baccini & Brunner's industrial ecology approaches represent the multi-layered origins of UM. Geddes provided the initial ecological metaphor, but Wolman created the first measurable metabolic model.

This evolution laid the foundation for the methodological and spatial expansions of the 2000s, from GIS-enabled flow mapping to comparative metabolic indicators for megacities, developments that subsequently brought UM into mainstream urban planning and policy.

2.1.2 The Emergence of Quantification (MFA, SFA, LCA, Energetics)

The methodological evolution of UM accelerated rapidly from the 1970s to the early 2000s, driven by the growing environmental crises of pollution, resource depletion, and urban expansion. As Wolman's original metabolic model demonstrated the feasibility of quantifying urban inputs and outputs, researchers began seeking analytical tools capable of capturing urban systems with increasing precision. This period marks the "quantification era" of UM, in which the field shifted from conceptual analogy to a rigorous, data-driven science. Many advances are central to this transformation: the development of Material and Substance Flow Analysis (MFA/SFA), the adoption of Life Cycle Assessment (LCA), the rise of ecological energetics (emergy analysis), and the integration of GIS and remote sensing for spatializing flows.

Material Flow Analysis (MFA) emerged as the cornerstone methodology of modern UM with the influential work of Baccini and Brunner (1991), who formalized the study of the "metabolism of the anthroposphere." MFA provides a systematic approach for quantifying the stocks and flows of materials entering, circulating within, and exiting urban systems. By treating the city as an open, mass-balanced system, MFA enables the calculation of metabolic efficiency, accumulation rates, and waste generation. This approach has become foundational to industrial ecology and directly informed comparative UM studies, including Kennedy's standardized indicators for megacities (Kennedy et al., 2007), a more simplified application compared to the complexity of MFA. Substance Flow Analysis (SFA) expanded MFA's scope by tracing individual materials like nitrogen, phosphorus, heavy metals, or plastics.

In parallel, Life Cycle Assessment (LCA) introduced a temporal and systemic dimension to metabolic analysis. Rather than focusing solely on the city's immediate flows, LCA evaluates the environmental impacts of materials and processes "from cradle to grave," capturing embodied energy, emissions, and long-term burdens. This methodological shift enabled UM to be linked to climate action, carbon accounting, and long-term sustainability assessments, reinforcing cities as key sites of environmental responsibility.

Further development came from ecological energetics, particularly the work of Howard T. Odum and subsequent emergy analysis. These approaches treat energy quality, transformation pathways, and ecological work as an important to understanding urban function. Emergy accounting emphasizes that cities depend disproportionately on high-quality external energy sources, revealing structural dependencies and vulnerabilities.

The final methodological leap was the integration of Geographic Information Systems (GIS) and remote sensing in the 1980s and 1990s. These tools allowed metabolic data to be spatialized for the first time. Instead of simple numerical tables of resource inputs and outputs, researchers could now map energy use, heat distribution, waste flows, vegetation cover, and land-use patterns.

Together, MFA/SFA, LCA, emergy analysis, and GIS-based spatialization created the quantitative backbone of contemporary urban metabolism. They allowed researchers to measure flows with unprecedented detail, compare cities systematically, and identify inefficiencies and hotspots. However, this quantification era also introduced a lasting limitation: persistent technical and biophysical bias. Because these tools rely heavily on measurable physical inputs and outputs, they struggled to account for socio-spatial inequity, governance structures, cultural practices, lived experience, or the distribution of environmental burdens. What this review a UM blind spot between what UM can measure and what cities experience, is a methodological gap in the field under focus in this dissertation.

2.1.3 Spatialization and Integrative Phases: Kennedy, IABR, MoC

The early 2000s marked what many scholars describe as the renaissance and integrative phase of UM, when the field moved beyond biophysical accounting toward spatial applications, comparative indicators, and policy relevance. This period is most strongly associated with the work of Christopher Kennedy, whose contributions transformed UM from a largely descriptive metaphor into a standardized diagnostic science.

Kennedy's research developed a comprehensive suite of indicators, water, energy, materials, biota, waste, climate, and people, creating a layered framework for analyzing resource efficiency and environmental performance in megacities. Kennedy moved the concept from ecological analogy to urban policy, developing standardized indicators for megacities and making comparative analysis possible. His work marked a transition from isolated case studies toward benchmarking, revealing metabolic similarities and differences between cities such as London, Tokyo, New York, Cairo, Amsterdam, and São Paulo. This comparative framing demonstrated that UM is not accidental, it is the cumulative consequence of land-use patterns, infrastructure, governance, and economic structure.

Parallel contributions came from Sabine Barles, whose historical analysis of Paris grounded UM in long-term urban development. Her work illustrated how industrial systems, spatial design, and resource management shape the metabolic evolution of cities. Barles helped ground the theoretical in historical and empirical reality, showing how industrial systems, spatial design, and resource management shaped the city's long-term metabolic evolution.

practice-oriented initiatives such as the International Architecture Biennale of Rotterdam (IABR, 2014), which demonstrated how UM could be operationalized in urban planning. The IABR "Urban Metabolism of Rotterdam" project linked flows, heat, waste, water, goods, people, to spatial opportunities and proposed interventions such as green corridors, reactivated industrial zones, and climate-adaptive waterfronts. This study successfully transcended theoretical mapping by translating abstract material and energy flows into a series of visionary spatial proposals. The IABR provided one of the first explicit demonstrations of how UM could guide multi-scalar spatial design, from the metropolitan system down to block-level interventions.

This period is critically defined by its expansion beyond biophysical flows. Scholars linked metabolic accounting to political ecology, governance, public design, and interventions in design, marking a shift from descriptive analysis toward prescriptive and integrative approaches.

This integrative phase also exposed the limits of earlier UM work. While spatialization expanded the field, social and equity dimensions remained neglected and despite strong advances in methodology, most UM studies during this period still focused on European and North American, with a few in east Asia focused on Japan, China and South Korea, leaving Global South cities like my chosen site understudied.

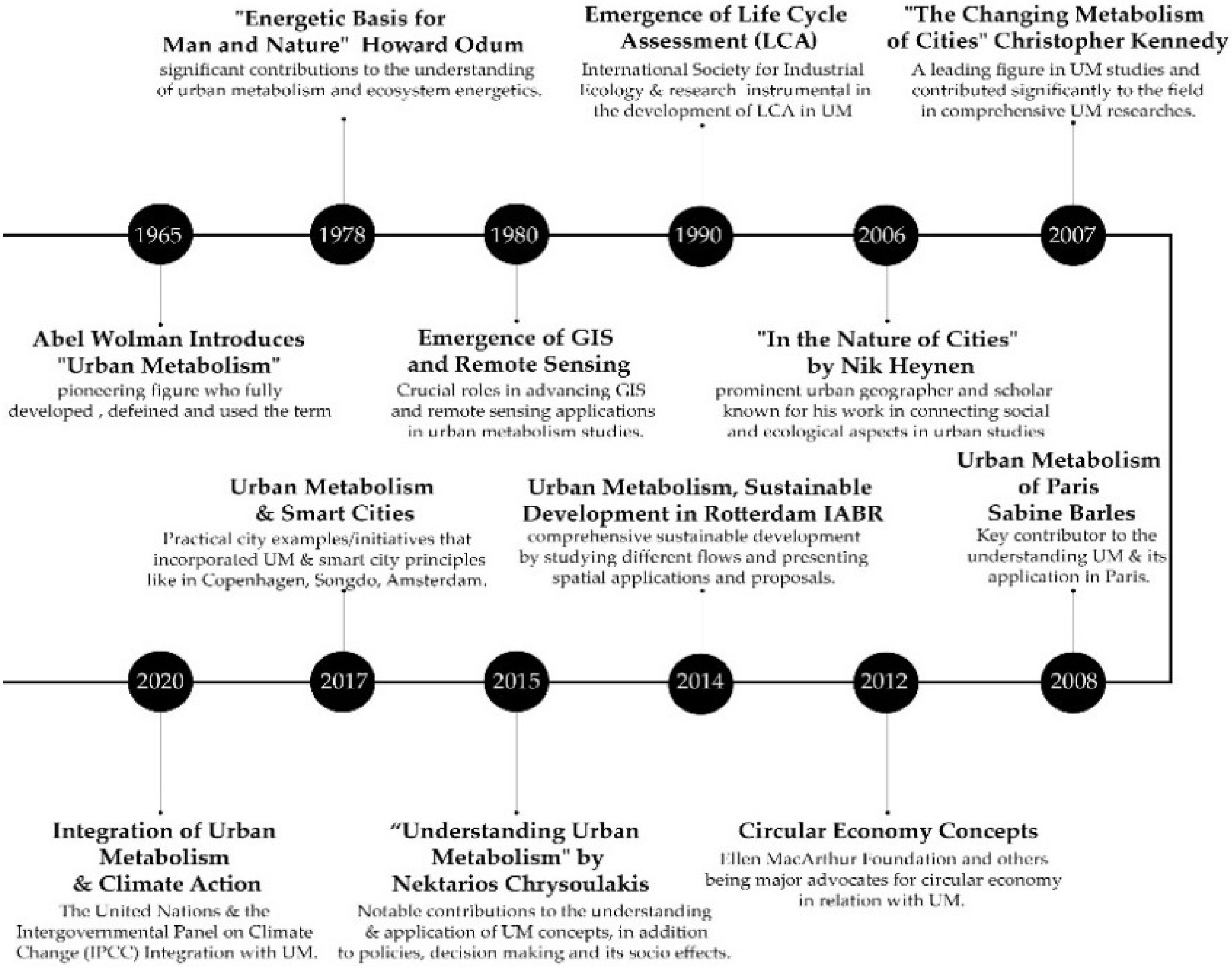


Figure 5. The historical timeline of UM and main nodes, illustrating major conceptual, methodological, and applied developments, as a simplified version of what is included in Sections 2.1.1–2.1.3 *(Source: Anas Tuffaha 2023).*

In summary the evolution of UM can be understood as a gradual expansion from metaphor to quantification, and from quantification to spatial integration.

The timeline above illustrates these milestones, showing how UM has evolved across conceptual, methodological, and applied domains. It also highlights a key insight that motivates this dissertation, despite advances in tools and spatialization, socio-spatial equity and indirect flows remain notably underrepresented in UM research, as will be discussed in the gap analysis in Section 2.2.

2.1.4 Synthesis: From Indications to Applications to Implications.

As the historical evolution of UM demonstrates, the field has progressed through several distinct but interconnected phases. Early work established indications: biophysical measurements that quantify the metabolic functioning of cities through inputs, outputs, and balances (Wolman, 1965, Baccini & Brunner, 1991).

Followed by the subsequent spatial and comparative turn, marked most strongly by Kennedy's indicator framework and practice-oriented studies such as the IABR Rotterdam project, introduced a second phase: applications. In this stage, metabolic data became actionable. Flow maps were translated into spatial scenarios, design proposals, and planning strategies that addressed heat, water, waste, and other interventions.

Yet a third and increasingly unavoidable layer has emerged from political ecology, environmental justice scholarship, and recent GI-equity research: implications. This includes the socio-economic and spatial consequences of metabolic processes, who benefits from metabolic "incomes," who bears metabolic "burdens," and how zoning, land value, governance, and inequity shape these outcomes. The conceptual diagram below synthesizes this historical trajectory as a cyclical movement:

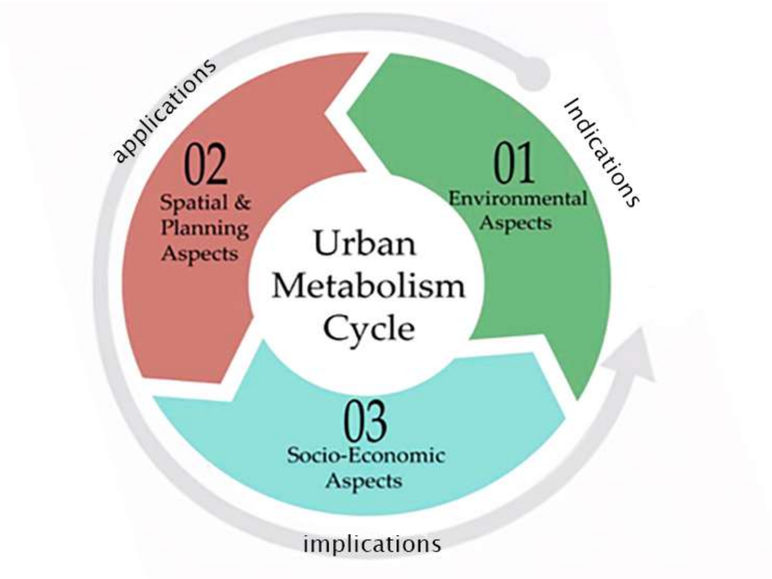


Figure 6. Metabolic cycle: indications, applications, implications. *(Source: Anas Tuffaha,2022).*

Indications – environmental and biophysical signals that reveal pressures and flows. Applications – spatial, design, and planning responses informed by metabolic understanding. Implications – socio-economic and justice-related outcomes that emerge from & feed into the cycle.

Placing UM within this cycle clarifies why the contemporary field must integrate environmental analysis with spatial design and socio-economic interpretation. It also explains why approaches that address only one stage, such as biophysical side, cannot fully diagnose metabolic inequity. This dissertation adopts this three-part logic: by using GI as a crossflow element to show indications, test applications, and reveal implications across Amman's uneven socio-spatial landscape.

2.2 The Quantitative–Qualitative Divide in UM Literature

Despite UM's evolution, my review of many essential UM literature reveals a divide. Often at the expense of understanding how these flows are spatially distributed and socially experienced.

2.2.1 From Efficiency to Equity

The historical evolution of UM reveals a persistent epistemological divide between quantitative, efficiency-oriented metabolic accounting and qualitative, socio-spatial interpretations of how flows are experienced, governed, and distributed. UM has historically been shaped by biophysical accounting traditions, rooted in engineering, industrial ecology, and systems energetics driven by the efficiency paradigm like measuring inputs, outputs, and resource balances.

In other words, the question that dominated UM for four decades was: "How much does the city consume?" not "Who benefits or suffers from these flows?" This efficiency paradigm shaped nearly all high-impact UM studies until the 2010s. In my analysis, the earliest generations of um research were rooted in resource balance models that treated the city as a technical system rather than a socio-spatial one. These approaches excelled at diagnosing efficiency but were blind to distribution, access, or environmental justice.

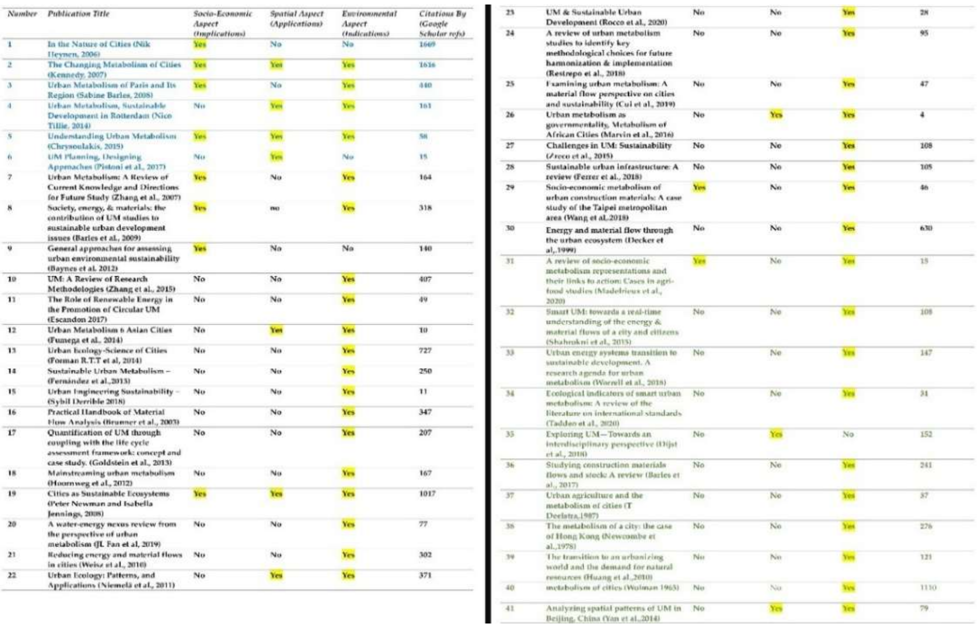
To empirically verify this problem, this dissertation conducted a structured review of 41 highly cited um publications, chosen based on citation influence and disciplinary diversity (Full dataset in appendix C). Each publication was coded across three analytical dimensions: environmental/biophysical aspects, spatial aspects and socio-economic aspects.

1. **Quantitative Flows:** The tracking and measurement of physical inputs and outputs (e.g., energy in GJ, water in m^3, materials in tons, waste, carbon emissions).
2. **Spatial Aspects:** The explicit consideration of urban form, land use, geographic distribution of flows, infrastructure layout, or the spatial implications of metabolic processes.
3. **Socioeconomic Dimensions:** The analysis of policy drivers, governance structures, economic incentives, social equity, inequality, public perception, or behavioral patterns related to metabolic flows.

The publications were coded for their engagement with quantitative flows, spatial aspects, and socio-economic dimensions. The process was not mutually exclusive, and a single article could be coded for different dimensions if it is integrated within them.

Finally, the citations count was borrowed in 2022, from Google Scholar because it is the largest interdisciplinary citation index. It captures books, reports, and cross-field publications (unlike Scopus/Web of Science), which generally includes many important UM Publications that span environmental science, geography, planning, engineering, and design making it a challenge. The focus of the citations count was not the journal prestige, but to identify influence.

These patterns are visualized in Figure 7 below, and the complete classification table is presented in Appendix C (Table C1).



Number	Publication Title	Socio-Economic Aspect (Implications)	Spatial Aspect (Applications)	Environmental Aspect (Indications)	Citations By (Google Scholar refs)
1	In the Nature of Cities (Nik Heynen, 2006)	Yes	No	No	1669
2	The Changing Metabolism of Cities (Kennedy, 2007)	Yes	Yes	Yes	1636
3	Urban Metabolism of Paris and Its Region (Sabine Barles, 2008)	Yes	No	Yes	440
4	Urban Metabolism, Sustainable Development in Rotterdam (Nico Tillie, 2014)	No	Yes	Yes	161
5	Understanding Urban Metabolism (Chrysoulakis, 2015)	Yes	Yes	Yes	58
6	UM Planning, Designing Approaches (Pistoni et al., 2017)	No	Yes	No	15
7	Urban Metabolism: A Review of Current Knowledge and Directions for Future Study (Zhang et al., 2007)	Yes	No	Yes	164
8	Society, energy, & materials: the contribution of UM studies to sustainable urban development issues (Barles et al., 2009)	Yes	no	Yes	318
9	General approaches for assessing urban environmental sustainability (Baynes et al. 2012)	Yes	No	No	140
10	UM: A Review of Research Methodologies (Zhang et al., 2015)	No	No	Yes	407
11	The Role of Renewable Energy in the Promotion of Circular UM (Escandon 2017)	No	No	Yes	49
12	Urban Metabolism 6 Asian Cities (Fumega et al., 2014)	No	Yes	Yes	10
13	Urban Ecology-Science of Cities (Forman R.T.T et al, 2014)	No	No	Yes	727
14	Sustainable Urban Metabolism – (Fernández et al.,2013)	No	No	Yes	250
15	Urban Engineering Sustainability – (Sybil Derrible 2018)	No	No	Yes	11
16	Practical Handbook of Material Flow Analysis (Brunner et al., 2003)	No	No	Yes	347
17	Quantification of UM through coupling with the life cycle assessment framework: concept and case study. (Goldstein et al., 2013)	No	No	Yes	207
18	Mainstreaming urban metabolism (Hoornweg et al., 2012)	No	No	Yes	167
19	Cities as Sustainable Ecosystems (Peter Newman and Isabella Jennings, 2008)	Yes	Yes	Yes	1017
20	A water-energy nexus review from the perspective of urban metabolism (JL Fan et al, 2019)	No	No	Yes	77
21	Reducing energy and material flows in cities (Weisz et al., 2010)	No	No	Yes	302
22	Urban Ecology: Patterns, and Applications (Niemelä et al., 2011)	No	Yes	Yes	371
23	UM & Sustainable Urban Development (Rocco et al., 2020)	No	No	Yes	28
24	A review of urban metabolism studies to identify key methodological choices for future harmonization & implementation (Restrepo et al., 2018)	No	No	Yes	95
25	Examining urban metabolism: A material flow perspective on cities and sustainability (Cui et al., 2019)	No	No	Yes	47
26	Urban metabolism as governmentality, Metabolism of African Cities (Marvin et al., 2016)	No	Yes	Yes	4
27	Challenges in UM: Sustainability (Zreco et al., 2015)	No	No	Yes	108
28	Sustainable urban infrastructure: A review (Ferrer et al., 2018)	No	No	Yes	105
29	Socio-economic metabolism of urban construction materials: A case study of the Taipei metropolitan area (Wang et al.2018)	Yes	No	Yes	46
30	Energy and material flow through the urban ecosystem (Decker et al,.1999)	No	No	Yes	630
31	A review of socio-economic metabolism representations and their links to action: Cases in agri-food studies (Madelrieux et al., 2020)	Yes	No	Yes	15
32	Smart UM: towards a real-time understanding of the energy & material flows of a city and citizens (Shahrokni et al., 2015)	No	No	Yes	108
33	Urban energy systems transition to sustainable development. A research agenda for urban metabolism (Worrell et al., 2018)	No	No	Yes	147
34	Ecological indicators of smart urban metabolism: A review of the literature on international standards (Taddeo et al., 2020)	No	No	Yes	31
35	Exploring UM—Towards an interdisciplinary perspective (Dijst et al., 2018)	No	Yes	No	152
36	Studying construction materials flows and stock: A review (Barles et al., 2017)	No	No	Yes	241
37	Urban agriculture and the metabolism of cities (T Deelstra,1987)	No	No	Yes	37
38	The metabolism of a city: the case of Hong Kong (Newcombe et al.,1978)	No	No	Yes	276
39	The transition to an urbanizing world and the demand for natural resources (Huang et al.,2010)	No	No	Yes	121
40	metabolism of cities (Wolman 1965)	No	No	Yes	1110
41	Analyzing spatial patterns of UM in Beijing, China (Yan et al.,2014)	No	Yes	Yes	79

Figure 7. Summarizes the distribution of key themes across 41 highly cited UM publications. (The complete classification table, including publication metadata, aspect coding, and citation counts, is provided in Appendix B), *(Source: Anas Tuffaha 2023).*

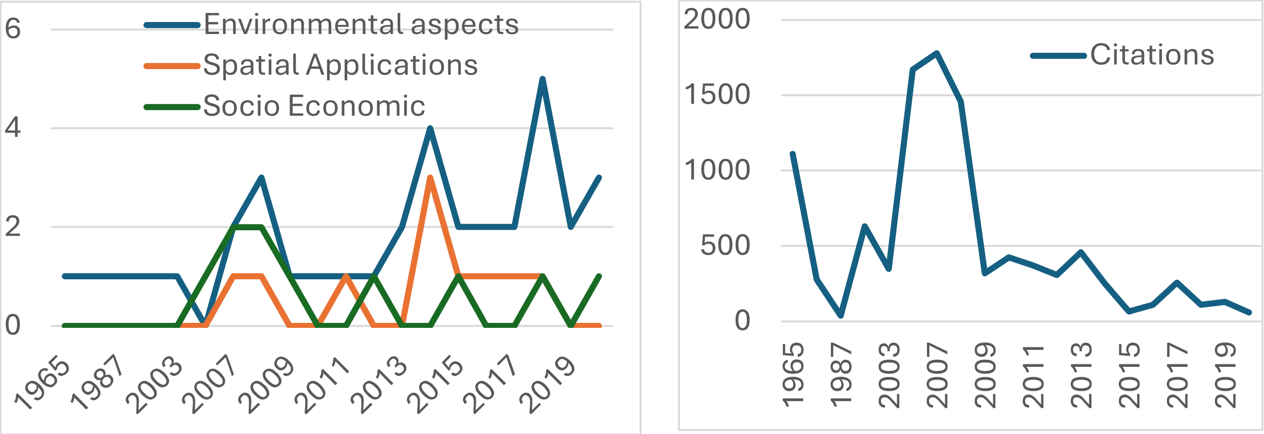


Figure 8. The list presented in two graphs showing the frequency of aspects and citations used. *(Source: Anas Tuffaha 2023).*

The results were clear, over 85% of the reviewed publications were primarily environmental/biophysical, fewer than 40% engaged meaningfully with spatial distribution, only ~25% engaged with socio-economic or justice-related issues.

The meta-analysis confirms a critical, structural imbalance in UM scholarship. quantitative flows dominate over spatial and socio-economic dimensions, revealing a persistent divide.

This divide is not a critique of the field's legitimacy. Instead, it reflects the historical evolution of UM and reveals a gap that contemporary research including this dissertation addresses where um diagnosis efficiency a lot more than equity, access, or lived experience.

2.2.2 Limited Consideration of People and Spatial Justice

The second gap revealed by the literature review concerns the near-total absence of "people as a metabolic flow." In which across the 41 influential publications:

Human factors like perception, comfort, behavior, and governance appear in around 10% of studies, while no foundational publication prior to 2007 treats people as a flow on par with energy or water. Finally, Socio-economic and spatial equity dimensions are the least represented categories in the entire dataset.

This leaves a conclusion in which, people are not passive inhabitants of the urban system, they are the primary agents who generate, modify, and experience metabolic flows. Yet people as a flow' was the least analyzed category in the entire corpus as presented in the figures below extracted from the previous table and detailed in Appendix C.

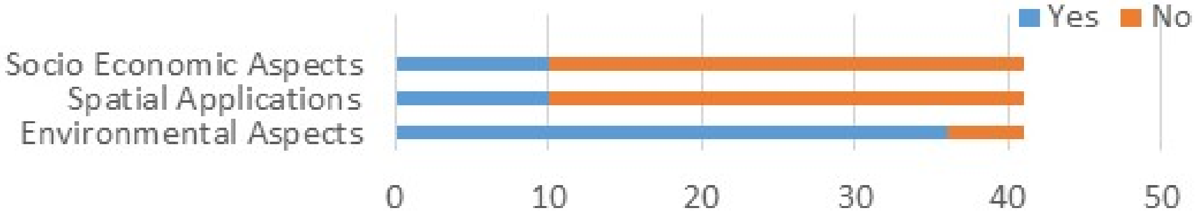


Figure 9. The classification of the publications within their represented aspects in UM *(Source: Anas Tuffaha 2023).*

This finding becomes even more significant when cross-referenced with political ecology scholarship. Heynen, Kaika & Swyngedouw (2006) demonstrated that resource flows are inherently political, embedded in power structures. However, this theoretical breakthrough did not produce a corresponding methodological revolution. In summary, UM can calculate kilowatt-hours, cubic meters, and tons.

But it cannot, in its classical form, explain many other aspects like who overheats, who lacks access to shade, which neighborhoods suffer metabolic burdens, how zoning or land value shape flow distribution, or how GI scarcity maps onto socio-spatial inequality. It is structurally not completely equipped to diagnose metabolic injustice because of its complexity to analyze, nevertheless its relationship with the metabolic flows are essential untapped opportunities.

2.2.3 Summary of Findings from the Structured Literature Review

The structured review of 41 influential UM publications provides a clear, empirical foundation for understanding the epistemological and methodological evolution of the field. The full classification of these publications, including authors, year, publication type, thematic dimensions, and citation counts, is presented in Appendix C (Table C1). Together, these findings validate the theoretical gap identified in Sections 2.2.1 and 2.2.2 and support the fundamental rationale of this dissertation.

1. Dominance of Quantitative, Biophysical Approaches

across the corpus, biophysical and environmental aspects were overwhelmingly represented. more than 85% of publications relied primarily on quantitative metabolic accounting, energy balances, water flows, material stocks, waste generation, emissions, or exergy analysis. This confirms the field's historical roots in industrial ecology and systems energetics. The meta-analysis confirms a critical, structural imbalance in UM scholarship. quantitative flows dominate over spatial and socio-economic dimensions.

2. Underrepresentation of Spatial Dimensions

Despite the spatial nature of cities, fewer than half of the 41 publications engaged meaningfully with spatial patterns, distribution, morphology, land use, zoning, or neighborhood-scale disparities. Studies that did integrate spatial analysis, such as Barles (2008), Goldstein et al. (2013), and the IABR Rotterdam project, were often those that achieved greater conceptual depth and higher citation influence. UM has been predominantly structured around city-wide balances, with limited capacity to map how metabolic flows manifest across different urban terrains.

3. Socio-Economic and Justice Dimensions Are the Least Represented

The most striking insight from the review is the limited treatment of socio-economic, equity, or governance-related aspects. In which Only 25% of the publications addressed: income disparities, governance structures, environmental justice or access to services. Even fewer explored how resource flows are distributed among different populations (metabolic justice).

4. "People as a Flow" Is Almost Completely Missing

The review confirms that people are not conceptualized as metabolic flows in most foundational studies. no pre-2007 study analyzed "people as a flow" quantitatively, only a handful after 2010 even acknowledged it conceptually. people as a flow were the least analyzed category.

5. The Most Influential Studies Were the Most Integrated

Many papers with the high citation count like Kennedy (2007), Heynen (2006), Goldstein (2013), tended to integrate three dimensions (environmental + spatial + socio-economic), even if unevenly. multi-dimensional um studies were the most widely cited, indicating a clear scholarly demand for integrated approaches.

6. Final implications on my dissertation

UM needs diagnostic instruments that can integrate people, biophysical flows, spatial patterns, and social inequities. In addition to discovering the relationship between these different elements under UM's span. This dissertation uses GI as the crossflow probe. In addition to that, UM lacks human scale and spatial methods, in which SVI and ENVI-met in addition to neighborhood level analysis in the dissertation try to address such aspects.

2.3 Green Infrastructure in Urban Metabolism

GI enters the field of UM as both a metabolic agent (modifying temperature, water, carbon, and biotic flows) and a diagnostic indicator of how environmental burdens and benefits are distributed across space. Because GI interacts with several metabolic domains like climatic, hydrological, ecological, and socio spatial. It provides a uniquely positioned lens for understanding where and why metabolic inequalities arise. The following subsections synthesize the scientific literature to establish why GI is essential to this dissertation's metabolic analysis.

2.3.1 GI as a Metabolic indicator (Cooling, Water, Carbon)

Within UM literature, metabolic flows are typically classified into energy, water, materials, climate, waste, and biotic elements like GI (Kennedy et al., 2007, Baccini & Brunner, 1991). Although GI represents only a small fraction of the biotic flow, it directly influences other flows and therefore functions as a crossflow metabolic indicator, a point increasingly recognized in ecological and landscape urbanism scholarship.

GI plays a significant role in the climate and energy flows of cities. Vegetation regulates heat exchange, reduces air temperatures, mitigates the urban heat island (UHI) effect, and lowers cooling energy demand (Bowler et al., 2010, Ziter et al., 2019). These processes involve evapotranspiration, shading, and altered surface energy fluxes, meaning trees and vegetated surfaces operate as thermodynamic agents within the urban metabolic system which influences microclimate regulation.

Through interception, infiltration, evapotranspiration, and stormwater absorption, GI reshapes the water flow of cities (Gill et al., 2007). In arid environments, GI's also have the capacity to slow runoff and improve micro-hydrological performance. Even small GI interventions can create large improvements in hydrological stability in water-scarce cities (Fletcher et al., 2015). According to Kennedy GI can also reinforce metabolic lock-in by maintaining existing linear resources, or unless designed properly reorient urban systems towards better income and outcome results.

Finally, it also has effects on Air quality as a flow, vegetation influences carbon flows, functioning as a carbon sink, oxygen producer, and air-quality regulator (Nowak & Crane, 2002). Species-specific physiological traits (leaf area index, stomatal behavior, transpiration capacity) further determine GI's capacity to modify CO_2 fluxes and vapor exchange, direct metabolic processes. These interactions show that GI is not merely an ecological amenity: it is simply a multi-flow interactor. Unlike grey infrastructure, which usually addresses a single flow GI contributes to climate, carbon, water, and biotic flows at once, giving it exceptional analytical potential for UM as why it's a chosen focal point in my dissertation.

2.3.2 GI Equity, Distribution, and Spatial Disparities

All metabolic flows, like any resource, have their benefits, not evenly distributed across cities. A growing body of evidence shows that GI tends to follow affluence, leaving marginalized neighborhoods exposed to disproportionate metabolic burdens.

Large-scale studies across U.S. and European cities show that neighborhoods with historically lower income or minority populations systematically have fewer trees, less shade, and significantly higher temperatures (Jesdale, Morello-Frosch & Cushing, 2013, Hsu et al., 2021). These patterns create thermal inequity, a direct metabolic inequality.

GI disparities also correlate with air quality degradation, higher pollution exposure, and reduced ecological services in disadvantaged districts (Wolch, Byrne & Newell, 2014). This mirrors metabolic analysis showing that environmental burdens accumulate spatially along lines of economic stratification (Bai et al., 2010).

Finally, it is also tied up with my chosen case study location, as discussed in chapter 1.1.3 earlier in environments like Amman, the consequences of GI scarcity are more severe.

2.3.3 GI and Social–Spatial Justice

Spatial justice literature provides an essential theoretical foundation for linking GI distribution to UM. Henri Lefebvre's *Right to the City* (1968), David Harvey's reinterpretations (1973, 2008), and Edward Soja's concept of "spatial justice" (2010) establish the principle that the organization of space reproduces social power. In my dissertation the relationship is interconnected and goes in both ways

Spatial Justice Meets Urban Metabolism: When integrated with metabolic thinking, this framework allows new questions like:

Who receives the cooling and air-quality benefits of GI? Or Who lives in neighborhoods with higher metabolic burdens (heat, pollution, water stress)? How do zoning, land value, and planning systems mediate these flows?

Swyngedouw (2006) demonstrates that resource flows, water, energy, material, are fundamentally socio-political. Applied to GI, this means that vegetation patterns reflect power, governance, and exclusion, not only environmental conditions.

GI Meets Spatial Justice: The unequal distribution of GI becomes a material expression of injustice, for example:

Less shade leads to more heat stress, and fewer parks could lead to reduced health benefits, and poorer neighborhoods usually have diminished metabolic resilience. These disparities are not simply ecological, they are governance outcomes, tied to zoning, land value, and planning decisions (Brownlow, 2006, Anguelovski, 2016).

While the presence of GI alone does not determine quality of life, a substantial body of literature demonstrates a consistent association between lower GI provision and heightened exposure to environmental burdens, including heat stress, pollution, and reduced access to restorative environments. These disparities are not merely ecological phenomena, but socio-political outcomes shaped by zoning regimes, land valuation, and historical planning decisions (Brownlow, 2006, Anguelovski, 2016).

GI as a Corrective tool: GI can also operate in the inverse direction in which adding a new canopy leads to reduced heat burden**,** shaded streets help increase walkability and eventually equitable GI planning led to improved metabolic flows stability.

This produces a diagnostic–corrective loop, where GI both reveals metabolic inequity and offers pathways to mitigate it.

In a final statement, UM has rarely integrated equity, spatial justice, and socio-economic dynamics into flow analysis, and in from the previous literature review and study aims, GI provides a small capability to aid this missing bridge which is tested in the applications section.

2.4 Urban Metabolism in Practice: Global Cases

This section surveys how UM has been applied in practice across scales, in addition, I focused on how adaptive-reuse and circular projects implement metabolic thinking.

Socio economic effects are also studied, from global case studies, and the practical diagnostic tools the literature recommends. The aim is to show what works at different scales, what is transferable to Amman, and where gaps persist that this dissertation's GI diagnostic toolkit.

2.4.1 UM Across Scales

UM has been operationalized at multiple scales, building / plot, street and neighborhood, district, and metropolitan, each scale revealing different intervention opportunities and constraints.

The Applications on both building level, and on large city levels can be observed and seen in literature, such as Rotterdam's International Architecture Biennale (IABR) project, "Urban Metabolism Sustainable Development in Rotterdam", stands as a seminal example. It successfully transcended theoretical mapping by translating abstract material and energy flows into a series of visionary spatial proposals. The project identified specific metabolic "hotspots", such as waste heat from port industries and stormwater runoff from vast impervious surfaces, and designed targeted interventions like green corridors to channel cool air and repurposed industrial zones for urban agriculture, creating a direct pathway from metabolic analysis to spatial design, the vast difference in scale can be observed in Pistoni, R's (2017) analysis, in addition to Pincetl, S. (2012).

In a similar vein, on a much smaller scale Schoonship a floating neighborhood in Amsterdam operates on explicit circular metabolic principles at a micro-scale. Its design incorporates decentralized renewable energy generation, closed-loop water systems featuring greywater recycling and green roofs for rainwater capture, and shared facilities that reduce material consumption. Crucially, the metabolic performance of Schoonship is monitored in real-time, providing a valuable and rare empirical dataset on the efficacy of neighborhood-scale circular urbanism.

Table 2.

Represents the application of urban metabolism principles across different scales

Scale	Example Projects	Primary Scope & Approach	Key Metabolic Focus
Metropolitan / City Scale / District Scale	Rotterdam's IABR Project (Tillie et al., 2014) Barles' Historical Analysis of Paris (Barles, 2009) [7]. Hammarby Sjöstad (Stockholm).	Systemic Flow Mapping & Strategic Visioning: Uses quantitative data (Material Flow Analysis) to map city-wide flows of energy, water, waste, and materials. Identifies metabolic "hotspots" and leverages spatial planning to propose large-scale interventions.	Connecting abstract flow data to visionary spatial proposals (e.g., repurposing industrial zones, designing green-blue corridors). Informing long-term urban policy and infrastructure investment. shared facilities.
Building / Site Scale	De Ceuvel (Amsterdam), Metabolon (Lindlar, Germany) Schoonschip (Amsterdam) [14].	Circular Retrofit & Phyto-technology: Focuses on adaptive reuse and hyper-local circularity. Use on-site technology and nature-based solutions (e.g.,	Closing resource loops on a single plot. Demonstrating metabolic principles through experimental architecture and landscape design. Real-time

		phytoremediation) to clean soil, manage waste, and generate energy. Employs participatory design and smart monitoring.	performance monitoring. shared facilities.

Kennedy's comparative studies consistently demonstrated that metabolic efficiency is not a simple function of wealth but a complex product of climate, urban form, infrastructure, and technology. The synthesis of this work reveals a clear metabolic hierarchy:

Table 3.

Categorizes cities into a hierarchy of metabolic efficiency

Metabolic Ranking	Example Cities From bibliography	Key Characteristics
More Efficient	London, Seoul, Tokyo, Copenhagen	Dense urban form, significant use of public transit and district energy systems, temperate climate, advanced waste and water management.
Intermediate	New York, São Paulo, Beijing, Shanghai	Mixed characteristics: high density but high energy demand, developing infrastructure, growing industrial and transport sectors.
Less Efficient	Denver, Rotterdam, Calgary, Cairo	car-dependent sprawl, extreme climates requiring high heating/cooling loads, energy-intensive economies.

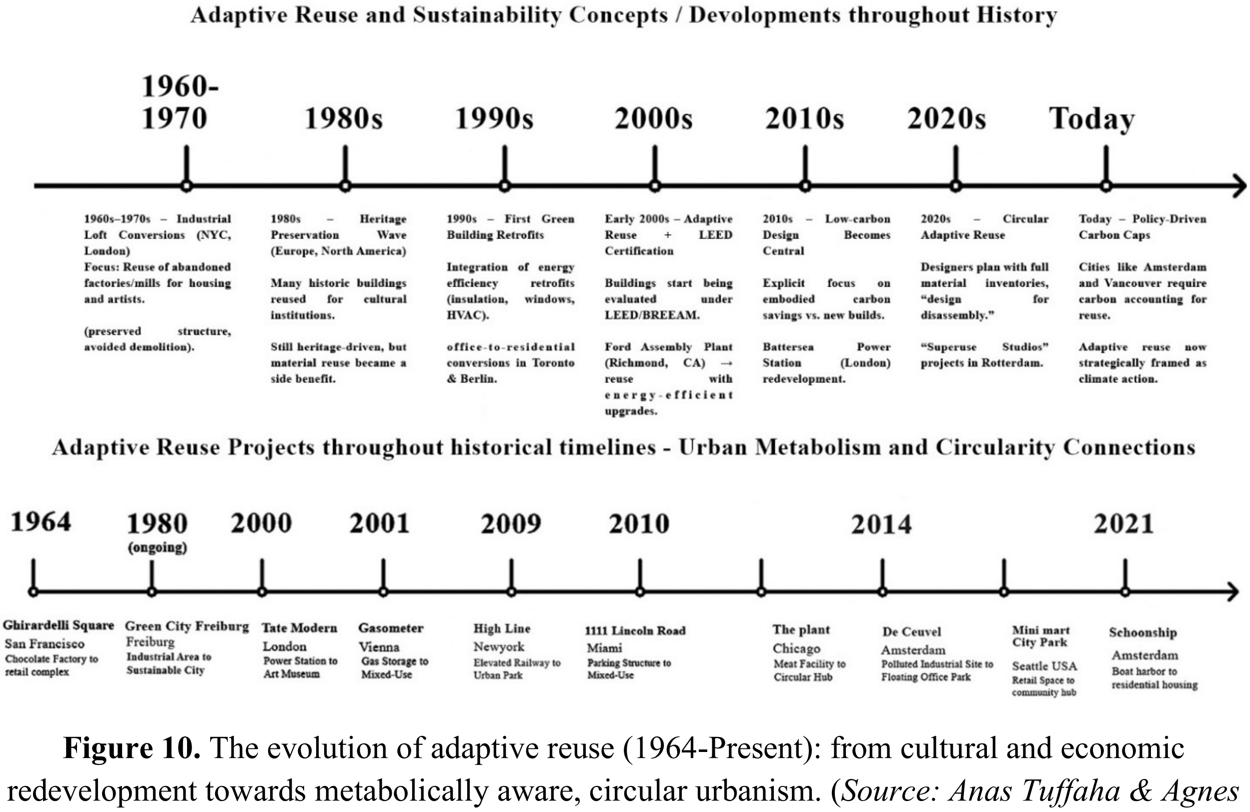
2.4.2 Adaptive Reuse and Flow Recalibration

Adaptive reuse projects provide concrete micro-scale examples of metabolic thinking. On paper, Circular economy principles are tied to adaptive reuse by sharing a very common aim which is the ability to save materials, waste, reusing embodied materials and closing loops. These elements are still embodied from a metabolic perspective by reprograming flows within neighborhoods (energy sharing, greywater), and integrating GI to restore local biotic flow, phytoremediation, and using existing elements to benefit different flows. This shift noticed when analyzing some new urban metabolic projects like De Ceuvel and Schoonship shows how adaptive reuse inherently adopts strategies from urban metabolism, by prioritizing material conservation, minimizing waste, and extending the life of existing structures. adaptive reuse reflects the same principles found in circular economic frameworks on a larger flow basis, showing examples like shared services in neighborhoods to reduce wasted resources in demand, and monitoring real time flows usage and wastes.

These cases are important because they translate abstract flow-mapping into spatial proposals and testable interventions (green roofs, bioswales, shared energy). for global south contexts like Amman, the lesson is not to copy high-tech solutions in particular, but to adapt their principles like using GI to heal polluted areas and soils, prioritize water retention, and target micro-infrastructure (courtyards, street trees, permeable surfaces) that shift neighborhood metabolic performance.

The timeline below illustrates a clear evolution of adaptive reuse and sustainability practices over the past six decades. Early projects, such as Ghirardelli Square (1964) and Tate Modern (2000), emphasized heritage preservation and the purpose of industrial or cultural buildings, retaining embodied energy and minimizing material waste. During this period, adaptive reuse primarily focused on architectural conservation and functional transformation, laying the groundwork for integrating sustainability concepts. Over time, projects began to explicitly incorporate energy efficiency, green certifications, and low-carbon strategies, culminating in contemporary initiatives like Schoon Schip (2021), which actively integrate circular economy principles, shared energy networks, and ecological interventions, demonstrating a sophisticated application of UM at both building and neighborhood scales.

This historical progression highlights the critical distinction between preserving material value and engaging with systemic urban flows. While early adaptive reuse conserved embodied energy and material resources, later projects extended this logic to energy sharing, water management, and GI, aligning more closely with the principles of urban metabolism.



1960s–1970s – Industrial Loft Conversions (NYC, London)
Focus: Reuse of abandoned factories/mills for housing and artists.

(preserved structure, avoided demolition).

1980s – Heritage Preservation Wave (Europe, North America)

Many historic buildings reused for cultural institutions.

Still heritage-driven, but material reuse became a side benefit.

1990s – First Green Building Retrofits

Integration of energy efficiency retrofits (insulation, windows, HVAC).

office-to-residential conversions in Toronto & Berlin.

Early 2000s – Adaptive Reuse + LEED Certification

Buildings start being evaluated under LEED/BREEAM.

Ford Assembly Plant (Richmond, CA) → reuse with energy-efficient upgrades.

2010s – Low-carbon Design Becomes Central

Explicit focus on embodied carbon savings vs. new builds.

Battersea Power Station (London) redevelopment.

2020s – Circular Adaptive Reuse

Designers plan with full material inventories, "design for disassembly."

"Superuse Studios" projects in Rotterdam.

Today – Policy-Driven Carbon Caps

Cities like Amsterdam and Vancouver require carbon accounting for reuse.

Adaptive reuse now strategically framed as climate action.

Figure 10. The evolution of adaptive reuse (1964-Present): from cultural and economic redevelopment towards metabolically aware, circular urbanism. (*Source: Anas Tuffaha & Agnes Sallay, 2024).*

2.4.3 Socio-economic Lessons from Global Cities

Through global cities, research consistently demonstrates that the benefits of GI do not distribute evenly, instead, they closely follow patterns of wealth, power, and historical development. Numerous studies show that greener, cooler, and ecologically healthier environments tend to cluster in high-income districts, while marginalized or lower-income areas receive fewer trees, fewer parks, and substantially higher environmental burdens. This socio-environmental sorting has been documented in cities as diverse as Los Angeles, Mexico City, Beijing, Berlin, and Melbourne, revealing a universal pattern in which GI becomes a spatial expression of inequality (Wolch et al., 2014, Nesbitt et al., 2019, Fernández-Álvarez, 2019, Wu et al., 2018).

For example, Studies in Los Angeles, Chicago, Detroit, and Baltimore show that neighborhoods with higher incomes and higher proportions of white residents possess significantly more tree canopy and cooler surface temperatures (Jesdale et al., 2013, Schwarz et al., 2015, Grove et al., 2018). Conversely, low-income districts show, higher land surface temperatures (Hoffman et al., 2020) and higher exposure to particulate pollution (Clark et al., 2014).

In Mexico City, Fernández-Álvarez (2019) shows a striking correlation between land value, informal settlement patterns, and GI distribution. Wealthier boroughs such as Benito Juárez or Miguel Hidalgo enjoy substantially greater vegetation and lower thermal stress, while informal hillside settlements remain heat-exposed and environmentally underserved.

What emerges from these cases is a form of stratification: neighborhoods with abundant GI experience cooler microclimates, better air quality, stronger biotic flows, and lower exposure to pollution, while under-resourced districts accumulate metabolic burdens, heat, particulate matter, stormwater runoff, and reduced ecological resilience. These disparities cannot be explained by environmental conditions alone, they are shaped by governance decisions, zoning codes, land value dynamics, redevelopment incentives, and decades of socio-economic sorting (Brownlow, 2006, Anguelovski, 2016). In this sense, GI becomes not simply an ecological asset but a marker of political and economic processes, revealing where metabolic “incomes” are concentrated and where metabolic “costs” are offloaded.

A similar pattern is evident in rapidly urbanizing Asian cities, where districts undergoing high-value redevelopment tend to achieve significant greening, while migrant-worker housing and older industrial belts remain exposed to extreme heat and poor air quality. European cities, although generally greener, face a different metabolic dilemma: new parks and green corridors often trigger green gentrification, where environmental improvements raise land values and displace precisely the communities they were meant to benefit (Anguelovski et al., 2019, Haase et al., 2017). Thus, even in greener contexts, metabolic benefits are not guaranteed to be socially equitable.

This creates a metabolic injustice, GI gravitates towards wealthier areas instead of needed areas when strategic planning is missing. the flows of heat, carbon, air, water, and ecological services align with socio-economic hierarchies. It also highlights why UM must incorporate governance, land markets, and socio-economic drivers into its framework. Material flows alone cannot explain why some neighborhoods enjoy cooler temperatures and ecological resilience while others face intensified heat islands and environmental stress.

For contexts like Amman, where zoning codes, land values, topography, and historic demographic patterns have produced a sharp east–west divide, these global lessons are especially relevant.

2.4.4 Review of Foundational Tools from literature

Material flow analysis (MFA) and substance flow analysis (SFA) form the original quantitative backbone of urban metabolism. developed within industrial ecology and improved by Baccini and Brunner, these methods treat the city as an open, balanced system and provide rigorous accounts of the stocks and flows of materials that enter, circulate, and leave urban systems. MFA and SFA allowed researchers to produce the first precise metabolic inventories for cities and to expose hotspots, inefficiencies, and pollution drivers. Because of their mass-balance logic, these methods were central to the quantification era of UM. They delivered numerical clarity where previously there was only metaphor. Yet, by design, they offer limited spatial or social interpretation, MFA tells us how much moves through a city but not how those flows map onto neighborhoods, policies, or lived experience.

Life cycle assessment (LCA) extended metabolic inquiry by introducing a temporal and systemic perspective. LCA reframes impact as cradle-to-grave trajectories and links urban material choices to embodied emissions and long-term environmental burdens. applied to infrastructure, buildings, and urban materials, LCA helped connect um to climate mitigation debates and to carbon accounting. still, the strengths of LCA are its breadth and temporal rigor rather than its capacity to resolve who benefits or who is harmed at the street or neighborhood scale: LCA clarifies life-cycle burdens, but it does not locate their socio-spatial distribution.

Energetics approaches, emergy analysis building on Odum’s systems ecology, emphasize energy quality, transformation pathways, and cities' dependency on high-quality external energy inputs. These perspectives deepen our understanding of systemic inefficiencies and ecological dependencies, revealing how cities are sustained by flows of concentrated energy and materials. Their conceptual power lies in exposing structural vulnerabilities and the real energetic cost of urban lifestyles. yet these methods remain oriented toward system-level diagnosis rather than neighborhood-scale justice: they explain systemic metabolism but not the mechanisms that allocate benefits or burdens unevenly across populations.

The adoption of geographic information systems GIS and remote sensing marked a pivotal spatial turn for UM. for the first time, metabolic data could be mapped and visualized: heat patterns, vegetation cover, land use, energy demand, and water flows could be analyzed in place. gis enabled researchers to ask where flows occur, not only how large they are, and it made possible comparisons between urban form and metabolic outcomes. However, spatialization alone does not automatically produce a social diagnosis, maps show the distribution of temperature or canopy, but they do not by themselves explain the governance, land-market, or policy processes that produced that distribution. in other words, GIS brought UM into space but did not, on its own, bring um into justice.

Practice-oriented frameworks and comparative indicator work, for example, Kennedy’s suite of indicators for megacities, the metabolism of cities platform, and applied projects such as the IABR Rotterdam study, translated metabolic thinking into policy-relevant tools and design proposals. These efforts shaped UM and inspired this dissertation as a tool for benchmarking and strategic planning, linking flow accounting with interventions such as green corridors or circular district proposals. They demonstrated that metabolic thinking could inform spatial design and policy. yet their typical scale is city- or district-level, while invaluable for strategic decisions, these approaches often lack the human-scale granularity and the socio-economic framing necessary to diagnose uneven exposure to metabolic burdens in specific neighborhoods.

More recently, the emergence of 'smart' sensors and real-time monitoring has offered the promise of fine-grained metabolic visibility. where available, these data streams can show temporal dynamics of temperature, air quality, energy consumption and water use at resolutions that were previously unattainable as well as the ability to share resources on a neighborhood level.

Taken together, the literature on um methods shows both extraordinary analytic power and a persistent blind spot. the established toolkit, MFA/SFA, LCA, energetics, GIS, comparative indicators and smart monitoring provides robust ways to quantify, compare and visualize flows, but these methods do not by themselves produce a human-centered, spatially-explicit diagnosis of metabolic injustice. This creates a structural methodological gap in urban metabolism: the lack of human-scale, spatially explicit, socio-economically sensitive diagnostic tools. That gap is precisely what this dissertation addresses. rather than replacing the foundational tools of um, GI as an effective flow and element can be a diagnostic framework developed which builds on their strengths while adding the missing layer: it uses spatial metrics and street-level observation (SVI), species-level physiological analysis, ENVI met microclimatic simulation, and governance/zoning audits to reveal where metabolic burdens accumulate, who experiences them, and how targeted GI interventions can redistribute benefits.

In other words, traditional um tools remain and are essential for quantification and system understanding, but they must be complemented by human-scale, context-sensitive techniques to diagnose and redress metabolic inequities. The methodological synthesis proposed in this dissertation is therefore presented as a necessary extension of the field, the essence is that it keeps the rigor of industrial ecology and energetics while adding the spatial, perceptual and governance lenses needed to turn metabolic diagnosis and by understanding their relationship with each other, while using GI as a pathway for such analysis instead of studying hundreds of flows under the metabolic chain to reach equitable, implementable urban design and policy.

2.5 Amman: Literature Review

Despite its rapid urbanization, environmental stress, and spatial inequities, Amman remains almost entirely absent from the global literature on UM. While cities such as Beijing, Paris, Rotterdam, Tokyo, and São Paulo have been extensively studied, the Middle East, and arid cities more broadly, have received limited metabolic attention. This gap is significant because these cities operate under fundamentally different metabolic conditions than the temperate, resource-rich contexts in which UM methodologies were originally developed, within the context of arid cities, GI tends to be even more important and effective which makes the relationship between GI and UM more emphasized in the dissertation.

2.5.1 Amman's Context and the Limitations of Urban Metabolism in Arid Cities

In the global UM literature, arid cities are severely underrepresented. Studies in the Middle East have typically focused on water scarcity (MWI, 2016), energy consumption (Taleb & Abu-Hijleh, 2013), or heat islands (Al-Shawabkeh et al., 2023), but rarely on metabolism as an integrated socio-ecological framework.

The position of Amman stands out, Jordan is consistently cited as “one of the most water-scarce countries in the world” (World Bank, 2021), a condition that produces structural pressures on every urban process, from household consumption to energy demand, infrastructure planning, and ecological performance. Water scarcity is compounded by climate, as Amman sits in a “hyper-arid to semi-arid zone with exceptionally low natural recharge and high evaporative stress” (Mohsen, 2007), creating a metabolic condition fundamentally distinct from the temperate cities that dominate UM literature.

These climatic pressures intersect with Amman’s extremely low vegetation cover. Several studies note that “green spaces in Amman are scarce, unevenly distributed, and insufficient to meet residents’ environmental needs” (Fzaydat, 2020). The city’s NDVI levels are among the lowest in the region, contributing to intensified heat exposure, reduced ecological buffering, and weakened metabolic resilience. As Fzaydat emphasizes, “Amman’s GI suffers from fragmentation, lack of strategic planning, and large disparities between districts” (2020). These patterns directly shape the city’s metabolic flows, heat, water, carbon, and ecological exchange, making GI scarcity not an aesthetic concern but a metabolic vulnerability.

Ababsa (2011) documents that Amman remains characterized by strong contrasts between poor, highly populated neighborhoods, education and other socio-economic factors, As Daher notes, “Amman’s rapid growth has produced a fragmented urban fabric marked by socio-spatial inequalities that shape residents’ daily environmental experience” (2008). In which It is very important to state how the city grew from a population of 330,000 in 1961 to over 4.5 million by 2022, driven by successive waves of regional migration and refugee inflows (Department of Statistics Jordan, 2022).

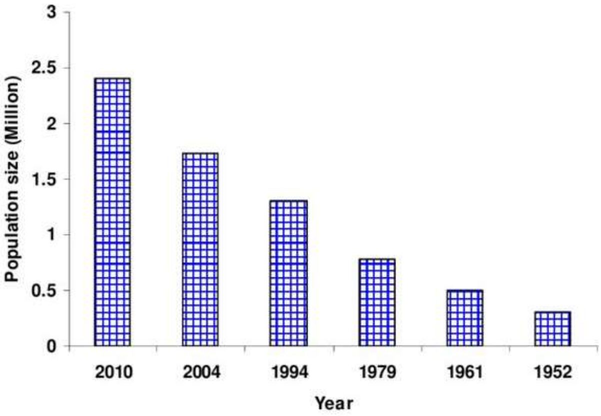


Figure 11. Development of Amman population in the period from 1950s to 2010. *(Source: Zeyad Makhamreh, Analyzing the state of Urban growth in Amman, 2011).*

This positions Amman as a prototype of unique cities with high aridity under urban metabolism analysis. To contextualize Amman’s metabolic condition, it is also valuable to compare it to other Global South cities where metabolic research exists.

Table 4.

Metabolic case studies across the Global south comparative list

City	Climate Type	Existing UM Studies	Dominant Stressors	Key References
Amman	Arid.	None (no full UM studies).	Extreme heat, severe water scarcity, fragmented governance, spatial inequity, low vegetation, car-dependence.	No comprehensive MFA/SFA/LCA studies exist. Spatial inequity documented by Ababsa (2011). GI scarcity highlighted by Fzaydat (2020).
Cairo	Arid / Semi-arid.	Limited UM studies (mainly energy, waste, emissions)	Extreme density, heat, water dependency on Nile, transport emissions.	Included in Kennedy's megacity comparison (Kennedy et al., 2015). Sectoral MFA on materials and emissions exists. Governance fragmentation noted in UN-Habitat reports.
Mexico City	Temperate high-altitude.	Multiple UM-sectoral studies (water, waste, materials).	Pollution, land subsidence, groundwater over-extraction, heat pockets.	Water and material metabolism studied by Barles (2009) and Bai et al. (2010). GI inequity and socio-spatial metabolism highlighted by Fernández-Álvarez (2019).
Beijing	Continental.	Extensive UM research across MFA, LCA, SFA.	Pollution, material throughput, energy demand, heat, rapid expansion.	One of the most studied UM cities globally (Zhang et al. 2015, Kennedy et al. 2015). Rich MFA/LCA datasets. Strong material-flow scholarship.
São Paulo	Subtropical.	Moderate UM literature (energy, water, waste).	Flooding, pollution, inequality, infrastructure stress.	Kennedy et al. include São Paulo in comparative work, strong focus on water & waste metabolism.
Lagos	Humid.	Very limited UM work.	Informal growth, flooding, waste accumulation, water insecurity.	UM gaps highlighted by Bai et al. (2010), no Full metabolism studies.

This comparative table shows that Amman is a good example because it combines several metabolic stressors and deep spatial inequality yet lacks any complete metabolic assessment.

2.6 Synthesis: Theoretical Gap and Need for an Integrated Framework

The historical and methodological evolution of UM reveals a field of significant analytical power yet marked by clear blind spots. As demonstrated throughout this chapter, UM has progressed from Wolman's early quantifications to the sophisticated hybrid approaches of Kennedy, Barles, and the IABR. However, the dominant orientation of the field has remained technical in which UM privileges quantification, efficiency, and biophysical flows, while offering limited engagement with the socio-spatial realities through which cities are lived, governed, and contested. The structured review of 41 influential UM publications has shown conclusively that over 85%

emphasize environmental–biophysical accounting, while fewer than 25% meaningfully incorporate socio-economic or spatial justice perspectives, and “people as a flow” is almost entirely absent. These findings empirically validate a persistent gap between UM’s quantitative efficiency and the qualitative dimensions of urban justice.

This dissertation emphasizes that the gap itself without any integration or showing strength of the divide is not enough, instead it is essential to analyze this qualitative gap and dimensions of urban justice within the urban metabolic flows.

It is also important to state that GI cannot by itself produce justice, and spatial justice cannot be reduced to vegetation patterns alone, the literature review issues many different cases showing the strength of GI, Because of its multi-flow interaction (as established in Section 1.1), and a socio-political artifact shaped by governance, land markets, and planning histories.

Because GI is highly sensitive to socio-economic conditions, its distribution often becomes a material record of inequalities: a phenomenon documented in Los Angeles, Beijing, Mexico City, and many others. What my earlier work described as “the interrelated cycle in which UM flows imply one another” becomes visible most clearly through GI. Environmental burdens such as heat stress, pollution, or stormwater load are metabolically produced, but spatially distributed, they accumulate disproportionately where GI is limited, fragmented, or inaccessible.

UM has the tools to quantify flows but lacks the instruments to interpret their spatial justice implications. GI, precisely because of its crossflow metabolism, offers a viable methodological bridge, not as a definitive measure of justice, but as a diagnostic lens capable of revealing where metabolic burdens concentrate and why. The synthesis emerging from this chapter therefore leads to three foundational insights that justify the dissertation’s methodological direction:

First, the literature demonstrates that UM cannot remain restricted to biophysical accounting. The neglect of socio-economic aspects, people as a flow and even Spatial justice, as argued by Lefebvre, Harvey, and Soja, is not an external add-on but an intrinsic property of urban systems, incorporating it into metabolic thinking is both theoretically necessary and empirically overdue.

Second, GI offers an analytically tractable way to aid this integration. Because it interacts with climate, water, carbon, ecology, human comfort, and land-use policy, GI serves as a crossflow indicator capable of exposing the uneven distribution of metabolic risks and benefits. Rather than being a core element, it is posited as a diagnostic and assisting probe.

Third, Amman’s metabolic conditions and the absence of prior UM studies in the region create a strong argument for developing a new framework. The city’s arid climate, resource scarcity, fragmented governance, and deep spatial inequities represent an extremely common global condition, contributing to UM theory especially with a city lacking GI.

In summary, this dissertation as born from literature review and analysis, shows UM as the analytical tools to measure how flows move, where spatial justice provides the lens to understand who benefits, and who bears their burdens. GI is the medium through which these two dimensions can be connected, not as a universal metric, but as a spatially and expressive diagnostic instrument.

CHAPTER 3 – METHODOLOGY

3.1 Methodologies and Logic

This chapter outlines the methodological logic, analytical framework, and diagnostic tools used to examine GI as an urban metabolic instrument in Amman.

3.1.1 Overall Methodological Approach

The methodological design of this dissertation is structured around a layered diagnostic logic, conceptualized through an analytical metaphor.

This methodology presented in different tools connecting UM AND GI, can be seen in figure 12. Represented conceptually, presenting the dissertation figuratively in the following way:

In this framework, Amman functions as the main laboratory test site: characterized by extreme metabolic pressures. Rather than serving as a representative or average city, Amman is treated as a stress-test environment in which metabolic imbalances are intensified and therefore analytically legible.

Within this laboratory, UM operates as the sustainable urban concept or system. UM provides the overarching structure for understanding how cities function through interdependent flows of energy, water, climate, biota, materials, and people. Each of these flows can be understood as a diagnostic chamber within the broader metabolic system, distinct but interconnected domains through which pressures, inefficiencies, and inequities manifest.

Within and across these metabolic chambers, GI is employed as an analytical lens and crossflow carrier. GI is not treated as an isolated environmental asset, nor as a singular solution. Instead, it is examined as a component that moves across multiple metabolic and in particular lived urban experience as presented in red in figure 12. (people and governance, or spatial justice). By tracing how GI performs, fails, or is absent across these intersecting flows, the research reveals where metabolic burdens accumulate, where benefits are unevenly distributed, and how spatial form, land value, and governance structures shape these outcomes.

Methodologically, the dissertation combines established analytical tools from urban metabolism, urban climate science, and spatial analysis with context-specific applications in Amman. Universal methods, such as microclimatic simulation, spatial mapping, street-level observation, and policy analysis, are not treated as ends in themselves. Rather, they fit into arid, resource-scarce, and socio-spatially fragmented urban contexts. The research does not propose new universal measurement instruments, instead, it demonstrates how existing tools can be reconfigured from UM lens and by being used with GI to address questions that conventional UM approaches don't tackle often, particularly those related to human-scale exposure , spatial justice and how basic methods architects and planners can use in GI could inform us about incomes and outcomes of the city.

This diagnostic–interpretive logic underpins the structure of the tools introduced in the following sections and establishes the foundation for the proposed Urban Metabolic framework developed in this dissertation.

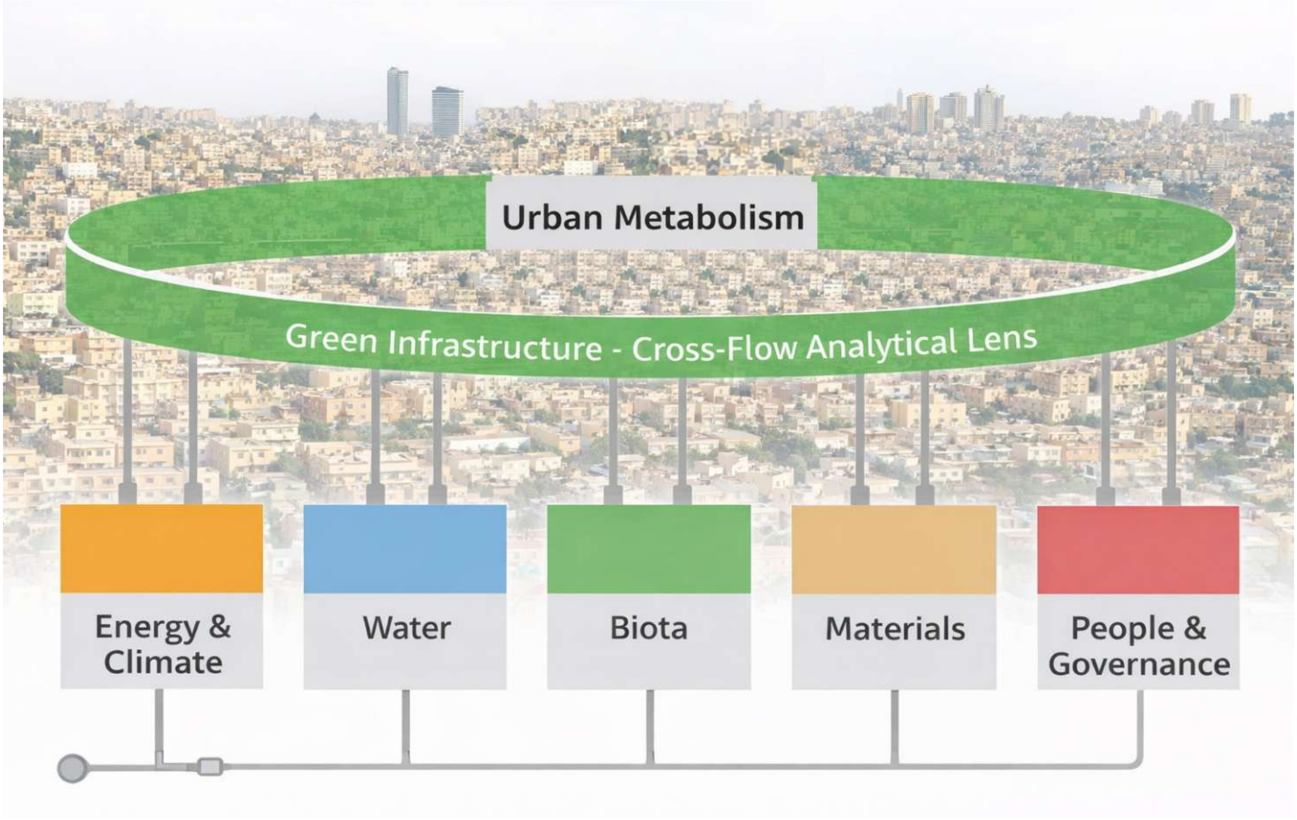


Figure 12. Conceptual representation of the methodological framework. (illustrating Amman as the empirical test zone, UM as the governing analytical system, metabolic flows as diagnostic chambers, and GI as a crossflow analytical lens).

Metabolic phenomena are examined at street, neighborhood, district, and city scales, recognizing that metabolic inequity rarely manifests uniformly across space. Street-scale analysis captures perceptual and experiential conditions, such as perceived greenery, shade, and walkability, that city-wide datasets cannot resolve. Neighborhood-scale simulations reveal how urban form and GI configuration influence microclimate and exposure, while policy and governance analysis operates at all and especially broader scales to identify structural constraints in the cities outcomes.

The research applications also explicitly recognize that metabolic performance has both objectively measurable dimensions like temperature, vapor flux, canopy coverage, and material configuration and subjectively experienced dimensions, such as comfort from surveys or observations, perceived environmental quality, and everyday mobility. These dimensions are not treated as competing forms of knowledge but as complementary layers of diagnosis. Together, they allow the analysis to move beyond abstract efficiency metrics toward a nuanced understanding of how metabolic conditions are produced, experienced, and contested in everyday urban life.

Conceptually, this methodological approach positions GI as both diagnostic and interpretive. It reveals metabolic stress where it is scarce or poorly configured, and it provides a means of testing how targeted spatial interventions could recalibrate flows.

3.1.2 Linking Objectives and Methods

The selection of methods in this dissertation follows directly from the research objectives and the layered diagnostic logic outlined in the previous section.

The first objective, through the literature review in Chapter 2, which helped understand how governance, zoning, and socio-economic aspects are embedded in metabolic studies, necessitates a policy and governance analysis capable of tracing how regulatory frameworks precondition the spatial distribution of GI and environmental burdens. This method addresses indirect metabolic flows, such as governance and institutional decision-making, which remain largely invisible in traditional biophysical UM accounting.

The first tool used is to diagnose human-scale metabolic conditions and lived experience, street-scale metabolic profiling is employed using Street View Imagery (SVI). This method captures perceptual exposure, continuity of greenery, enclosure, and walkability conditions that cannot be resolved through remote sensing or city-scale datasets. It allows indirect metabolic flows related to people, comfort, and daily routines to be operationalized spatially.

To quantify microclimatic effects and test how spatial configurations influence thermal and atmospheric conditions, microclimatic simulation using ENVI-met is applied at the neighborhood scale. This tool enables the research to move from qualitative diagnosis toward measurable metabolic consequences of design decisions and GI configuration, particularly in relation to heat stress, vapor flux, and cooling potential.

Recognizing that vegetation is not metabolically uniform, tree species analysis is introduced to examine species-specific physiological performance. This method allows GI to be treated as an active metabolic agent rather than a homogeneous surface, an especially critical distinction in such environments where cooling capacity, water demand, and carbon exchange vary significantly between species.

In parallel, the dissertation introduces a neighborhood-level urban metabolic performance assessment, applied comparatively across four district-study neighborhoods in Amman. This method synthesizes metabolic flows like climate, biota, people, and governance, at the neighborhood scale, allowing spatial disparities in metabolic performance to be identified and compared.

Finally, spatial justice indicators are employed to synthesize environmental, spatial, and socio-economic findings. This step ensures that metabolic performance is interpreted not only in terms of efficiency, but also in terms of equity, exposure, and access, linking metabolic flows to questions of uneven vulnerability and socio-spatial inequality. It allows us in this dissertation to understand an important research question, testing the relation between UM and GI with the indirect flow (spatial justice).

Together, these methods form an integrated diagnostic system in which each tool addresses a specific analytical gap while contributing to a unified interpretation of UM through GI. The alignment between research objectives, diagnostic tools, and their analytical contributions is summarized in Table 5. Below is an end to Chapter 3.1 presented.

Table 5.

Summary of diagnostic tools used in the dissertation, showing their associated metabolic dimensions, analytical contributions to UM, and practical relevance

Diagnostic Tool	Primary Metabolic Dimension Addressed	Analytical Contribution to UM	Practical Value
Street-Scale Metabolic Profiling (SVI)	GI in relation to People, climate and materials flow.	Operationalizes lived experience, perceived greenery, enclosure, and walkability as metabolic indicators.	Enables architects and planners to diagnose street-level heat stress, shading deficits, and GI continuity.
Microclimatic Simulation (ENVI-met)	Many flows interconnected, mainly GI, and materials formed in relations to Climate, energy, and spatial justice flows.	Quantifies the thermal and atmospheric effects of urban form and GI configuration, giving an ability to link spatial design to measurable metabolic outcomes.	Allow scenario testing of GI and spatial interventions before implementation.
Tree Species as Metabolic Agents	GI in relation to water, air flows, and climate.	Treats vegetation as an active metabolic agent, distinguishing species-specific cooling capacity, water demand, and carbon exchange.	Guides evidence-based species selection for arid and water-scarce urban environments.
Neighborhood-Level Metabolic Performance Assessment	All Flows interconnected.	Provides a holistic metabolic profile of neighborhoods.	Supports comparative diagnosis across neighborhoods and identification of metabolic hotspots.
Policy & Governance Analysis	Governance, spatial justice and People in relation to GI.	Links observed metabolic disparities to zoning, land value, and institutional decision-making.	Supports equitable planning strategies and redistribution of environmental benefits.

3.2 Diagnostic and Solution Based Tools Used

This section presents the five diagnostic and solution-oriented tools selected for this dissertation, each designed to interrogate a specific dimension of UM through the lens of GI.

3.2.1 Tool 1: Street-Scale Metabolic Profiling (SVI Method)

Street-scale metabolic profiling is employed in this dissertation as a human-scale diagnostic tool for analyzing the performance, visibility, and spatial continuity of GI within the urban metabolic system. The method is based on the systematic use of Street View Imagery (SVI), primarily Google Street View, as an analytical lens for capturing how metabolic conditions are experienced at pedestrian levels. While top-down remote sensing (e.g., satellite NDVI, LIDAR) has long served UM studies, it suffers from a critical shortcoming: it does not capture human-scale experience or vertical GI (Wang et al., 2021), such as green walls, trellises, under canopy shade, or small urban trees, Street Metabolism directly addresses this gap.

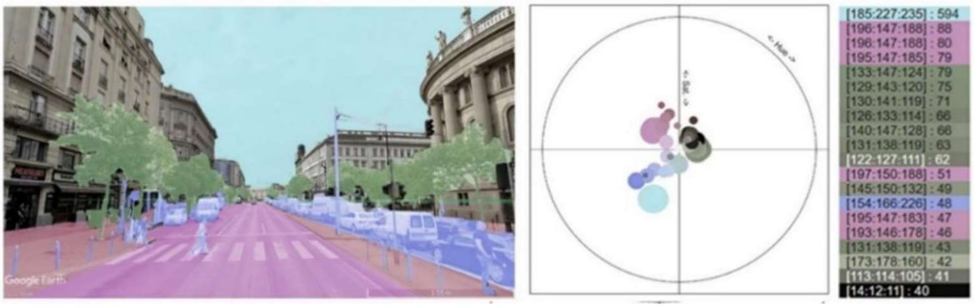
Since the traditional methods do not capture the vertical, perceptual, and experiential dimensions of the street environment. Elements such as tree canopies, vertical greenery, façade vegetation, shaded sidewalks, and micro-scale enclosure, all of which are metabolically active, are often partially or entirely invisible from aerial perspectives. This methodological gap is particularly problematic for GI-focused analysis, where performance is closely tied to human exposure and street-level configuration.

The Street-Scale Metabolic Profiling method directly addresses this limitation by repositioning the street as the primary unit of metabolic observation. In this approach, systematically sampled Street View images are collected along representative street segments within selected neighborhoods. These images constitute a visual cross-section of the urban metabolic environment as encountered by residents, pedestrians, and everyday users.

In this approach, SVI are systematically captured along street corridors in selected neighborhoods. Then these images are analyzed then processed using either manual color sampling (e.g., Photoshop, Illustrator) or automated AI-based object recognition to isolate key metabolic indicators:

- Vegetative coverage (e.g., trees, shrubs, green facades).
- Hardscape prevalence (asphalt, concrete, impermeable surfaces).
- Canopy continuity.
- Human activity and thermal exposure.

Results are then separated in colored pixels for each isolated object, giving percentages of what is perceived in each Google street image as presented in the figure below.



	Percentage of perspective in GSI
Sky	34%
Green	5%
Pedestrian Walkways	22.5%
Buildings & Construction	35.5%
Objects & Street Furniture	3%

Figure 13. Introducing my approach of filtering the image. (separated and numbered colors in IDs to distinguish different objects in a GSI and measure their percentages).

The core analytical logic of the method lies in treating the visible street surface as a proxy for multiple metabolic processes. Vegetation visible at street level is interpreted as an indicator of cooling potential, evapotranspiration capacity, carbon exchange, and microclimatic buffering. Conversely, the dominance of hardscape elements such as asphalt, concrete, and exposed building surfaces signals higher heat retention, reduced permeability, and increased metabolic burden. In this sense, the visual composition of the street functions as a metabolic transcript, encoding information about the balance between productive (green/blue) and burdensome (grey) urban surfaces. Moreover, this methodology enables the creation of "green view indices" (GVIs) at scale, a method recently validated by urban morphology studies in cities such as Singapore, Boston, and Barcelona (Li et al., 2015, Naik et al., 2017).

This also as a tool is much easier for students and planners to use, unlike thermal drones, ENVI-met licenses, or multispectral satellites, Street View imagery is free, publicly accessible, and requires minimal training. When combined with color-thresholding techniques or AI (e.g., semantic segmentation via DeepLabV3), this tool can generate quantitative outputs such as percentage greenness per street segment, identifying areas in metabolic deficit.

Methodologically, the captured SVI images are processed through a structured visual decomposition workflow. Using color-range selection techniques, imagery is segmented into distinct surface categories, including vegetation, impervious surfaces, sky, and built form. The proportional representation of each category is then quantified through pixel-based analysis. While the broader literature often refers to this output as the Green View Index (GVI), in this dissertation it is reinterpreted as a Street-Level Metabolic Performance Indicator (SLMPI), emphasizing its functional relationship to metabolic flows rather than its aesthetic dimension alone.

This reinterpretation is central to the methodological contribution of the dissertation. Rather than treating street greenness as a visual amenity, the method frames it as a measurable indicator of metabolic performance, directly linked to climate regulation, thermal comfort, and environmental exposure. Streets with low SLMPI values are understood as zones of heightened metabolic stress, characterized by increased heat accumulation, reduced shading, and diminished ecological buffering.

The technique can be replicated rapidly across large urban areas and adapted to different levels of technical capacity, ranging from manual image processing to automated classification using computer vision or AI-based segmentation.

Beyond its technical utility, street-scale metabolic profiling introduces an important shift within UM research. Its re-centers human perception and lived experience as legitimate sources of metabolic data, bridging the gap between abstract flow accounting and everyday urban conditions. Empirical research has shown that perceived greenness and aerial vegetation metrics often diverge significantly, especially in dense or vertical urban environments. By capturing what people see and experience, the SVI method complements and corrects top-down metabolic indicators.

Within the framework of this dissertation, Street-Scale Metabolic Profiling serves interconnected purposes. First, it operationalizes indirect metabolic flows related to people, comfort, and daily exposure. Second, it provides a spatially explicit diagnostic of GI continuity and deficiency at the street level, it also goes beyond that, giving quantitative numbers and ratios for different pixels in images, in addition to giving the perceived view of us as users in our daily lives.

3.2.2 Tool 2: Microclimatic Simulation (ENVI-met)

One of the technically advanced tools employed in this dissertation is the use of ENVI-met, a high-resolution, three-dimensional microclimate simulation software. Originally developed by Michael Bruse in the early 2000s, ENVI-met has become one of the most widely validated and research-backed tools for modelling surface/vegetation interactions at the neighborhood scale. While ENVI-met is frequently applied in urban climate studies and environmental design research, its systematic integration into UM as a diagnostic instrument remains limited. This dissertation explicitly addresses that gap by employing ENVI-met as a tool for metabolic flow analysis rather than as a purely comfort-oriented simulation environment.

ENVI-met simulates complex interactions between vegetation, building materials, urban geometry, airflow, radiation exchange, and humidity using spatial grids that can reach resolutions as fine as 0.5–2.0 meters. This level of detail is particularly important for capturing the localized effects of GI, whose metabolic influence operates at micro-scale, often invisible to city-wide or satellite-based analysis. The software produces a range of outputs connected to UM and our environment like:

- Air temperature and surface temperature (energy and climate flows).
- CO_2 flux and concentration (carbon flow).
- Evapotranspiration and vapor flux (water and latent energy flows).
- Wind velocity and turbulence (airflow, dispersion, and comfort dynamics).

These outputs extend beyond descriptive thermal comfort metrics and provide quantifiable indicators of how energy, water, and carbon circulate through urban space. In metabolic terms, ENVI-met allows the city to be analyzed as a thermodynamic and biophysical system, revealing how heat is absorbed, stored, and released, how vegetation modifies atmospheric composition, and how water is retained or lost through evapotranspiration. As such, ENVI-met functions as a micro-scale metabolic mapping tool, aligning directly with UM's focus on flows rather than static form (Kennedy et al., 2007, Baccini & Brunner, 1991).

The relevance of ENVI-met to GI analysis is well established in urban climate literature. Numerous studies have demonstrated that vegetation simulated through ENVI-met significantly reduces near-surface air temperatures, moderates urban heat island intensity, and improves thermal comfort through shading and evapotranspiration (Bowler et al., 2010, Emmanuel & Krüger, 2012, Ziter et al., 2019).

Unlike simplified surface-temperature models, ENVI-met explicitly accounts for plant physiology, canopy structure, soil moisture, and radiation balance, making it particularly suited for evaluating GI performance as a metabolic agent rather than a passive land-cover category, it is also suitable for understanding if GI even has an affect by completely simulating no existing tree or vegetation cover within the same scenario, which has been applied multiple times in my study. In addition to all that, the relationship between surface materials and the distribution of spaces or urban forms with surface temperatures in cities, which can lead to many interesting findings.

A novel methodological contribution of this dissertation lies in how ENVI-met is used to evaluate different urban forms within Amman, forms that are related to positioning of buildings, streets and vegetation. In addition to that species-specific metabolic performance, developed further in Tool 3. By parameterizing different tree species (e.g., *Melia azedarach*, *Olea europaea*, *Ceratonia siliqua*) using physiological inputs such as leaf area index, stomatal resistance, root depth, and transpiration capacity, shifting toward flow efficiency, particularly relevant in environments where water demand and cooling effectiveness vary significantly between species (Shashua-Bar et al., 2011, Middel et al., 2015).

Another critical strength of ENVI-met is its ability to capture temporal dynamics. Simulations are run over 24–48-hour cycles, allowing the analysis of diurnal temperature variation, peak heat stress periods, nighttime cooling rates, and thermal recovery lag. From a metabolic perspective, this temporal resolution is essential: it reveals not only how hot an area becomes, but how efficiently it dissipates accumulated energy, an indicator of metabolic stability rather than momentary comfort. Full details of grid configuration, soil models, boundary conditions, and meteorological forcing data are provided in Appendix C (Simulation Configurations).

Importantly, ENVI-met simulations reveal urban metabolic vulnerabilities. Areas characterized by high proportions of impervious surfaces and minimal vegetation consistently exhibit slow nocturnal cooling, elevated surface temperatures, reduced air circulation, and increased CO_2 concentration.

These are not merely “hot spots” but metabolic pressure points, locations where energy and material flows are inefficiently regulated, increasing reliance on artificial cooling and exacerbating environmental stress. To understand how ENVI met functions and is presented within the upcoming applications in Chapter 4, here is an example of ENVI met simulations applied in Amman presented in Figure 13.

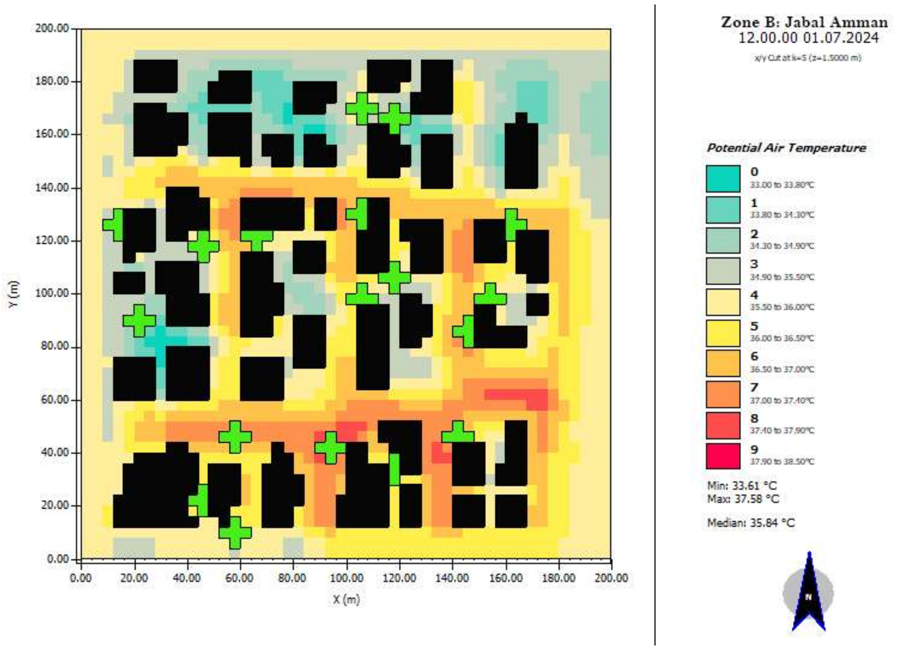


Figure 14. Microclimatic simulation output for Jabal Amman neighborhood.

The simulated domain covers a 200 × 200 m grid, representing a typical residential urban block configuration within the neighborhood. Built structures are shown in black, while vegetation elements are represented in green, corresponding to their modeled location and canopy extent within the simulation. The output is extracted at a horizontal section height of 1.5 m above ground level, corresponding to average pedestrian height and therefore suitable for assessing human-scale thermal exposure. A north arrow is included to indicate orientation and prevailing spatial relationships. The color gradient on the right-hand legend represents Potential Air Temperature (PAT) values generated by the simulation, ranging from lower (cooler) to higher (warmer) temperatures across the domain. The legend further reports the minimum, maximum, and median air temperature values for the entire neighborhood, providing a summary metric of its microclimatic condition.

Within the framework of this dissertation, ENVI met is therefore repositioned from a design-support or visualization tool into a diagnostic engine aligned with UM theory. It bridges the gap between spatial design decisions and system-level metabolic interpretation, allowing GI interventions to be evaluated in terms of their capacity to recalibrate energy, water, and carbon flows. By integrating ENVI-met with street-scale profiling, species-level analysis, neighborhood metabolic assessment, and governance evaluation, the method contributes to a multi-scalar, flow-oriented understanding of urban performance, one that is particularly critical for arid zones.

3.2.3 Tool 3: Tree Species as Metabolic Agents

GI has long been recognized for its ecological and environmental benefits, however, within UM research, vegetation is most often treated as a homogeneous surface or "green cover". This abstraction obscures the fact that different tree species exhibit fundamentally different physiological, biophysical, and metabolic behaviors. As a result, conventional metabolic assessments frequently overlook the species-specific mechanisms through which vegetation contributes to temperature change, water flux, carbon exchange, and air quality.

This dissertation reframes tree species as metabolic agents, living components of the urban system with distinct capacities to absorb carbon, emit moisture, modify airflow, and regulate microclimate. Rather than approaching vegetation as a static land-cover category, this method treats individual species as designable and testable infrastructure elements whose metabolic performance can be evaluated and compared.

Using ENVI-met simulations (as introduced in Section 3.2.2), tree species are analyzed under controlled spatial and climatic conditions, allowing their relative metabolic behavior to be examined systematically. The study focuses on three species commonly found or proposed in Amman, Melia azedarach, Olea europaea, and Ceratonia siliqua, to explore how differences in physiological traits such as leaf area index, transpiration capacity, canopy density, and stomatal resistance translate into variations in cooling potential, vapor flux, and CO_2 exchange. The specific species parameters used in the simulations are documented in Appendix D (Table D2).

Each species demonstrates a distinct metabolic fingerprint, revealing different strengths and limitations when interacting with energy, water, and air flows. This enables species to be strategically aligned with specific metabolic roles: for example, high-transpiration species for cooling corridors, drought-tolerant species for water-scarce slopes, or dense-canopy species for shading and thermal buffering in pedestrian environments. Importantly, this approach supports metabolic equity, by identifying high-performing species that can be deployed in vulnerable or underserved neighborhoods, rather than concentrating effective GI only in high-value areas.

It is essential to clarify the scope of this method. The dissertation does not attempt to replace forestry science, botanical research, or long-term ecological studies that examine tree species through extensive statistical, ecological, or genetic analysis which Is extremely important. Instead, the purpose is to demonstrate how microclimatic simulation can be used by architects, planners, and urban designers to make informed, evidence-based decisions about species selection in relation to urban metabolic performance.

In this sense, the tool translates complex physiological knowledge into an accessible decision-support mechanism, focusing on metabolic flows most relevant to urban design practice, air temperature, evapotranspiration, vapor flux, and CO_2 exchange. These flows are directly connected to climate regulation, thermal comfort, air quality, and energy demand.

By integrating species-level simulation into the broader diagnostic framework, this method elevates GI from an aesthetic or symbolic element to a functional, living component of the urban metabolic system. It allows designers not only to ask how much GI is needed, but which species, where, and for what metabolic purpose. In doing so, the tool strengthens the link between UM theory and practical landscape decision-making. Within the broader logic of this dissertation, species analysis contributes to both diagnostic and prescriptive objectives. Diagnostically, it reveals where existing vegetation underperforms metabolically. Prescriptively, it enables scenario testing to optimize species selection before implementation.

3.2.4 Tool 4: Neighborhood-Scale Urban Metabolic Performance Assessment

While UM studies have traditionally operated at the city or metropolitan scale, this dissertation introduces a neighborhood-scale metabolic performance assessment to capture spatial disparities that are systematically obscured by aggregate city-wide indicators.

City-scale metabolism tends to homogenize data, producing average values for energy use, water consumption, vegetation cover, or waste generation that mask localized inequalities in exposure, access, and environmental burden. In contrast, metabolic inequity is most strongly experienced at the neighborhood and street scales, where urban form, land value, governance decisions, and infrastructure provision directly shape daily life.

This tool operationalizes UM at the neighborhood scale by translating flows into a diagnostic framework applied across four selected study neighborhoods in Amman. The objective is not to reproduce full material flow accounting at a smaller scale, but rather to construct a relational metabolic profile that reveals how different neighborhoods perform relative to one another across key flows relevant to GI, climate exposure, and lived experience.

The assessment builds on Kennedy's metabolic flow typology but adapts it to hyper-local conditions by redefining how each flow is measured.

Instead of relying on city-wide totals (e.g., total water consumption or total energy demand), each flow is represented through neighborhood-specific indicators that are observable, spatially explicit, and directly connected to everyday urban conditions. For example, biota is assessed through canopy cover, species presence, and accessible green space rather than total urban biomass, climate is examined through ENVI-met-derived air temperature and exposure patterns rather than regional climate averages, and people-related flows are interpreted through walkability, comfort, and street-level conditions rather than population density alone. The specific criteria used to operationalize each metabolic flow at the neighborhood scale are summarized in Figure 15. Below:

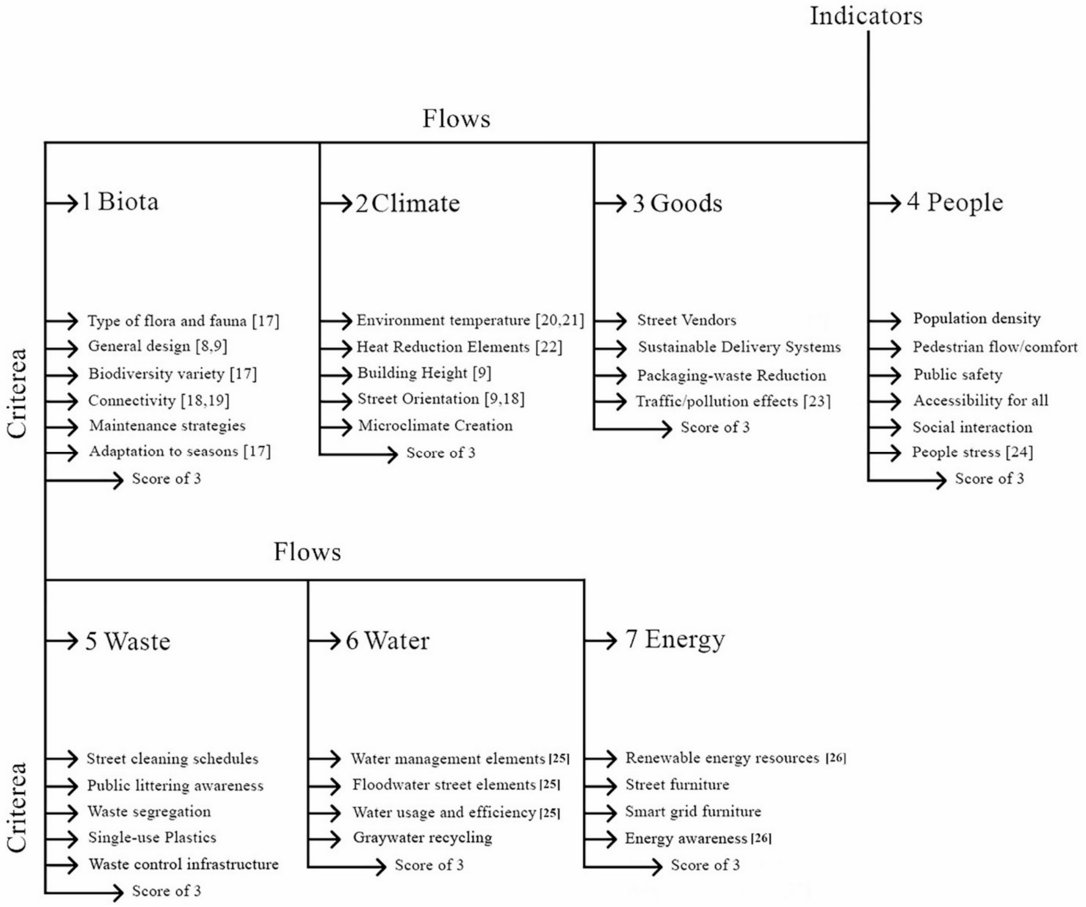


Figure 15. Street-Level Urban Metabolism assessment framework.

The flows assessed at the neighborhood scale include biota, climate, water, energy, materials/goods, waste, and people. Each flow is interpreted through indicators appropriate to neighborhood-scale observation and design intervention. This approach explicitly acknowledges that metabolic flows are not purely technical processes but are mediated by urban design, infrastructure quality, and governance decisions. As such, the neighborhood-scale assessment acts as a bridge between biophysical metabolism and socio-spatial conditions.

Most importantly, the neighborhood-scale metabolic assessment directly supports the dissertation's spatial justice inquiry. By revealing how resource flows, environmental comfort, and GI benefits vary sharply between neighborhoods, the method exposes the uneven metabolic consequences of urban form and planning decisions.

3.2.5 Tool 5: Policy, Governance Analysis and Spatial Justice Indicators

This dissertation treats policy, governance, and spatial justice not as external contextual factors, but as integral components of the urban metabolic system. While traditional UM studies focus on material, energy, and biophysical flows, this research operationalizes governance and spatial justice as indirect metabolic flows that precondition how resources, environmental benefits, and burdens are distributed across the city.

Urban policies, zoning regulations, land-use codes, development controls, and infrastructure standards, function as a metabolic blueprint. As many codes are, they determine where GI is permitted or restricted, how much surface permeability is allowed, whether shading is mandated, and which neighborhoods receive investment or neglect. In this sense, governance does not merely influence metabolism, it scripts it. The metabolic performance of a neighborhood is therefore inseparable from the regulatory and institutional frameworks that shape its spatial form.

Methodologically, policy and governance analysis is employed to trace how planning regulations, zoning categories, land value regimes, and institutional fragmentation shape the spatial distribution of GI and associated metabolic outcomes. This analysis focuses on identifying regulatory asymmetries, situations where areas with higher environmental demand (e.g., heat exposure, density, car dependency) are governed by weaker ecological requirements, while other areas benefit from inherited or unintended ecological advantages. Rather than evaluating policy effectiveness in normative terms, the method examines policy as a causal driver of metabolic inequity.

This metabolic inequity is researched in this dissertation in a way where I test its relationship to UM and GI, as indirect flows. The methods and applications are done by analyzing the regulations and legislation of the city like building codes, zoning regulations and comparing it to GI distribution and NDVI rates of the city.

In another example, by comparing neighborhood-scale metabolic indicators, such as canopy presence, thermal exposure, walkability conditions, and GI continuity, against socio-economic and regulatory patterns, the research identifies where metabolic benefits concentrate and where metabolic burdens accumulate. Finally, in the last research done, a comparison between highly successful cities metabolically from incomes and outcomes perspective and lower ones are studied in areas with different wealth distribution, by analyzing NDVI distribution to understand the relationship between the triangle of UM, GI and Spatial Justice.

Within the proposed diagnostic framework, policy and spatial justice analysis functions as the synthesizing layer. It translates thermal simulations, street-scale observations, species performance, and neighborhood metabolic profiles into an understanding of who benefits from urban metabolic flows and who bears their costs. In doing so, it ensures that the dissertation's metabolic diagnosis remains grounded in lived urban realities and capable of informing equitable, evidence-based planning and design interventions.

3.3 Integrated Framework: The Urban Metabolic Cycle

This integrated framework establishes the methodological foundation for Chapter 4, where the diagnostic cycle is applied empirically to Amman. By positing UM as the main practice and GI as the probe that is connected to the different flows and incomes of the city these methods and applications help incorporate GI as a main aim of the research but also help cover the blind spot of spatial and socio-economic gaps that can be more understood. Traditional UM methods are essential and key to its study, the dissertation does not propose alternative methods but proposes helpful tools that can be incorporated with these methods as presented in figure 16.

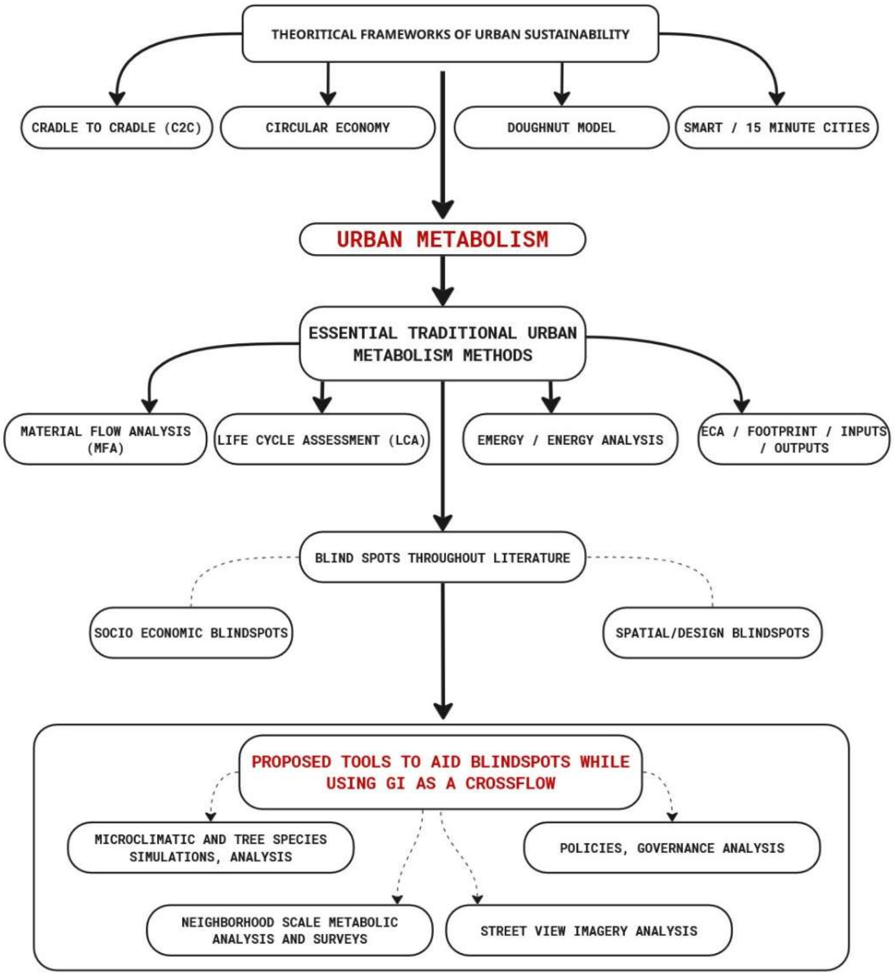


Figure 16. Integrated urban metabolic diagnostic framework, illustrating the relationship between sustainability theories, traditional metabolism methods, blind spots, and tools used. *(Source: Anas Tuffaha 2023, updated in 2025).*

CHAPTER 4: RESULTS AND THEIR DISCUSSION

This chapter presents the empirical findings of this dissertation, translating the theoretical critique established in the literature review into an applied, multi-method framework. It moves from the macro-scale of theoretical discourse and urban spatial configurations to the micro-scale of tree species selection, and temperature reduction, demonstrating how GI serves as the central diagnostic and corrective instrument of UM.

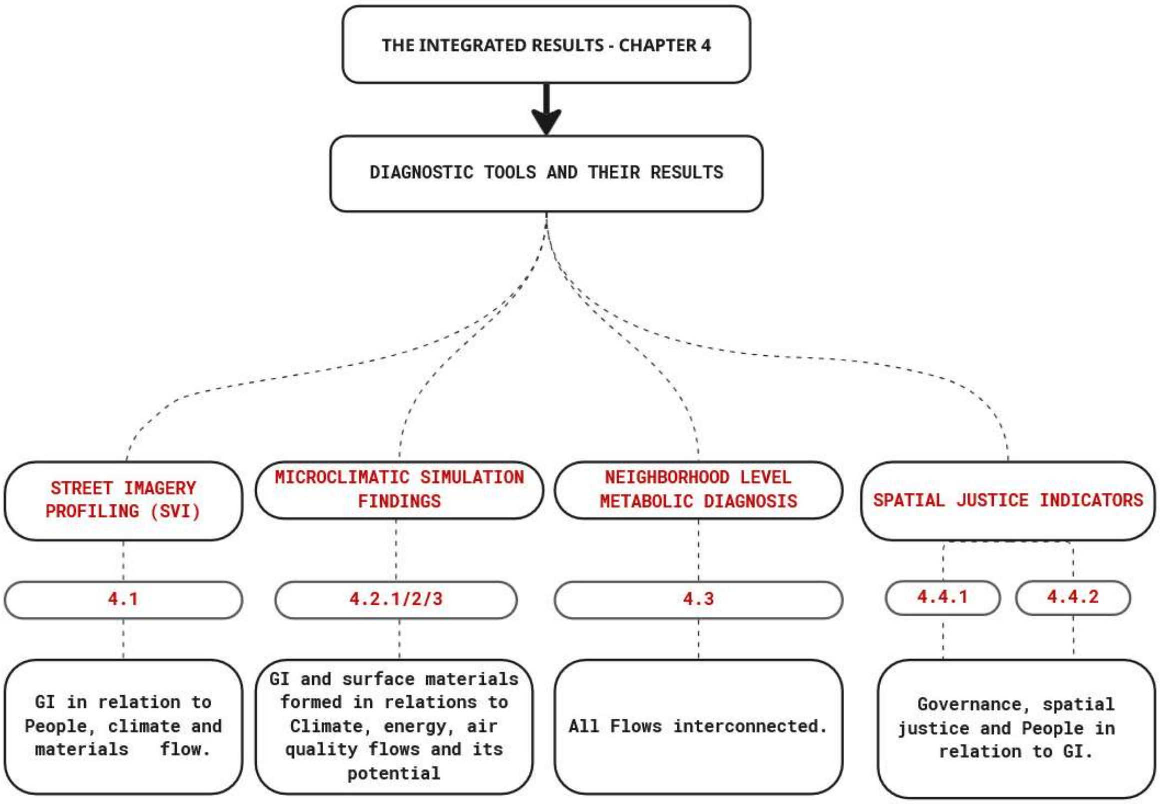


Figure 17. Integrated research workflow for empirical analysis *(Source: Anas Tuffaha 2023, updated in 2025).*

4.1 Street View Imagery ("Street Metabolism") as a Diagnostic Tool for Urban Metabolic Performance

This section details the methodological response developed from the foundational study, *In search for urban landscape development tools: Street View Imagery (SVI) Analysis* (Tuffaha A., & Sallay Á., 2022, Vol. 1). The following subsections present the application and results of the "Street Metabolism" method introduced by that research.

4.1.1 The Method and its aim

As introduced in Chapter 3.2, and subchapter 3.2.1, this method operationalizes GI as a focal point in the analysis, with the ability connect it directly with an indirect flow of urban metabolism, which is people (perception) in addition to surface materials used, this connection gives the ability analyze the perception in pixels, mixing a quantitative with a qualitative ability, for auditing the distribution and quality of metabolic assets at the neighborhood and street scale.

This method also is different from traditional remote sensing methods, such as NDVI derived from satellite imagery, which offers a valuable bird's-eye view of vegetative cover but suffers from significant limitations like failing to capture human experience of the urban landscape.

4.1.2 The "Street Metabolism" Methodology: A Technical Overview

The core innovation of the Street Metabolism method lies in its adaptation of accessible image editing software, like Adobe Photoshop, to perform a granular analysis of Google Street View (GSV) imagery. The process, developed and refined for this research, involves a series of steps to isolate and quantify key elements of the streetscape, which can be replicated within a small amount of time.

The process begins, in which GSV images were systematically captured for a diverse set of locations. Using image editing auto selection by color to distinguish street options and isolating systematically captured GSV images for a diverse set of locations into layers, resulting in a layered composition where greenery is preserved in its original color (or a designated highlight color), and the non-green urban fabric (buildings, pavement, sky) is rendered in grayscale.

The processed image is then analyzed using pixel-counting functions (available in Photoshop or through dedicated script-based tools). This yields a precise percentage of the image's composition that is comprised of greenery, a metric known in broader literature as the Green View Index (GVI).

In the context of this dissertation, the GVI is reinterpreted as a Street-Level Metabolic Performance Indicator, as it directly correlates with the presence of GI, which regulates core metabolic flows of cooling, carbon sequestration, and rainwater absorption.

Here a more detailed method can be used in order to separate each layer with a color, The color range selection technique was repeated iteratively to isolate not only greenery but also other key streetscape components with blue Representing sky and water features, Grey/Brown: Representing buildings and impervious surfaces and other Elements like street furniture and vehicles can also be isolated.
By assigning a unique color to each category and calculating their respective pixel percentages, the method generates a detailed quantitative breakdown of the entire visual streetscape. This provides a rich dataset on the proportional allocation of space to (green/blue) versus burdensome (grey) surfaces.

4.1.3 Results:

The application of the Street Metabolism method across different representative cuts and locations as a test in Budapest, and a few in Vienna and Munich yielded different results as presented in the figure 18. Below in which each chosen site presents its street view image, the color separation methods and the ratio percentages.

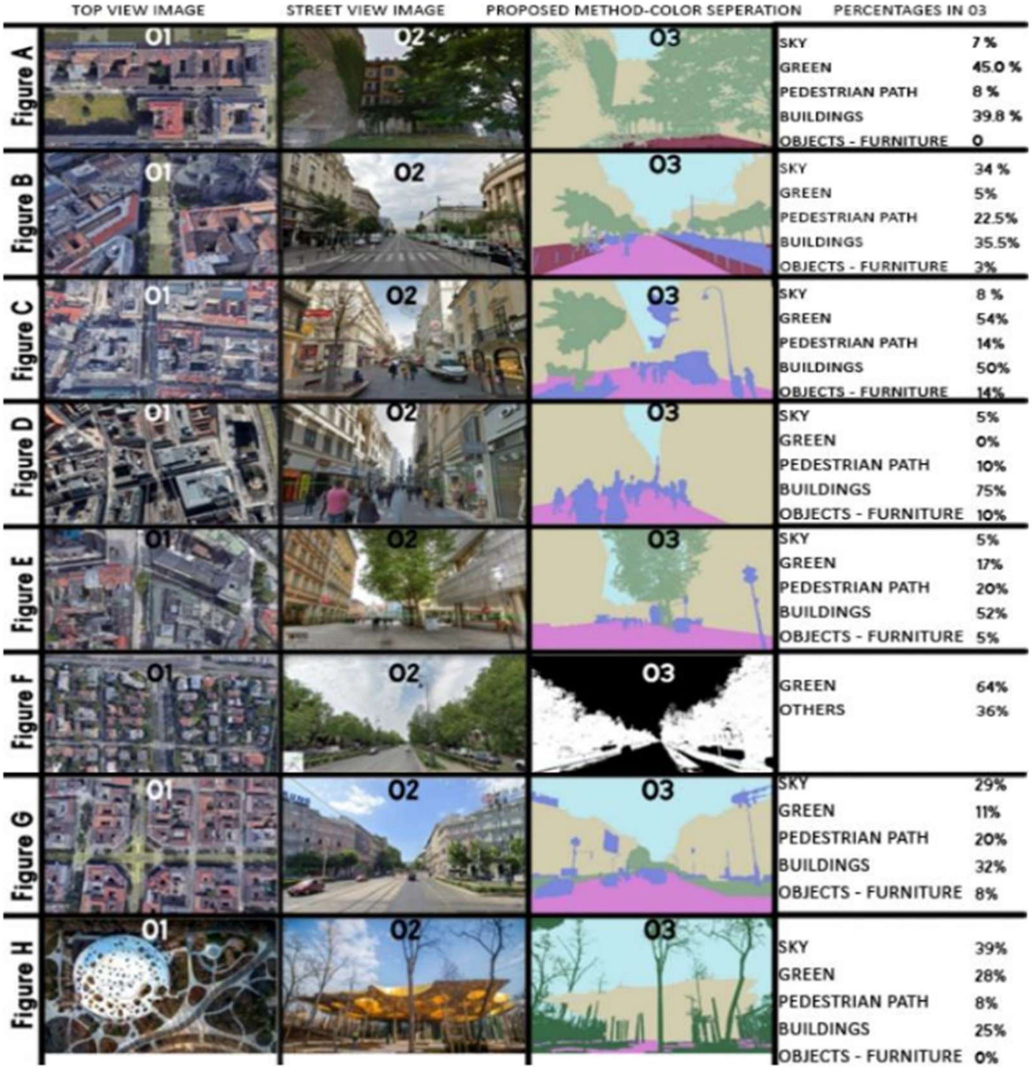


Figure 18. Comparative Street View Imagery (SVI) analysis across urban typologies.

The findings, summarized in the figures, reveal significant disparities across different urban typologies, in addition to findings with each image analysis like:

- **High-Performing Metabolic Corridors:** Andrássy út (Figure F), the tree-lined boulevard, was found to have a remarkably high GVI of approximately 40% in the SVI's chosen. This indicates a street where nearly half of the human visual field is occupied by metabolically active vegetation, correlating with lower ambient temperatures, higher aesthetic quality, and greater pedestrian comfort. Similarly, the tree alley along Bajcsy-Zsilinszky út (Figure B) showed abundant greenery, functioning as a vital "green lung" that facilitates air purification and cooling flows.
- **Metabolically Deficient Zones:** In stark contrast, the Kärntner Strasse, which runs from Stephan Platz in Vienna (Figure D, used for comparison) showcased a building-oriented streetscape with near 0% green coverage in the analyzed view. This absence of GI indicates an area highly vulnerable to the urban heat island effect, with minimal capacity for climate regulation or carbon absorption, placing a higher metabolic burden on artificial cooling systems.

- **Complex, Multi-Functional Metabolic Hubs:** Public squares, such as the Oktogon transportation stop (Figure G), presented a complex metabolic picture. The analysis revealed a diverse composition of green areas (~11%), transportation infrastructure (trams, cars ~10%), and hardscape. This breakdown is invaluable for planners, illustrating the competing demands on space in high-traffic nodes and highlighting opportunities to increase the proportion of metabolically productive GI amidst the chaos of movement.
- **Vertical and Obscured Metabolism:** The analysis of a vertical green wall (Figure A) and the House of Hungarian Music (Figure H) proved particularly powerful. These cases demonstrated the unique advantage of SVI over satellite analysis: the ability to account for vertical greenery and greenery obscured by structures from an aerial view. This confirms that Street imagery is essential for a complete audit of a city's GI, capturing elements that are functionally critical for metabolic regulation but invisible to top-down metrics.

The quantitative results from the Budapest case studies provide a rigorous, data-driven diagnosis of the city's metabolic landscape, translating theoretical UM concepts into measurable street-level performance indicators. The extreme variance in GVI values, from a high of 64% in a dense tree alley to an absolute low of 0%, does not merely describe aesthetic differences but quantifies a dramatic disparity in metabolic capacity.

The multi-element breakdown of complex hubs like Oktogon square (11% green, 32% buildings, 8% objects) further refines this diagnosis, revealing the precise metabolic competition between flows, the significant allocation of visual field to vehicles and hardscape directly quantifies the dominance of mobility and built infrastructure over ecological metabolic functions, providing planners with an exact compositional template for rebalancing these flows through targeted interventions.

4.1.4 Discussions and Conclusions:

This Street Metabolism methodology fundamentally helps UM studies by creating a vital feedback loop between urban form and metabolic function, enabling a form diagnostic urban form in precise positions and hotspots of the city. The percentages generated for each streetscape component (e.g., 75% building coverage, 5% sky) act as direct inputs for predictive metabolic models. For instance, these values can be cross-referenced with ENVI-met simulations later to calculate exact energy savings from added canopy cover or to model the reduction in surface runoff achievable by converting a specific percentage of asphalt to permeable green space.

By moving beyond greenery to audit the proportion of grey, impervious surfaces, the primary culprits of urban hydrological dysfunction and heat retention, the method quantifies the "metabolic burden" of a streetscape. This allows cities to not only map zones of metabolic deficiency but also to precisely calculate the intervention dosage required to achieve a desired metabolic outcome, such as a target cooling degree or stormwater retention capacity.

In this way, the Street View imagery ceases to be a simple picture and becomes a quantifiable metabolic transcript, decoding the complex interplay of flows at the human scale and providing the essential empirical link between the design of a street and its performance within the larger metabolic system.

Street Metabolism isn’t just mapping hotspots, is a diagnostic instrument for spatial justice. The measurable disparity in GVI between different streets, often underpinned by historical planning decisions and socioeconomic factors, is a direct metric of metabolic inequality. In summary, the higher the GVI, the better the cooling and comfort of the people and users are, it is not just appearing green from above, it is essentially comfortable.

Obstacles, sidewalks, heat traps, or even low sky visibility and high gray coverage in the pixels of the image that create visually oppressive streets can be seen showcasing psychological pressures.

A street with a low GVI is not merely less attractive, it is hotter, more polluted, and less resilient, burdening its residents with a negative metabolic experience. By rendering this inequality visible and quantifiable, the tool provides irrefutable evidence for targeted investment in GI as a means of achieving both metabolic efficiency and spatial justice.

Furthermore, the method's reliance on widely available, low-cost (often free) tools like GSV and photo editing and even future AI replicability makes it perfectly suited for application in data-scarce contexts of the Global South, a key objective of this thesis. It democratizes metabolic analysis, enabling community groups, local planners, and researchers in cities like Amman to conduct their own audits without needing advanced technical capacity or resources.

In the end, the Street Metabolism methodology helps bridge the quantitative-qualitative divide identified in UM literature. It transforms the subjective "view from the street" into objective, quantifiable data on metabolic performance, providing a crucial missing link between high-level flow analysis and on-the-ground urban design. It also uses the available GI seen in the pixels as a main indicator with its ratios in comparison to other objects seen.

4.2 Microclimatic Simulations as Metabolic Indicators

This segment extends the diagnostic toolkit by integrating the findings from both the study of “temperature as an urban metabolic indicator: Simulating spatial configurations in arid neighborhoods” (Tuffaha, A. & Sallay, Á., 2023), and “tree species as metabolic indicators: A Comparative Simulation in Amman, Jordan” (Tuffaha, A. & Sallay, Á.). The following subsections detail the application of microclimatic simulation to quantify urban metabolic performance, building upon the spatial audit provided by the Street View Imagery analysis.

4.2.1 Temperature and GI as a Metabolic Indicator in Amman

The UM framework posits the city as a complex, dynamic system defined by the continuous flow of energy, materials, and information. While this metaphor is powerful, its utility for planners and designers hinges on the ability to transition from abstract systemic description to quantifiable, spatially explicit diagnosis. This research operationalizes UM through the lens of microclimatic properties, asserting that air temperature is not a mere environmental output, but a primary, integrative indicator of a neighborhood's metabolic health tied to GI, this method explained in subchapter 3.2.2, represents the equilibrium point of all energy fluxes within an urban volume, the balance between solar gain, anthropogenic heat emission, evapotranspiration, longwave radiation, and convective heat exchange, to be put simply, the relation between GI, climate, energy and even indirect elements such as spatial configurations can be put to test.

In arid capitals like Amman, this thermodynamic balance is critically disrupted. The Urban Heat Island (UHI) effect exemplifies a profound metabolic pathology: a positive feedback loop where inefficient energy flows (excessive solar absorption by asphalt and concrete, waste heat from air conditioning) create thermal stress, which in turn drives higher energy consumption for cooling, further exacerbating the problem. This cycle places a disproportionate burden on municipal infrastructure and household economies, making thermal management a core issue of urban efficiency, equity, and resilience. (Taleb, D. & Abu-Hijleh, B, 2013), (Al Shawabkeh et al. 2023)

Building on the spatial audit provided by the "Street Metabolism" method, this section employs high-resolution computational fluid dynamics (CFD) modeling via ENVI-met to move beyond mapping metabolic assets and into simulating their functional performance. Where street-level imagery, or NDVI answers "where is the greenery?", microclimatic simulation answers "how effectively is this greenery, configuration, and the surrounding urban form, regulating core energy and water flows?" This allows us to diagnose metabolic efficiency at the scale where it is most acutely experienced, the neighborhood block, and to prescriptively test spatial interventions before they are built.

4.2.1.2 Methodology: A Controlled Experiment

To isolate the metabolic impact of urban form, a rigorous, controlled simulation protocol was designed, treating the urban block as a laboratory for testing. In short, two nearby neighborhoods (Zone A and B) were analyzed using ENVI met in 4 different spatial scenarios. (The precise configuration for the baseline models in Zones A and B is detailed in Appendix D, Table D1).

Model Selection and Baseline Calibration: I digitally reconstructed a representative 150x150m block, this typology, characterized by mixed-use concrete structures, minimal setback vegetation, and asphalt-dominated streets, serves as the baseline or "control" model. It embodies the resource-intensive, linear metabolic status quo common in rapidly urbanizing contexts. A replicative microclimatic simulation was then applied to another 150x150 block to make sure of the results and ensure precision of the outcomes. Besides analyzing both zones in their baseline context, named Zone A, and Zone B respectively, they were then analyzed in 3 other configurations as seen later.

ENVI-met Simulation Parameters: To ensure scientific rigor and replicability, the simulation was configured with a high-resolution grid, capturing the intricate interactions between buildings, surfaces, and vegetation. Key input parameters were meticulously defined as Meteorological Forcing Simulations (peak summer period (July, 12:00 PM)) using Energy Plus Weather (EPW). Material Properties like Surface albedo, volumetric heat capacity, and radiative properties were specified for local materials: dark asphalt ($\alpha \approx 0.10$), concrete ($\alpha \approx 0.20$-0.30), high-albedo limestone paving ($\alpha \approx 0.50$-0.60) and finally vegetation parameters using the native species Cupressus sempervirens as the neighborhood vegetation chosen, which were modeled with accurate Leaf Area Index (LAI), stomatal resistance, and root depth to realistically simulate their transpiration cooling and shading effects.

Here are the four distinct spatial configurations that were simulated, each representing a different metabolic strategy:

- **Baseline Configuration:** The existing fabric, representing high entropy.

- **Green Pockets & Corridors:** This intervention tests the metabolic principle of biophysical infusion. Incremental amounts of unbuilt land (300m² to 1800m²) were introduced, not as ornamental landscaping, but as functional, vegetated patches according to the arid neighborhood specification, which is more unbuilt land than grown green pockets, with 4 mid-sized trees grown per lot only.

- **Courtyard Block Configuration:** This tests the principle of metabolic internalization and buffering. By reconfiguring buildings to incorporate internal courtyards (covering 25% to 100% of the block), the design creates a protected micro-climate. This typology reduces the building's thermal load by shading its own mass, thereby lowering the anthropogenic energy flux required for cooling.

- **Semi-Superblock Configuration:** This tests the principle of strategic flow re-engineering. It targets the most metabolically burdensome element (asphalt) for removal (500m² to 3500m²) and replacement with permeable, high-albedo surfaces. This intervention directly reduces heat absorption, mitigates stormwater runoff (a water flow), and prioritizes pedestrian mobility over vehicular flows, thereby altering the neighborhood's fundamental flow patterns.

4.2.1.3 Results and Analysis: Metabolic Performance Benchmarks

The ENVI-met simulations generated highly granular data, translating urban form into precise metabolic performance indicators.

1. **The Metabolic Baseline:** A System Under Stress, baseline simulation confirmed a state of metabolic inefficiency, with the model recording an average temperature of 36.78 °C in zone A and 36.11°C in zone B, with thermal hotspots at asphalt-rich intersections reaching 38 °C. This quantifies the significant "metabolic cost" of conventional design, manifesting as excessive thermal waste that strains both ecological systems) and social systems.

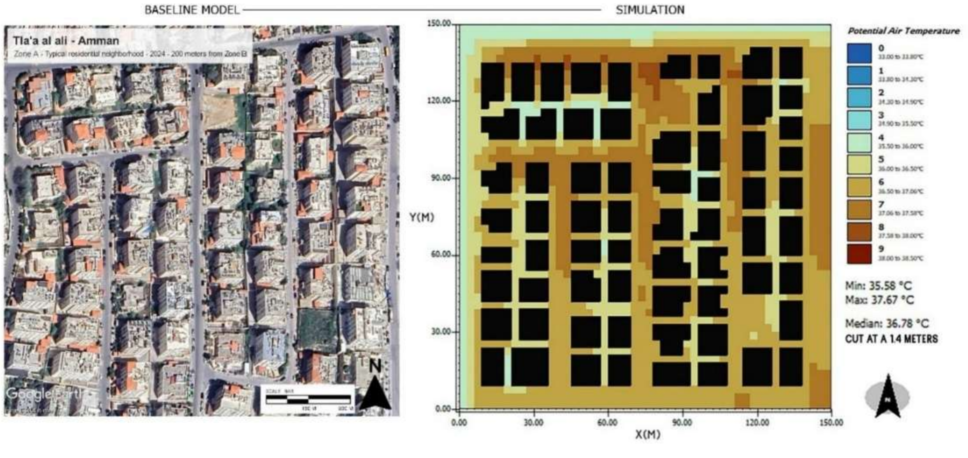


Figure 19. Baseline microclimatic conditions for Zone A (Amman).

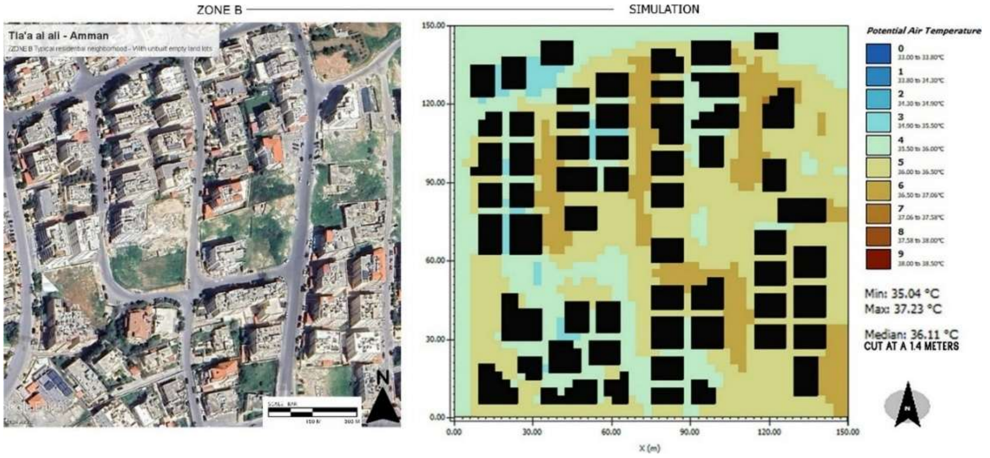


Figure 20. Baseline microclimatic conditions for Zone B (Amman).

2. **Green Pockets**: The results demonstrated a linear and predictable relationship between unbuilt land and cooling. It is found in the simulation that every 100m² of vegetated land reduces local temperature by 0.1 °C in Amman's two neighborhoods studied. Within the studied neighborhood it shows that converting 5% of a block's area (approx. 1,125m²) yields a 1 °C reduction. In Amman this provides planners with a calculative tool for metabolic budgeting: achieving a desired cooling outcome requires a quantifiable investment in GI. This strategy functions as a distributed network of metabolic "relief valves." (Russo, A, 2018).

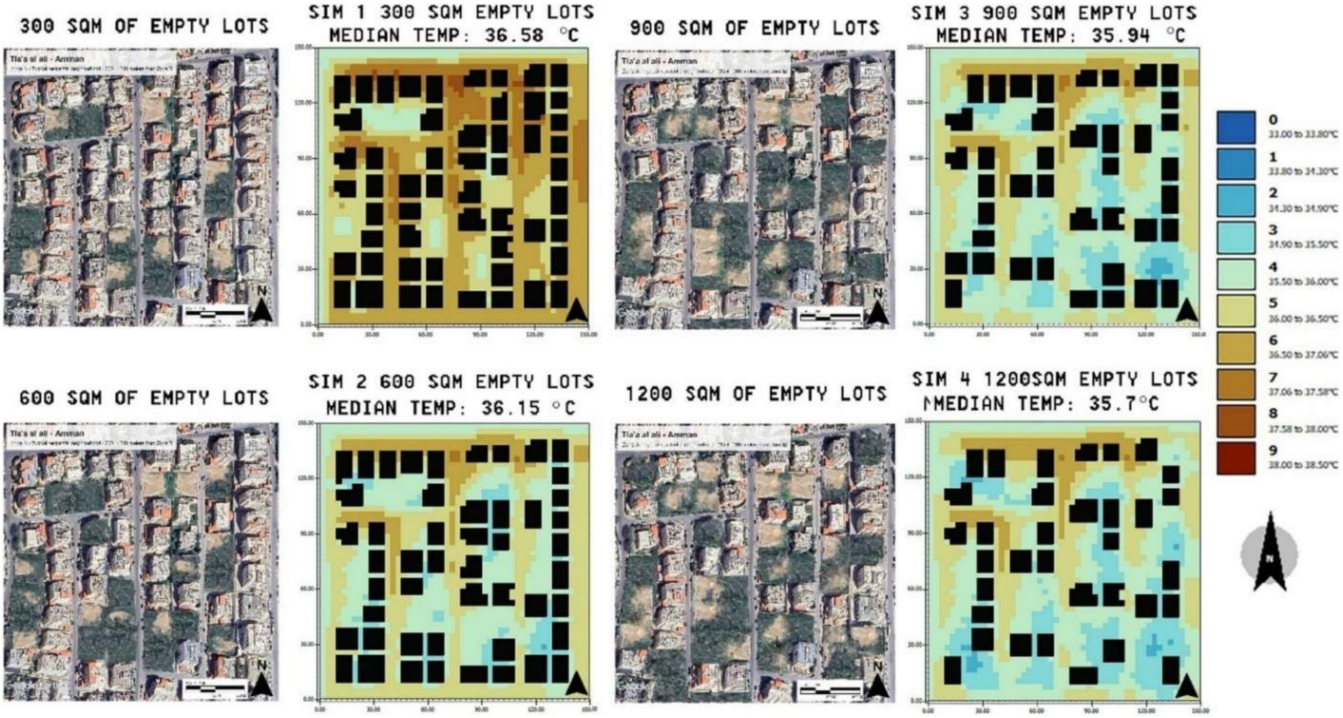


Figure 21. Simulation of Baseline zone A in different proposed scenarios of empty lot ratios using ENVI-met.

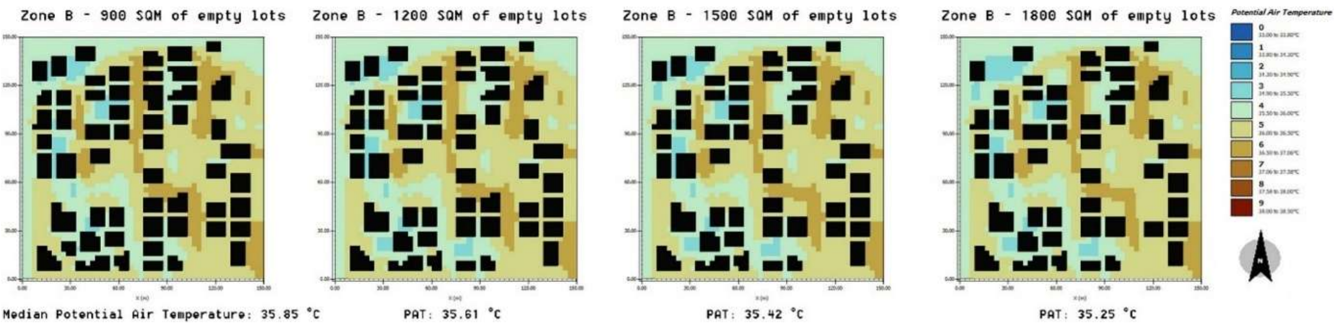


Figure 22. Simulation results in Zone B by progressively increasing empty land pocket sizes from 600 to 1800 m^2.

3. **Courtyard Blocks:** The results revealed a dual effect. The overall neighborhood median temperature saw a moderate reduction of 0.5 °C, but the critical finding was the dramatic 2.5 °C differential between the external street (~36.8°C) and the internal courtyard spaces (34.3 °C). This highlights the typology's primary metabolic value: it creates highly efficient, localized zones of comfort, effectively decoupling interior living conditions from harsh external climates. The gain is realized through significantly reduced energy demand for interior cooling, a flow essential in aggregate city-scale analysis. (Diz Mellado, 2024).

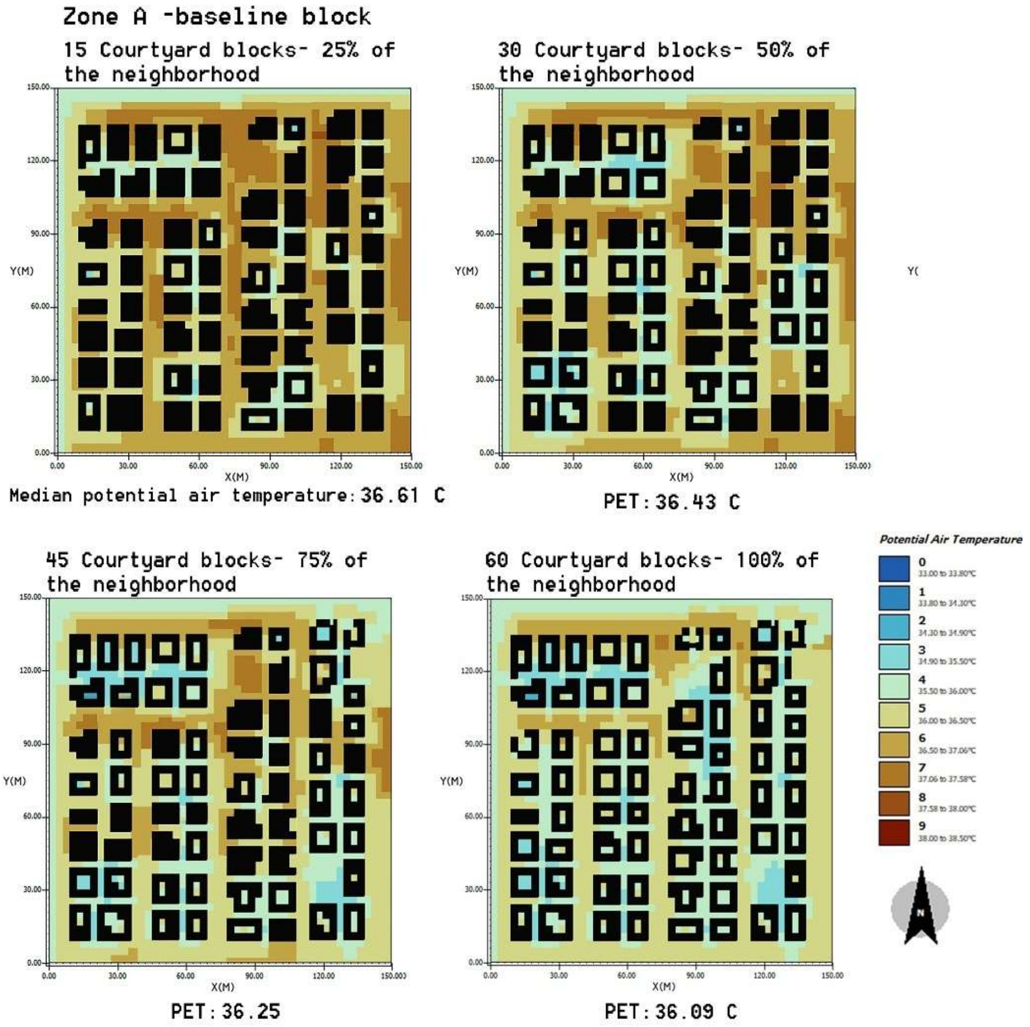


Figure 23. Simulations with thermal changes in Zone A under increasing courtyard footprint.

4. **Semi-Superblocks:** This configuration proved the most effective per unit of intervention. A critical metabolic threshold was identified: the removal of the first 500m² of asphalt yielded the most significant temperature drop. Achieving a 1 °C reduction in median temperature required removing only 8% of the total asphalt coverage. The principle of diminishing returns beyond this threshold is a crucial insight, it argues convincingly for targeted, strategic intervention over blanket, resource-intensive policies. This approach offers the highest metabolic return on investment (MROI), making it ideal for resource-constrained cities.

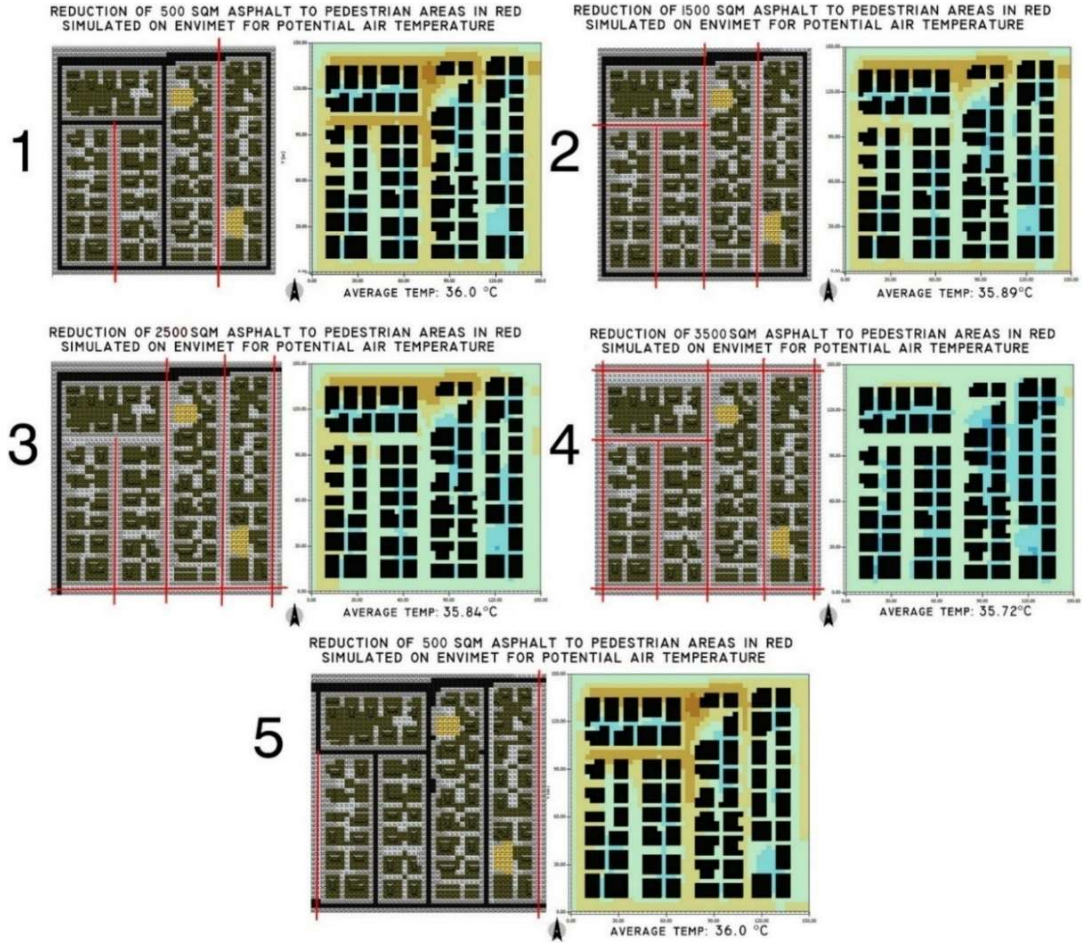


Figure 24. Results of ENVI-met simulations in Zone A under asphalt reduction scenarios.

The results of each zone in detailed numbers can be seen in the tables below:

Table 6.

Performance of Spatial Interventions in Zone A

Configuration	Intervention Scenario	Potential Air Temperature	Mean Cooling ΔT (°C)
Baseline	Original State	36.80 °C	0.00
Green Pockets	300 m² Converted	36.58 °C	-0.22
	600 m² Converted	36.15 °C	-0.65
	900 m² Converted	35.94 °C	-0.86
	1200 m² Converted	35.70 °C	-1.10

Courtyard Blocks	25% Footprint	36.61 °C	-0.19
	50% Footprint	36.43 °C	-0.37
	75% Footprint	36.25 °C	-0.55
	100% Footprint	36.09 °C	-0.71
Semi-Superblocks	500 m^2 Asphalt Removed	36.00 °C	-0.80
	1500 m^2 Asphalt Removed	35.89 °C	-0.91
	3500 m^2 Asphalt Removed	35.72 °C	-1.08

Table 7.

Performance of Spatial Interventions in Zone B

Configuration	Intervention Scenario	Potential Air Temperature	Mean Cooling ΔT (°C)	Mean ΔT (°C) from Fully built baseline
Baseline	Original State (has 600 m2 of unbuilt area)	36.11 °C	0.00	−0.63
Fully built baseline	a hypothetical variant with 0 m2 unbuilt area	36.74 °C	+0.63	0.00
Green Pockets	600 m2	36.11 °C	0.00	−0.63
	900 m2	35.85 °C	−0.26	−0.89
	1200 m2	35.61 °C	−0.50	−1.13
	1500 m2	35.42 °C	−0.69	−1.32
	1800 m2	35.25 °C	−0.86	−1.49
Semi-Superblocks	500 m2 removed	35.95 °C	−0.16	−0.79
	1500 m2 removed	35.84 °C	−0.27	−0.90
	2500 m2 removed	35.79 °C	−0.32	−0.95

4.2.1.4 Discussion: Synthesizing Metrics into a Metabolic Design Framework

The results of my simulations transcend mere thermal analysis, they allow me to propose the foundation for a new, evidence-based method in metabolic urban design. At the core of this paradigm is the capacity to translate complex thermal dynamics into prescriptive planning tools that reshape how cities set and achieve policy goals. Instead of relying on abstract guidelines, in simulated zones and neighborhoods, this can operate as an engineering discipline with measurable outcomes. For instance, a city aiming to reduce neighborhood peak temperatures by 1.5°C can use these findings to back-calculate the precise interventions required, such as converting 7.5% of the urban surface into green pockets while pedestrianizing 10% of asphalt roads. In addition to that, translating ways to reduce temperatures in the city through spatial design in neighborhoods, connecting GI such as scenario 2, or material surfaces in scenario 4, helps planning as a discipline of metabolic optimization rather than aesthetic speculation.

Equally important, the study helps highlight how thermodynamics provides a framework for spatial justice study. A neighborhood deprived of GI and dominated by asphalt is not simply less visually appealing, it is physiologically hotter, exposing its residents to greater thermal stress, forcing them to spend a larger share of their income on cooling energy, this non-linear response reveals an important planning insight: the relationship between intervention intensity and metabolic benefit is not proportional. The removal of the first, approximately 8% of asphalt coverage produces the highest cooling benefit per unit of intervention, while subsequent reductions yield diminishing thermal returns. From an UM perspective, this identifies a critical intervention threshold where metabolic efficiency gains are maximized relative to spatial and financial investment. This finding supports the concept of metabolic return on investment (MROI), where limited resources can be strategically allocated to achieve disproportionately high metabolic benefits. In resource-constrained cities such as Amman, this principle is particularly relevant, as it enables planners to prioritize targeted, high-impact interventions rather than economically unrealistic transformations.

The simulations further demonstrate that no single intervention offers a universal solution, rather, resilience is best achieved through a hybrid metabolic strategy. Semi-superblocks, for example, can be used to strategically reduce asphalt-heavy surfaces, while distributed green pockets provide cooling benefits and biodiversity corridors. Courtyard typologies contribute additional comfort by lowering interior heat loads and reducing building energy demands. The choice of which combination to deploy can then be tailored to the specific character of the urban context.

The deep need in such an arid city is important to replicate in different neighborhoods by creating such simulations in each zone, while exact numerical outcomes. For instance, a cooling rate of 0.1°C per 100m^2 of intervention, will vary depending on latitude, humidity, and prevailing wind patterns, the causal relationships and methodological approach remain universal. By providing this tool set, the study enables cities, particularly in the Global South.

4.2.1.5 Conclusion and Future Directions

UM is defined by many different flows, nevertheless each flow interconnected can be aided by such a method, by leveraging ENVI-met as a metabolic diagnostic tool, this study has answered the call laid out in this dissertation's introduction to move beyond metaphor and use GI as a diagnostic or corrective instrument in urban metabolism. The simulations provide irrefutable proof that GI and urban form are not passive backdrops but active agents that dictate a neighborhood's thermodynamic function, directly shaping the flows of energy, water, and human comfort. In example 2 in which specified vegetations instead of built areas were made, changes in temperatures that lead to less energy use, water and better human comfort can lead to much less outcomes in the metabolic balance of the city.

This study serves as a cornerstone of the novel, multi-method tools for auditing metabolic performance, demonstrating how high-resolution microclimatic simulation integrates seamlessly with street-view imagery to create a replicable model. Where "Street Metabolism" audits the distribution of GI, ENVI-met diagnoses its functional performance, aiding in bridging the quantitative-qualitative divide by linking spatial form to experiential and energetic outcomes. This disparity represents the metabolic manifestation of the "misshapen" UM produced by policy and planning decisions, rendering metabolic inequality visible and measurable through the very lens of GI.

Most significantly, this research translates diagnostic findings into actionable knowledge by providing a prescriptive, evidence-based design manual for metabolic recalibration. It creates the requested decision-making matrix that provides planners with clear metrics within the specified neighborhood of course, demonstrating that to achieve a 1°C reduction, cities should invest in 5% green space or strategically remove 8% of asphalt. The study offers evidence-based amendments to urban policy by providing the scientific basis to mandate maximum asphalt coverage ratios and minimum unbuilt land percentages in zoning codes. Furthermore, it identifies the principle of diminishing returns and critical thresholds, proving that strategic, phased intervention is metabolically and financially more efficient than blanket policies.

4.2.2 Tree Species Performance in Arid Climates

This research identifies and investigates a pervasive issue, focusing on choosing tree species according to their match with metabolic flows like water, air quality and other elements. Instead of having what I termed as “metabolic mis selection” a condition occurs when a species is chosen for its short-term, often visual, benefits while inadvertently introducing long-term metabolic inefficiencies or drawbacks that undermine urban resilience. These drawbacks can include excessive water consumption, allelopathic effects that reduce biodiversity, high emissions of biogenic volatile organic compounds (BVOCs) that contribute to poor air quality, or structural weaknesses that limit lifespan and ecosystem service provision.

To test this hypothesis and provide a diagnostic corrective, this study employs a rigorous simulation-based framework to evaluate tree species not as generic "greenery," but as distinct mediators of urban energy, carbon, water, and ecological flows.

4.2.2.1 Methodology: A Multi-Scalar Simulation of Physiological Traits

As mentioned in subchapter 3.2.3, the methodology integrates two complementary layers of analysis to construct a comprehensive metabolic profile for each species, moving from intrinsic traits to emergent performance within the urban matrix. The first layer involved a detailed comparative ecological assessment based on a synthesis of botanical, physiological, and ecological literature. This assessment moved beyond a simple scoring system to a qualitative profiling of key functional traits that directly influence urban metabolic flows. These traits included canopy density and leaf area index (LAI), which govern shading capacity and radiation absorption, rooting architecture and depth, which determine water procurement strategies and impacts on infrastructure, flowering phenology and faunal associations, which indicate value for urban biodiversity, and biochemical profiles, including pollen allergenicity and isoprene emission rates, which define a species' role in atmospheric metabolic exchanges.

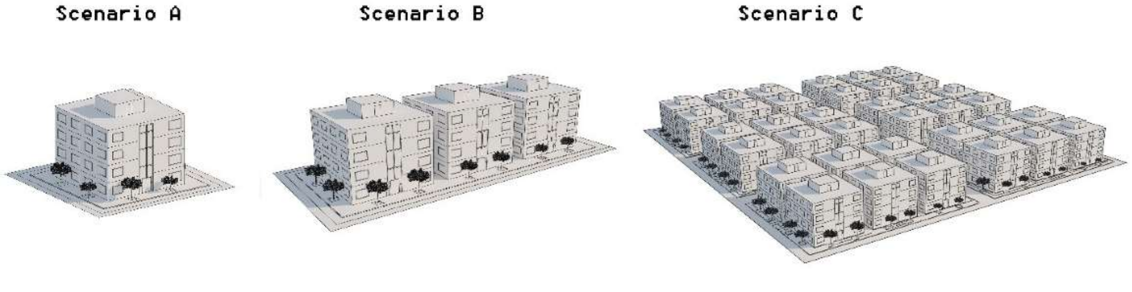


Figure 25. Simulation scenarios for tree species metabolic performance.

The second, core and the method that is using simulations in my metabolic study is the methodological layer, which utilizes high-resolution microclimatic simulation via ENVI-met 5.6.1 to translate these physiological traits into quantifiable metabolic outcomes. Three tree species prevalent in arid urban settings were selected for this controlled comparison: the fast-growing, widely planted *Melia azedarach* (Chinaberry) , the culturally iconic but ecologically complex *Olea europaea* (Olive), and the deep-rooted, native *Ceratonia siliqua* (Carob), all being extremely commonly grown in Amman and some of them like chinaberry in a very high surprising rate. To capture the scale-dependency of metabolic functions, each species was modeled across three nested urban scenarios: a single residential plot (20x20m), an urban street segment (60x20m), and a neighborhood cluster (150x150m). The simulations, calibrated for peak summer conditions in an arid climate, generated precise data on three key metabolic output variables: air temperature reduction (°C) as an indicator of energy flow regulation, CO_2 flux (mg/m²·s) as an indicator of carbon metabolism, and vapor flux (g/kg·m·s) as an indicator of water metabolism via evapotranspiration.

4.2.2.2 Results: Divergent Metabolic Profiles and Trade-offs

The spatial configuration and grid resolution for the three simulation scenarios (A-C) are specified in Appendix D.1, Table D2, while the main figure showcasing the simulation results below.

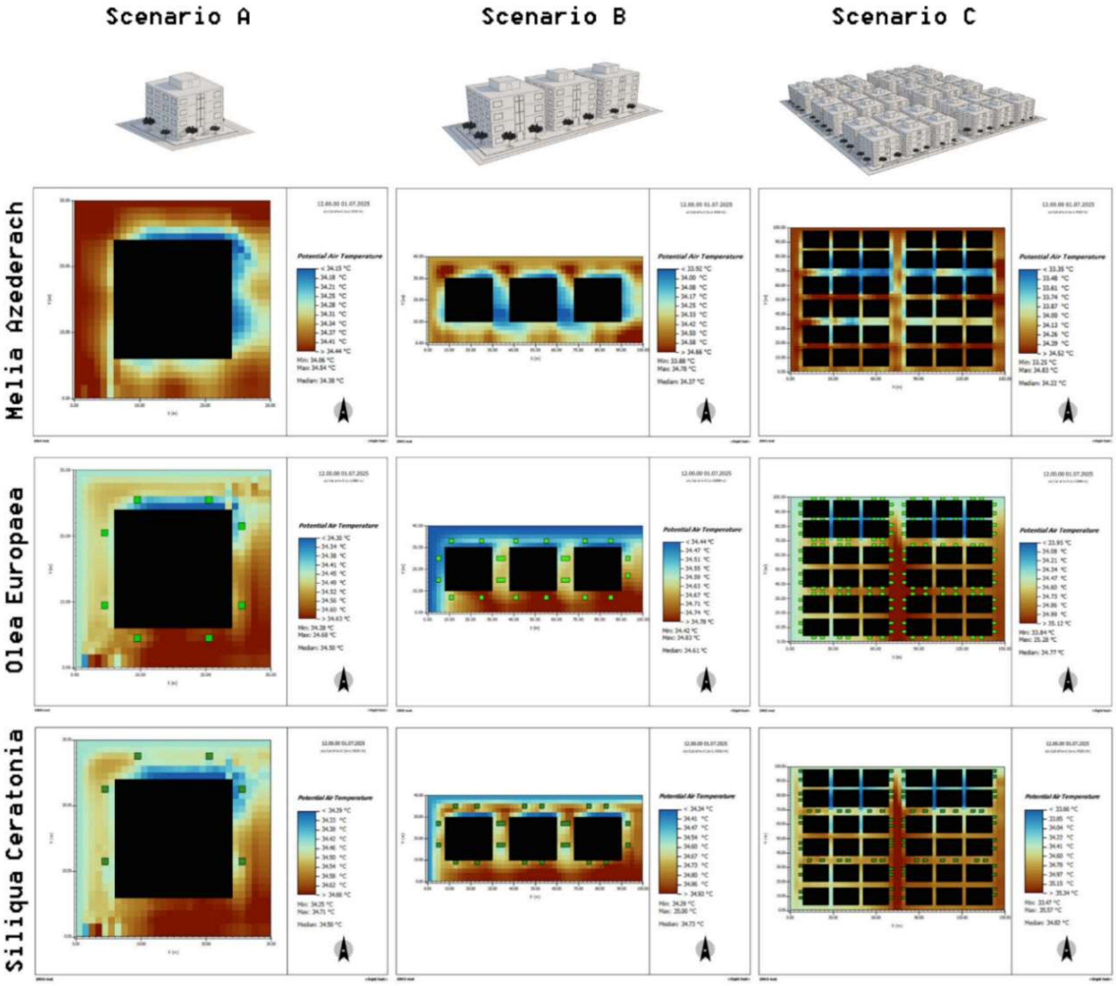


Figure 26. ENVI-met simulations of Melia azedarach, Olea europaea, and Ceratonia siliqua in terms of median air temperature, CO_2 flux (mg/m²s), vapor flux (g/kg·m·s) in scenarios A–C.

The findings revealed profoundly divergent metabolic profiles for each species, providing clear empirical evidence for the metabolic mis selection hypothesis and demonstrating that tree species choice is a determinant of local metabolic performance in neighborhoods, this can also be aided when looking at the 4th option with no trees at all, a very common element in some neighborhoods of Amman, in which a slight amount of tree additions and their different species has an affect on the overall temperature changes, and later with the choices of trees, the air quality and CO2 flux, incorporating flows like climate, energy and air quality together with GI.

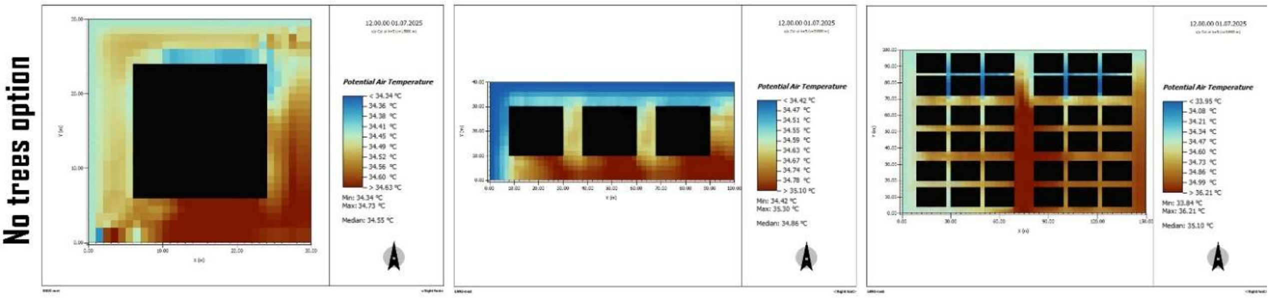


Figure 27. ENVI met simulation results in an empty option in terms of median air temperature, C02 Flux and vapor flux across scenarios A-C.

Melia azedarach exhibited a metabolic profile characterized by high-performance coupled with significant liabilities. It delivered the most substantial immediate cooling effect, reducing ambient air temperature by up to 0.88°C at the neighborhood scale compared to a bare scenario. This rapid cooling is a potent metabolic function. However, this benefit came with associated costs: a high and consistent rate of water use through evapotranspiration, presenting a significant metabolic drain in a water-scarce context. Furthermore, the literature review confirmed its high isoprene emissions, which can act as a precursor to ground-level ozone formation under intense sunlight, thereby negatively impacting the air quality metabolic flow. Its shallow root system and low biodiversity value further position it as a metabolically inflexible species, offering a narrow suite of services at a high resource cost.

Olea europaea presented a metabolically conservative profile. It provided moderate, reliable cooling and carbon sequestration, with a water use rate like *Melia* but backed by a higher drought tolerance. Its evergreen foliage provides year-round shading, a stable metabolic benefit. However, its primary metabolic drawback is not resource-related but socio-ecological: its prolific production of allergenic pollen introduces a significant negative flow into the urban system, adversely affecting human health and comfort. This makes its metabolic contribution deeply ambiguous, providing regulatory services while at the same time imposing a public health burden.

In contrast, *Ceratonia siliqua* demonstrated a metabolically integrative and scalable profile. Besides being native unlike *Melia azedarach*, its immediate cooling effect was robust, its capacity for carbon sequestration increased dramatically as the context expanded from a single plot to a full neighborhood block. Similarly, its water use, while lower than the other species at the plot scale, demonstrated a responsive increase at the larger scale, indicating an efficient and adaptive evapotranspiration strategy. This scalability is underpinned by its deep rooting architecture, which allows it to access stable groundwater, making it highly drought-resilient and metabolically efficient. This relation to lower water usage is also essential to the metabolic flow of water in the outcomes of a city like Amman in a very arid location. Neighborhoods repeated on a vast 1,680 square kilometers, could feature much less water usage and incorporate less temperatures with it as an outcome to the system.

Table 8.

ENVI-met simulation outputs for median air temperature, CO_2 flux, and vapor flux across Scenarios (A–C) for Olea europaea, Melia, Ceratonia siliqua, and no trees

Species	**Scenario**	**Median Temp (°C)**	**CO_2 Flux (mg/m^2s)**	**Vapor Flux (g/kg·m·s)**
Olive	**A**	34.50	−0.64	0.05
	B	34.77	−0.66	0.05
	C	34.85	−0.66	0.05
Chinaberry	**A**	34.38	−0.60	0.05
	B	34.37	−0.64	0.05
	C	34.22	−0.66	0.05
Carob	**A**	34.50	−0.01	0.01
	B	34.73	−0.25	0.03
	C	34.82	−0.29	0.03
No trees	**A**	34.55	N/A	N/A
	B	34.86	N/A	N/A
	C	35.10	N/A	N/A

4.2.2.3 Discussion: Operationalizing GI as a Diagnostic Metabolic Tool

This species-level analysis represents a critical advancement in the application of UM theory as a method that connects GI with other metabolic flows in the system. It aids UM framework at is not solely an instrument for analyzing cities at a macro-scale (e.g., entire material and energy budgets) but is equally potent as a diagnostic lens for micro-scale, biological urban components. By evaluating trees as metabolic agents, we can dissect the complex interplay of urban flows in a different level, in addition to its availability and ease of use for planners and designers who lack intense knowledge regarding each tree species.

This approach transforms GI from a passive, monolithic amenity, often measured only by acreage or canopy covering into an active, differentiated, and diagnosable metabolic infrastructure. The methodology provides a powerful tool to audit a city's existing urban forest. we can ask beyond, "How much green do we have?" to ask "What is the metabolic performance of the chosen species?" A prevalence of species with high water demands and high BVOC emissions in a water-scarce, or air-polluted city is a definitive diagnostic of a metabolically inefficient and vulnerable system.

Furthermore, this framework is fundamentally prescriptive. It allows policymakers and designers to select species based on desired metabolic outcomes, creating a tailored palette for different urban contexts. A heat-vulnerable, low-income neighborhood might prioritize species with the highest cooling per unit of water consumed. A corridor suffering from poor air quality would prioritize low-BVOC, high-particulate-capture species. An area designated for ecological connectivity would prioritize high-biodiversity value natives.

This research, therefore, helps establish GI as a diagnostic and corrective instrument of urban metabolism. The choice of a tree is revealed to be a strategic decision that ripples across the urban system, influencing energy demand, water budgets, carbon cycles, air quality, and public health. Cities can avoid the pitfalls of metabolic mis selection and instead use evidence-based approaches to biological planning from a descriptive metaphor into a generative design science.

4.2.3 Latent GI as Metabolic Reserve (Institutional Gardens)

This subchapter introduces a complementary and illustrative study based on *“Measuring Local Climate Effects of Institutional Gardens in Budapest” (Takácsné Zajacz et al., 2024*), published in Land (MDPI) in which I was part of the team in, supports the methodological logic of this dissertation by demonstrating how underutilized green spaces can function as latent metabolic reserves within urban systems. The analysis is intentionally not presented as a parallel case study to Amman, but rather as a supporting methodological illustration showing how microclimatic simulation can reveal hidden metabolic capacity in existing urban landscapes.

The study applies ENVI-met microclimatic simulation to selected institutional gardens in Budapest, including hospital gardens and the Budafok cemetery. Although conducted in a central european climatic context, the relevance of this study lies not in geographical comparison, but in its demonstration of a transferable diagnostic principle: that GI already embedded in the urban fabric, yet often overlooked in planning and everyday use, can meaningfully contribute to regulating urban metabolic flows when strategically analyzed and enhanced.

Institutional gardens represent a specific category of GI that is publicly accessible, spatially fixed, and often protected from redevelopment, yet rarely optimized for climate regulation. From an UM perspective, these spaces constitute existing metabolic assets with the potential to absorb excess heat, moderate microclimates, and reduce cooling demand, without requiring new land acquisition or major infrastructural investment.

Using ENVI-met, the study modeled existing and proposed scenarios for three institutional contexts:
A hospital garden in a dense urban core, a hospital garden in a transitional urban zone, and the Budafok cemetery in a suburban residential area in which I had the opportunity to perform the simulations for the cemetery as part of the team. The simulations quantified changes in potential air temperature (PAT) under different vegetation and design configurations. The simulation focused on the strategic addition of 40 trees along pathways, in the Budafok cemetery as shown in the figures above showcasing the existing and additional intervention.

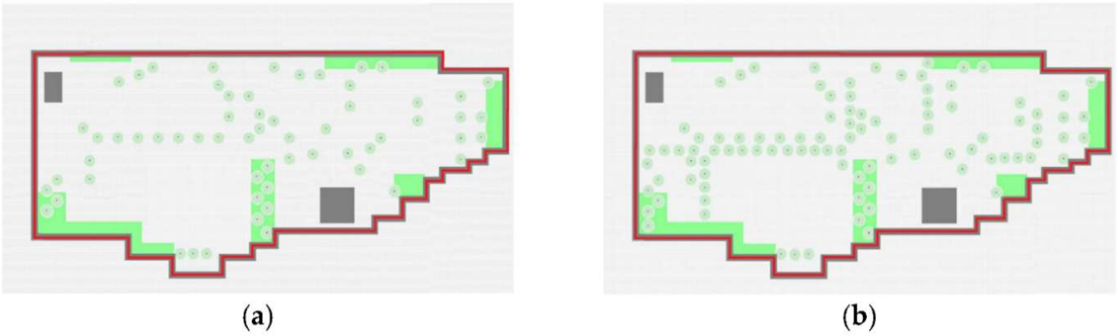


Figure 28. Budafok cemetery: (a) existing garden model, and (b) proposed garden model (created with ENVI-met 4.4.5 software).

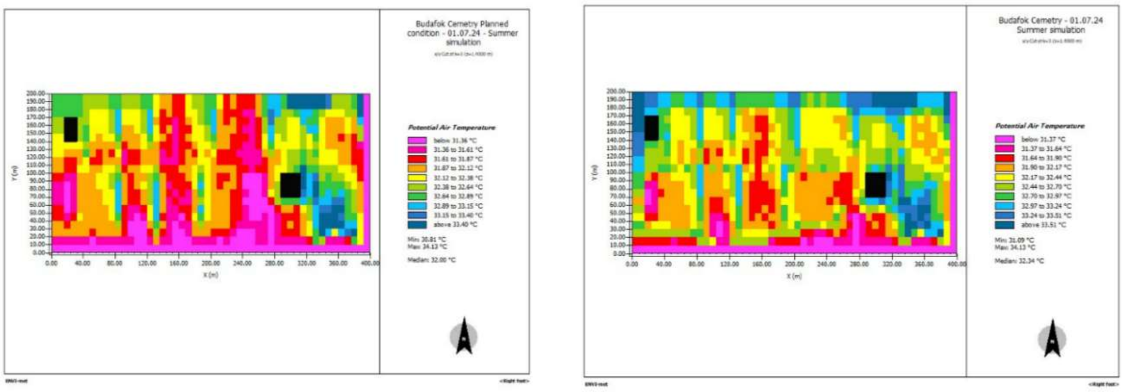


Figure 29. Simulation of the potential air temperature (PAT) in the garden of Budafok Cemetery during summer: (a) existing garden model, and (b) proposed garden model (created with ENVI-met 4.4.5 software).

This intervention resulted in a modest but meaningful PAT reduction of 0.34 °C during summer. Crucially, a winter simulation showed a slight warming effect (+0.23 °C), confirming the year-round thermal buffering capacity of vegetation. The results demonstrated that even modest, targeted interventions, such as increasing canopy cover, or reinforcing tree-lined pathways, produce measurable microclimatic benefits, with cooling effects ranging from localized reductions within the garden to spillover benefits affecting surrounding streets.

From an UM standpoint, these findings reinforce three key insights that directly support the dissertation's core framework: First, institutional gardens operate as micro-scale sinks for metabolic waste heat, converting incoming solar radiation into latent heat through evapotranspiration rather than storing it as sensible heat in hard surfaces. This directly contributes to regulating the city's energy and climate flow.

Second, the study demonstrates that metabolic improvement does not necessarily require new green space but can be achieved through the optimization of existing spatial assets. This insight aligns with the dissertation's emphasis on retrofitting and recalibrating urban metabolism, particularly relevant in land-constrained or resource-scarce cities such as Amman. Finally, while the Budapest study does not conduct a formal spatial justice analysis, it implicitly highlights the importance of access to cooling ecosystem services. In dense urban contexts where public green space is limited, institutional gardens can play a role in redistributing microclimatic benefits.

In relation to the broader dissertation, this subsection functions as methodological corroboration rather than empirical expansion. It reinforces the validity of using ENVI-met and GI analysis to uncover latent metabolic capacity, a principle that is subsequently applied in depth to Amman's neighborhoods in Sections 4.2 and 4.3. The detailed simulations configurations in Appendix D, seasonal analysis, and numerical outputs like ratios and outcomes can be seen in the tables presented in Appendix E2, ensuring methodological transparency while maintaining a focused empirical narrative in the main text.

4.3 NEIGHBORHOOD-LEVEL METABOLIC DIAGNOSIS

This section applies the integrated UM analysis on a neighborhood scale, through the research presented in "*Street level urban metabolism as a tool for mapping urban flows in Amman's neighborhoods" (Tuffaha, A. & Sallay, A, Scientific Reports).*

The study builds upon this research to present integrative case studies of Amman, demonstrating how the multi-method framework operates at a neighborhood scale. The diagnostic tools presented in Section 4.1, and 4.2, Street View Imagery, ENVI-met simulation, species analysis, are isolated tools that were also used in this analysis since their true potential is better realized under a holistic assessment.

4.3.1 Introduction: The Imperative of the Neighborhood Scale

By examining the inputs and outputs of resources like water, energy, and waste, UM provides a holistic perspective on city sustainability. This framework has often focused on the broader, metropolitan scale, as seen in foundational studies on cities' resource cycles and ecological impacts. However, examining UM at the micro-scale, particularly in street level, offers unique insights into how these dynamics manifest in everyday urban infrastructure.

While macro-level Material Flow Analysis (MFA) might tell us Amman's total water consumption, or total energy consumption, it would be very hard to spot out which neighborhood or district is responsible. In other words, total consumption is masked by city wide averages, without exposing the winners and losers at the hyper-local level. This study addresses this gap by advancing street-level UM as a meso-scale analytical framework, focusing on neighborhoods as dynamic units where systemic resource flows intersect with daily human experiences, offering planners granular insights into hyper-local challenges such as unattended green zones, rainwater collection, traffic-induced pollution, and uneven thermal comfort.

4.3.2 Methodology: Synthesizing the Toolkit into an Operational Model

The street-level UM study is the embodiment of the integrated framework proposed. It synthesizes many methods into a coherent diagnostic method for four representative Amman districts, downtown (Site A), Jabal Amman (Site B), Sweifeyeh (Site C), and Tla' Al Ali (Site D). (See Appendix E1, for the survey questions, answers, figures showcasing the 4 districts and some applications)

Figure 30. The chosen four zones for the methodological neighborhood level analysis.

A. The Seven-Flow Framework (The Metabolic Lens): As explained in chapter 3 (methodologies), The main criteria used to analyze the metabolic performance of each flow is an adaptation of Kennedy's metropolitan-scale flows, in addition to IABR's metabolic study in Rotterdam. Which follow the same flow pattern (Water, Energy, Materials/Waste, Biota, People, Climate, Goods) to the neighborhood level, For example (Tillie et al., 2014):

•**Biota:** Type of flora and fauna, general design, biodiversity variety, connectivity, maintenance, adaptation to seasons.

- **People:** density, flow and comfort, safety, accessibility, interaction and stress statistics (Gehl, 2011, Musselwhite, 2021).

- **Climate:** Quantified through neighborhood-scale microclimatic simulation (ENVI-met), using pedestrian-level air temperature cut at 1.6 M in scale to human height, building heights, street orientations, and heat reduction elements

- **Water:** Shifted from total urban consumption to neighborhood-scale hydrological behavior, evaluated through surface permeability, and stormwater runoff potential.

- **Energy:** Interpreted indirectly through cooling demand and heat accumulation, using surface materials, shading availability, and thermal performance from the previous simulations and energy awareness from surveys.

- **Waste:** Assessed through visible material accumulation and waste-management infrastructure, including bin availability, cleanliness, single use plastics, public awareness in surveys and signs of informal disposal within public space.

- **Goods:** Defined as the intensity of commercial and logistical activity, measured through traffic congestion, delivery presence, street vending, and pedestrian obstruction.

B. The Scoring System (The Diagnostic Output): A 1-3 scoring system for each flow is given for each criteria mentioned above, 1 being unsuccessful, 2 being visible but not successful and 3 being successful and evident. Finally for each flow a standardized to a score of 10 is calculated from the previous criteria. This scoring system aims to create a replicable model for auditing metabolic performance in data-scarce contexts.

4.3.3 Results: Diagnosing a Metabolically "Misshapen" City

1.Metabolic Inequality Codified in Urban Form:

The results demonstrated a clear gradient of metabolic flows performance is correlated with neighborhood typology, which is itself a product of zoning and historical development (Mansour & Abdelwahed, 2019, Jiang & Li, 2017)

  - **Jabal Amman (Site B):** Achieved the highest scores in Biota (6.67/10) and People/ walkability (6.11/10). Its older, more organic urban fabric with mixed uses, narrower streets, and greenery functioned as a more efficient metabolic unit. The survey confirmed this, with 44% of residents walking 3000-6000 steps daily.

  - **Tla' Al Ali (Site D):** Represented the metabolic struggles of newer, car-oriented planning. It scored lowest in Biota (3.98/10) and exhibited poor pedestrian conditions. The survey reflected this, with 63.89% of residents walking less than 3000 steps daily, indicating a reliance on cars and a metabolic system prioritizing vehicular flows over human ones.

  - **Downtown Amman (Site A):** Embodied the metabolic stress of a high-intensity commercial core. It recorded a moderate Biota score (5.0/10) but suffered from the lowest Goods flow score (3.33/10), plagued by severe traffic congestion and pedestrian obstruction from street vendors. This creates a metabolic contradiction where economic vitality overwhelms human and ecological flows, leading to an environment where over 50% of residents identified traffic as a primary concern.

- **Sweifeyeh (Site C):** Illustrated the metabolic inefficiency of transitional, car-centric development. It featured the lowest green space coverage (1.5%) and significant thermal stress, with ENVI-met simulations revealing extensive heat-trapping asphalt zones. However, the analysis also identified potential in its unbuilt land parcels, which functioned as informal quasi-courtyards, showing temperatures 2-3°C cooler than surrounding streets and pointing to latent opportunities for strategic green infusion.

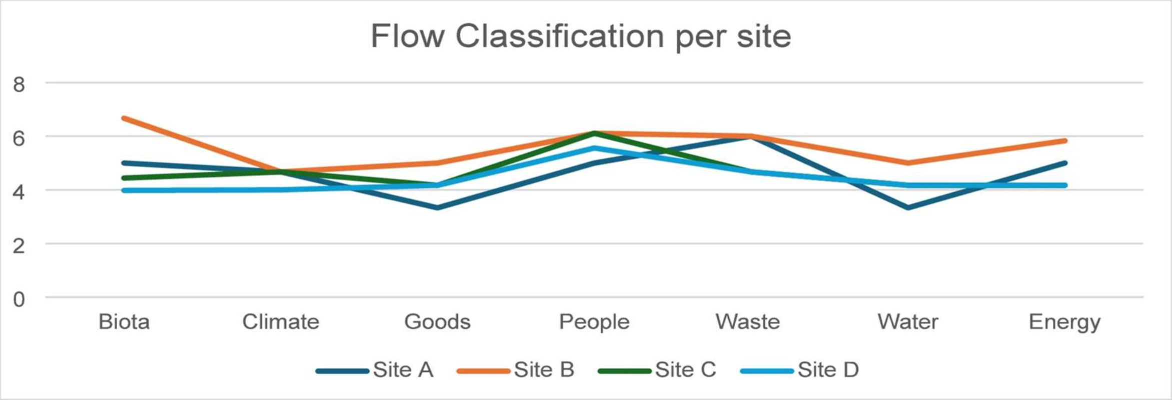


Figure 31. Comparative metabolic flow performance across four Amman neighborhoods.

2. GI as a and Metabolism flows:

The study provided evidence that GI is deeply connected to the results of the 7 metabolic flows.

- **The Biota-Climate-People Nexus:** A strong positive correlation when calculated ($r=0.85$, $p<0.001$) was found between the Biota score (GI) and the perceived walkability (People flow). Neighborhoods with higher greenery were not only cooler (as confirmed by ENVI-met) but also fostered more human activity, creating a positive metabolic feedback loop. (Frank et al., 2006, Giles-Corti & Donovan, 2002)
- **The Economic Gradient of GI:** The distribution of GI was not equitable. Wealthier (higher land value), and tourist-frequented areas (Site B) benefited from better-maintained greenery, while peripheral, lower land value areas (Site D) suffered from GI deprivation. This spatial injustice, quantifiable through the flow scores, is a direct manifestation of a "misshapen" metabolism.
- **Goods flow (traffic, vendors, congestion):** has a strong negative correlation with pedestrian comfort when calculated: $r=–0.73$, $p<0.001$. The higher the traffic score the lower greenery score the lower the comfort.

In general, Downtown district (Site A), suffered from high congestion and low scores in Goods and People flows due to its high commercial activity and outdated infrastructure. This reveals a metabolic system where economic flows (goods, traffic) overwhelm human and ecological flows, a direct consequence of planning policies that prioritize commerce over livability (TomTom, 2024, Gallup, 2024).

3. Initiatives insights

Neighborhoods like Tla' al Ali (D) and Sweifeyeh (C), which received lower grades in the biota analysis, are viewed by survey participants as lacking in greenery, with residents calling for improvements in parks, trees, and shaded areas where around 26% of C's residents asked for increasing walkable areas and over 28% asked for solving traffic congestion regarding urban development suggestions as seen in the Appendix E1. Conversely, Jabal Amman (B), with a higher biota grade, showed fewer complaints about greenery, confirming that neighborhoods with lower biota scores are perceived as having insufficient greenery by the people in the survey.

4.3.4 Discussion: From Integrated Diagnosis to Targeted Intervention

This street-level UM study does more than diagnose, it prescribes. It translates the findings from individual tools into actionable, spatially explicit interventions.

- **Validating the Microclimatic Findings:** The ENVI-met results from this comprehensive study confirm the principles found in Section 4.2. The cooling effect of "green pockets" and the thermal penalty of asphalt are not theoretical, they are measured realities in Amman's neighborhoods, areas in site B had better cooling and also used more courtyard housings than the other districts. (Taleb & Abu-Hijleh, 2013, Al Shawabkeh et al., 2023, Tong et al., 2021)). This provides the evidence base creating a decision-making matrix for planners, which can be seen to achieve a X°C reduction in neighborhood Y, invest in Z m^2 of green pockets.
- **Informing Policy Amendments*:*** The stark disparity in scores provides a solid foundation for evidence-based policy (Gao & Zhang, 2015). The findings argue for amending zoning codes to mandate performance-based metrics (e.g., a minimum Biota score of 6/10, a maximum surface temperature threshold) rather than simplistic land-use classifications.
- **Sequencing Interventions:** The study identifies priority areas. Addressing the most acute deficits in Goods flow (traffic congestion) on Site A might be a prerequisite for improving the People flow (walkability). Similarly, strategic asphalt removal (as suggested by the high impact of semi-superblocks in Section 4.2) in areas like Site D could yield the highest metabolic return on investment before more costly GI projects (Kaza et al., 2018).

4.3.5 Conclusion: The Street as the Metabolic Organ

The Street-Level UM study demonstrates that the neighborhood scale is not just an option for UM analysis but an important addition for meaningful urban intervention. By integrating previous tools into this application in a single, applied framework, this research:

1. It provides evidence that zoning and urban form actively influence metabolic inequality and that GI disparity is a robust proxy for overall neighborhood metabolic health which affects the other flows of the urban system.
2. Bridges the Quantitative-Qualitative Divide: It seamlessly helps integrate quantitative ENVI-met data with qualitative survey responses, presenting a hint on how “people as a flow" can be integrated into UM.
3. Provides a Translational Model: It offers a replicable, low-cost methodology for cities to audit their neighborhoods and districts metabolic health and prioritize interventions.

By diagnosing this organ's health with the tools developed in this research, we can begin the critical work of recalibrating cities for flow resilience and spatial justice, while understanding the hotspots of each district's flows (inputs and outputs).

4.4 Spatial Justice Indicators in Urban Metabolism

This section presenting two different applications, focused on Amman, does not propose spatial justice or GI as standalone determinants of urban metabolic health. Rather, it interprets them as diagnostic indicators through which metabolic inequities become legible in specific socio-spatial contexts.

4.4.1 Zoning codes, land value, and the Metabolic Fabric of Amman

This section extends the diagnostic analysis by incorporating the foundational research presented at the 8th Fábos Conference, "*Exploring the Interplay of GI and Urban Flows: Economic Disparities and Urban Metabolic Insights from Amman, Jordan (Tuffaha, A. & Sallay, Á.,* 2023)". That study examines if and how zoning regulations and land value actively shape the city's metabolic fabric from a GI perspective as a main aim of the dissertation. In addition to that, GI is neither a sufficient nor autonomous driver of spatial justice. Its analytical value in this research lies in its capacity to reveal how socio-economic, regulatory, and spatial processes materialize through environmental conditions leaving an effect on us. The following analysis conducts an audit of Amman's building codes to reveal the systemic policy mechanisms that produce the metabolic inequalities diagnosed at the street level.

4.4.1.1 Introduction: From Symptomatic Flows to Systemic Causes

The street-level UM analysis in the previous subchapter provided a high-resolution diagnosis of Amman's metabolic performance, revealing disparities in flows of people, climate, and biota at the neighborhood scale. It answered what flows and in which districts the urban flows are imbalanced. This section advances the investigation by addressing the fundamental *why*. It posits that the patterns observed on the street are not emergent or accidental but are systematically affected by the city's zoning codes and the economic land valuation they reinforce.

This research operationalizes the political ecology lens introduced in Chapter 1, asserting that UM is not a neutral biophysical process but also a socio-political construct. The laws that govern urban form, specifically, Amman's Building Codes (Zones A-D), act as a metabolic blueprint, proactively scripting the distribution of ecological benefits and burdens. By auditing the city through the lens of its own legal frameworks, this study helps us understand that spatial justice is not only influenced by policy but is fundamentally encoded within it.

4.4.1.2 Methodology:

To dissect the relationship between regulation and greenery, a mixed-methods approach was designed, combining quantitative spatial analysis with qualitative perceptual data to create a multi-layered diagnostic.

A. Theoretical Framework: The city was stratified into three distinct categories based on two intertwined variables:

- **Regulatory Class:** The official Building Code (A/B, C, D) as defined by the Amman Building and Zoning Regulations (2018).
- **Economic Value:** Land valuation data (JOD/sqm) sourced from Qoshan and governmental databases, which closely correlates with the regulatory zones.

This created a clear gradient for analysis:

- **Zone 1 with building code A/B:** Low-density, high-green prescriptions. Min. plot 1000m², 5m setbacks, 15% green coverage mandate and highest land value analyzed.
- **Zone 2 with building code C:** Medium-density, moderate-green potential. Min. plot 500m², 4m setbacks, estimated 7.5% green coverage, mid land values analyzed.
- **Zone 3 with building code D:** High-density, low-green reality. Min. plot 300m², 3m setbacks, estimated 5% green coverage, lowest land values analyzed.

This stratification explicitly treats the building code as the independent variable and with that the city's income and outcomes are affected by them.

B. Data Collection and Triangulation: Three streams of data were collected and cross-referenced for each zone:

B1: Urban Morphological Analysis like Typological Sketches: 3D illustrations of characteristic block typologies for each zone (See Figures below) in a standardized 100x100m model block created for each zone to calculate indicators:

- Floor Area Ratio (FAR) = Total Built Area / Total Land Area, Unbuilt Area Percentage = (Total Land Area - Built Area) / Total Land Area, Green Area per Capita = Total Green Space / Estimated Population, Population Density.

This translates abstract regulations into tangible urban form metrics that directly influence flows of air, heat, and density.

B2: Biophysical Flow Proxy (NDVI Analysis):

- **Data Source:** Sentinel-2 satellite imagery via Sentinel Hub.
- **Methodology:** Calculation of the average Normalized Difference Vegetation Index (NDVI) for selected areas within each zone. NDVI provides an objective, comparable measure of photosynthetic activity, serving as a direct proxy for the presence and health of GI.
- This step is to move from allowed green space (by code) to actual green space (on the ground).

B3: Socio-Perceptual Data (Resident Survey): A survey of 280 residents across the different building codes were organized to aid the Perceptions of neighborhood cleanliness, satisfaction with green space quantity/quality, and identification of primary urban issues.

To bridge the objective reality of the metabolic landscape with the subjective lived experience, capturing the "people as a flow" dimension often missing in UM studies.

4.4.1.3 Results: The Architecture of Metabolic Inequality

The 100×100m block for Zone A/B: demonstrates the effect of the 15% greenery mandate and large setbacks, with built-up areas occupying only 28% of the land. The result is a spatially generous layout with 12% dedicated green areas and 61% allocated to footpaths, providing significant metabolic capacity for cooling and permeability.

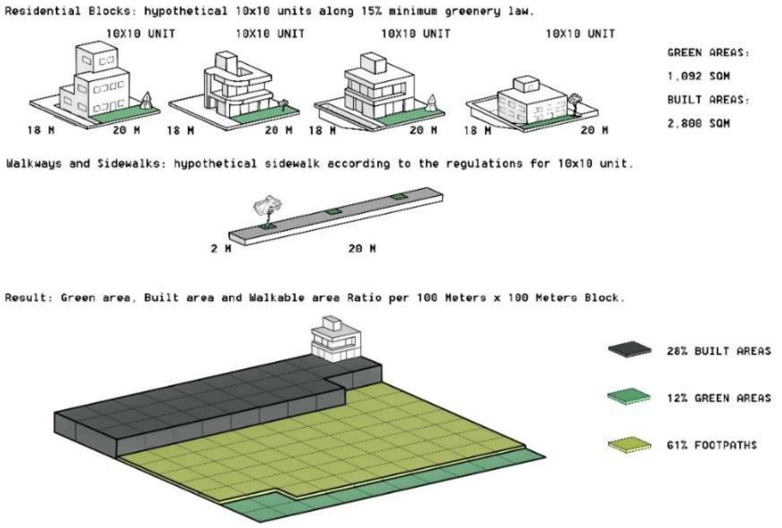


Figure 32. Building code, A/B – High-Value Areas distributions

The model block for Zone C: illustrates the regulatory reduction of unbuilt space. Built-up areas increase to 67%, while greenery drops to 8% and footpaths to 25%. This intermediate density produces a surface with higher temperatures, low water absorption, and with limited vegetation and circulation.

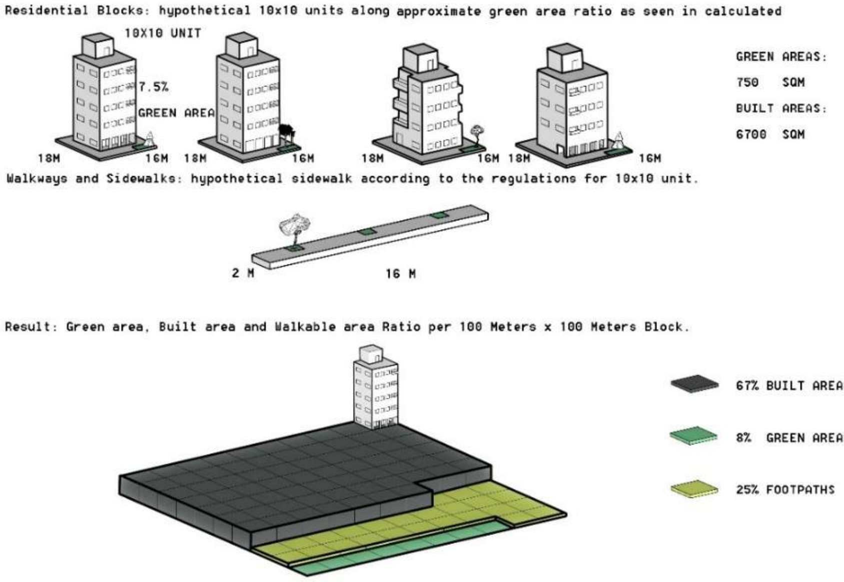


Figure 33. Building code C – Mid Value Areas distributions

The Zone D model: reveals the stark metabolic constraints of high-density zoning. Built form dominates 76% of the block, leaving just 5% for green areas and 19% for walkable space. This spatial compactness hardwires vulnerability into the urban fabric, heightening risks of heat island effects and reduced ecological function.

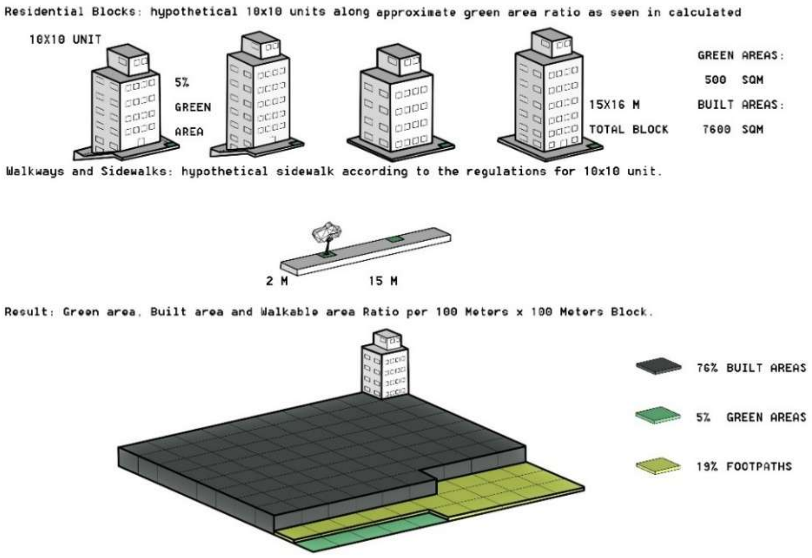


Figure 34. Building codes D – lower value areas distributions

The Regulatory Production of Metabolic Space:

The quantitative analysis of the 100x100m model blocks reveals a direct causal relationship between zoning code and metabolic potential (Table 1). The regulations legally dictate the very spatial geometry of flows.

Table 9.

Presents a comparative analysis of urban form and metabolic indicators across Amman's primary zoning categories

Aspects	Zone 1 (High Value)	Zone 2 (Mid Value)	Zone 3 (Low Value)
Building Code	A, B	C,	D
Floor Area Ratio (FAR)	0.28	0.67	0.76
Unbuilt Area (%)	72%	33%	24%
Modeled Green Area Per Person	8.93 SQM	1.40 SQM	0.82 SQM
Measured NDVI	0.129	0.065	0.046
Metabolic Implication	High resilience: significant capacity for cooling, stormwater absorption, and biodiversity.	Stressed function: moderate flows, potential for bottlenecks under climate stress.	High vulnerability: intense heat island effect, flood risk, low ecological function.

- **Zone 1's Advantage:** The code mandated low FAR (0.28) creates a landscape where 72% of the land is unbuilt. It allows for private gardens, infiltration zones, and air circulation corridors, resulting in the highest NDVI (0.129) and a generous 8.93 sqm of green area per person.

- **Zone 3's Constraint:** Conversely, the high-density code (FAR 0.76) forces a compact urban form where 76% of the land is sealed under concrete and asphalt. The minimal unbuilt area (24%) strangles the potential for GI, leading to a parched landscape (NDVI 0.046) and a 0.82 sqm of green area per person, less than one-tenth of the Zone 1 allocation.

4.4.1.4 Discussion: Metabolic Zoning and the Path to Spatial Justice

This study provides links that spatial injustice linked with zoning and coding regulations has evident proof on affecting different urban metabolic flows like temperature, materials, wastes and biota. As a direct output of urban governance. The zoning map is, in effect, a metabolic map interconnected with biota as a living flow in Amman.

It is also evident that people's perception is subjective with data revealing a dissonance between objective metrics and resident perception, a finding that deepens the understanding of urban metabolic justice. Despite possessing the highest objective green metrics (NDVI 0.129), nearly half (48%) of Zone 1 residents perceived their area as lacking in cleanliness and greenery. In stark contrast, Zone 3 residents, living with the city's less GI (NDVI 0.046), reported a higher perception of cleanliness (68% satisfaction). This also gives insights on how the street-level flows are inspired by zoning codes, which can be discovered through analysis of cities zoning regulations to ultimately understand any defects in the city's green areas, materials, waste management or temperature increase.

This dissertation argues that achieving metabolic stability and spatial justice requires moving from the model of land-use zoning to a new paradigm of performance-based zoning. Instead of regulating what a space *is* (e.g., residential, commercial), the code should regulate what a space does metabolically.

Amendments to the Amman Building Code could include mandating metabolic performance standards and implementing equitable incentives like: Setting maximum temperatures allowed according to simulations, requiring a minimum percentage of street level greenery visible to pedestrians, setting minimum unbuilt land percentage for every parcel to contribute to the city's ecological network, Allow developers in high-value zones to exceed density limits only by funding GI projects in low-value zones, creating a cross-subsidization model for metabolic justice and Offer incentives for exceeding GI targets, particularly in high-density Zone D, to counteract it.

4.4.1.5 Conclusion: Legislating Metabolic Justice

By diagnosing Amman through the lens of its own building codes, this research reveals that the unequal distribution of GI, is fundamentally a map of the city's political and municipal regulations. The fight for spatial justice can start with a regulatory reform to ultimately develop the incomes and outcomes of the city in a healthier way.

4.4.2 Spatial Justice as the Indicator of Urban Metabolism

The preceding methods have looked at different tools available and suggested tackling UM and GI interconnectivity in addition to flows on a neighborhood scale, this subchapter is looking at spatial justice as a third element interconnected with UM. This final section tests a triangle of criteria, between UM flows health, land value and GI. Testing to a degree whether spatial injustice in a city can be an indicator of its overall metabolic health.

4.4.2.1 Introduction: Synthesizing Form, Function, and Equity

While traditional UM has excelled at quantifying aggregate material and energy throughput, it has no current account for the distribution of these flows in specific locations. A city can appear efficient on paper, with decent recycling rates or falling per-capita water use, while harboring severe internal dysfunctions where environmental burdens are exported to marginalized neighborhoods masked by statistics. This condition of imbalance between metabolic flows is not a secondary social concern, it is a primary source of systemic vulnerability and a direct cause of metabolic flows imbalance.

This research, conducted in collaboration with Chenyu Du and Ágnes Sallay, analysis different cities by analyzing in 6 different neighborhoods per city, the NDVI, land value and metabolic success searching for any interconnectedness and relations in the process.

4.4.2.2 Methodology: Quantifying Metabolic Inequality

To test spatial equity connectedness to metabolic performance and GI, a rigorous comparative case study analysis was designed. Three cities were selected to represent a spectrum of documented metabolic health (The current paper is under review, to find the paper along with the supplementary data and the information needed for the analysis you can visit appendix D8 in the appendices section):

- **Amsterdam (developed metabolism):** selected as a reference case representing a city with relatively high metabolic integration and institutional capacity. Its urban development is characterized by strong planning governance, extensive GI networks, and long-standing environmental regulation. The city has been widely studied within UM literature, including Kennedy’s *metabolism of megacities* and is frequently cited for its integration of circular economy principles and equity-oriented planning frameworks (Doughnut Economics) (Voskamp, M, 2017, Kennedy, C, 2015).

  Amsterdam does not function as an “ideal” or normative benchmark, but rather as a context in which metabolic flows and GI are more evenly distributed across socio-economic groups. This makes it suitable for testing whether lower levels of spatial disparity correspond with higher overall metabolic coherence, particularly in relation to climate regulation and ecological buffering.

- **Amman (developing metabolism):** represents a city with an emerging and transitional metabolic profile, shaped by rapid urban growth as already explained in subchapter, 1.1.3, and 2.5. arid climate conditions, and chronic resource scarcity. Unlike Amsterdam, Amman lacks comprehensive UM studies, despite facing acute pressures. Its inclusion responds directly to the dissertations in addition to it being the main subject of this dissertation I am introducing.

  Amman occupies an intermediate position in the comparative framework. On one hand, relatively low industrial pollution and increasing investments in renewable energy, particularly distributed solar PV, suggest improving metabolic efficiency in certain flows. By the end of 2024, Jordan had approximately 2,073.9 MW of installed on-grid solar capacity, with a significant proportion concentrated in Amman, indicating a comparatively high per-capita adoption of rooftop solar within the region. On the other hand, fragmented governance, uneven GI distribution, and pronounced land-value gradients produce strong spatial disparities in environmental exposure.

  Within this methodology, Amman functions as a critical middle case, allowing the analysis to test how partial metabolic improvements coexist with persistent spatial injustice, and how these tensions manifest in neighborhood-scale environmental conditions (Ecomena, The Progress of Solar PV Sector in Jordan in 2024 (summary of grid operator/DSO numbers).

- **Cairo (stressed metabolism):** Cairo is selected as a case representing a structurally stressed urban metabolism, characterized by extreme population density, high resource dependency, and fragmented infrastructure systems. Previous UM studies of Cairo have primarily focused on sectoral flows, such as energy consumption, emissions, and waste, rather than integrated, equity-sensitive analyses, showing stressed incomes and outcomes and also implications as explained by Kennedy regarding people collecting plastics and waste from the street as a form of unorganized recycling (Kennedy, 2015, Mansour, 2019). At the same time, a substantial body of urban and political-ecology literature has documented Cairo as an unequal city in the Global South.

  Cairo's inclusion is essential not as an example of failure, but as a context where metabolic pressures and spatial inequities are particularly acute and empirically visible. Numerous studies have shown that rapid informal expansion, speculative real-estate development, and state-led megaprojects have produced a fragmented urban fabric in which low-income and informal neighborhoods experience chronic deficits in green space, public services, and environmental quality, while wealthier enclaves benefit from privatized greenery and infrastructure (Sims, 2015, Denis, 2012, Sabry, 2014). Environmental burdens, including heat exposure, air pollution, and inadequate waste management, are disproportionately concentrated in marginalized districts, reflecting long-standing patterns of socio-spatial exclusion (Bayat & Denis, 2000, Elshahed, 2018, Anguelovski et al., 2016).

The methodological innovation lies in the Income Stratification Gradient analysis. For each city, the urban fabric was stratified into six distinct socio-spatial categories based on land value and income (High, Mid, Low) and density (High, Mid, Low). Representative zones for each category were identified using census data and satellite verification to ensure comparability. The primary tool for diagnosis was the Normalized Difference Vegetation Index (NDVI), a remote sensing metric that quantifies vegetative abundance. NDVI values were calculated for each zone, providing metrics for average greenness (Mean NDVI), internal inequality (Standard Deviation), and distribution (Median, 90th Percentile).

The crucial synthetic metric developed is the High-to-Low Income Disparity Ratio: Disparity Ratio = (High Income NDVI) / (Low Income NDVI).

This ratio provides a simple, powerful, and instantly comparable number. A value of 1.0 indicates perfect equity. A value greater than 1.0 quantifies injustice, revealing how many times greener the environments of the wealthy are compared to those of the poor.

4.4.2.3 Results: The Gradient of Injustice and its Metabolic Correlation

The results of each neighborhood can be seen in Appendix E4 for more details. With the final remarks here:

- **Amsterdam (Disparity Ratio = 1.10):** Amsterdam demonstrates the lowest disparity ratio among the cases, reflecting a relatively even distribution of GI across income groups. Vegetation levels remain comparatively high throughout the city, and in some instances, lower-income, high-density areas exhibit equal or higher NDVI values than mid-income zones. This pattern is consistent with long-term planning practices that integrate public green spaces into dense urban areas. While disparities are not absent, the reduced gradient suggests that environmental benefits related to climate regulation and ecological buffering are more broadly accessible, supporting the city's overall metabolic coherence.

- **Amman (Disparity Ratio = 1.56):** Occupying a middle ground of metabolic stress, Amman shows a clear 56% green advantage for high-income areas. The analysis reveals a consistent social gradient, where wealthier western neighborhoods have significantly more greenery than denser eastern districts. This measurable inequity acts as a heavy weight on sustainability ambitions, exacerbating water scarcity and creating pockets of extreme climate vulnerability. Amman's intermediate ratio captures its status as a city where emerging metabolic policies are actively contested by entrenched spatial inequalities.

- **Cairo (Disparity Ratio = 2.68):** Cairo exhibits the highest disparity ratio among the three cases, indicating a pronounced difference in GI availability between high- and low-income areas. High-income zones display substantially higher vegetation levels (Mean NDVI ≈ 0.267), often associated with privately managed green spaces and controlled environments, while low-income, high-density districts show markedly lower vegetation cover (Mean NDVI ≈ 0.094). This contrast suggests that environmental buffering capacities, such as cooling potential and ecological regulation, are unevenly distributed across the city. The observed pattern aligns with existing literature describing Cairo's infrastructural strain, reliance on informal waste systems, and exposure to urban heat stress, and points to a strong association between spatial inequality and metabolic vulnerability rather than a singular causal explanation.

4.4.2.4 Discussion: Spatial Justice as a Diagnostic and Predictive Tool

This research reframes spatial justice from a primarily normative concern into a measurable diagnostic lens for evaluating urban metabolic performance. The Disparity Ratio functions not as a definitive measure of justice or sustainability, but as an indicative metric that highlights the degree to which metabolic benefits, such as cooling, ecological buffering, and environmental comfort, are unevenly distributed across socio-economic groups. As a diagnostic tool, the approach enables cities to conduct a rapid assessment of potential metabolic imbalance without relying solely on comprehensive city-wide material flow analysis. Elevated disparity values should therefore be understood as early warning signals of metabolic stress, suggesting heightened vulnerability and reduced resilience at the neighborhood scale. In this sense, the metric helps address a analytical question raised throughout the dissertation: for whom do urban metabolic systems effectively function?

When synthesized with the preceding analysis, the results reinforce a relational understanding of urban metabolism. Urban form influences metabolic performance, species selection affects the efficiency of GI, and spatial distribution determines how these benefits are experienced across populations. Interventions that improve metabolic efficiency at a technical level may therefore remain limited in their systemic impact if they are spatially concentrated and socially exclusive.

From a policy perspective, the findings suggest that investments in GI within underserved neighborhoods can be interpreted as strategic metabolic interventions, rather than solely as redistributive or welfare-oriented measures. While the Disparity Ratio should not be applied as a rigid regulatory threshold, it offers a transparent and communicable indicator that can support performance-based planning approaches and inform more equitable sustainability strategies.

4.4.2.5 Conclusion

In conclusion, this section demonstrates that spatial justice provides a meaningful lens through which urban metabolic health can be interpreted and compared. While efficiency-oriented indicators remain essential for understanding aggregate flows, they are insufficient on their own to capture how environmental benefits and burdens are distributed within cities.

The comparative evidence from Cairo, Amman, and Amsterdam suggests that lower levels of spatial disparity tend to coincide with greater metabolic coherence, while higher disparities are associated with heightened exposure to environmental stress at the neighborhood level. These findings do not imply a universal causal pathway, but they underscore the importance of incorporating spatial equity into urban metabolic analysis, as it is intertwined with its incomes and outcomes stability in its roots.

In this sense, equity is not framed as an external add-on to sustainability, but as an integral dimension of how urban systems function and endure.

CHAPTER 5 – DISCUSSION & CONCLUSIONS

This chapter interprets the conclusion and findings presented in Chapter 4 by situating them within broader context of the dissertation's main concerns on Urban Metabolism, GI, and spatial equity. It discusses what these findings reveal about how metabolic flows operate across scales, GI's part, and uneven distribution consequences.

5.1 Interpreting Urban Metabolism at the Neighborhood / District Scale

The dissertation explores how UM cannot only be analyzed exclusively at the city or metropolitan scale but also on smaller scales, While city-scale indicators are really valuable for capturing aggregate resource consumption and emissions, the results presented in Sections 4.1 and 4.3 demonstrate that such averages can hide spatial variation in how metabolic flows are experienced, regulated, and burdened across neighborhoods and districts.

UM as a sustainability concept, explains how flows of energy, climate, water, materials, biota, and people (incomes) circulate through the city and produce measurable outcomes. However, the research shows that these outcomes are not spatially uniform. Instead, they are shaped by so many elements and even by the flows percentages themselves, urban form, street configuration, land value, and governance decisions that operate most visibly at neighborhood and district scales. It is at these scales that the benefits and burdens of the metabolic system are unevenly distributed, making localized analysis essential for meaningful diagnosis.

The neighborhood-level metabolic assessment (Section 4.3) reinforces the importance of scale. By applying a multi-flow framework across four districts in Amman, the analysis revealed clear gradients linked to urban typology and development history. Older (more tourist based) mixed-use neighborhoods with more greenery and finer-grained street networks performed more efficiently across biota, climate, and people-related flows, while car-oriented districts built organically, with less land value, and high-intensity commercial areas show metabolic stress. While at the end the incomes and outcomes of the city would be the same, on a district level these patterns are variable and different between each other. It also demonstrates that neighborhood morphology acts as a mediator between abstract flows and their lived consequences.

At this scale, metabolic flows intersect with design decisions, everyday practices, and governance structures, making it possible to identify both dysfunctions and opportunities for targeted intervention. By shifting the analytical focus downward from aggregated city-wide indicators to street- and neighborhood-level diagnostics, the dissertation demonstrates how UM can move from descriptive accounting toward spatially actionable understanding.

The street-scale analysis using Street View Imagery (Section 4.1) illustrates this clearly. The green index at low pixel ratios showed streets dominated by impervious surfaces, traffic, and visual enclosure functioned as localized zones of metabolic pressure. These differences which show our perception are not visible in city-level vegetation or climate metrics, yet they directly shape everyday urban experience.

5.2 Green Infrastructure’s Position within Urban Metabolism

A central conclusion of this dissertation is that GI occupies a distinctive analytical position within UM. Rather than functioning as a standalone asset or part of biota as a flow, or a way to intervene, GI as previously discussed influences other flows even if lightly. This crossflow capacity positions GI as both a mediator and an indicator of metabolic performance at the neighborhood and street scales.

Within the UM framework, flows such as energy, water, climate, materials, biota, and people are typically analyzed as interconnected but analytically separable components. For example, vegetation alters surface and air temperatures (climate and energy flows), affects evapotranspiration and runoff behavior (water flow), supports ecological processes (biota), and shapes pedestrian comfort and mobility (people flow). Because of this multi-dimensional influence, changes in GI configuration produce spreading metabolic effects on all flows rather than isolated outcomes.

The findings from Chapter 4 show that GI consistently acts as a convergence point between different diagnostic tools. Street-level imagery captures how greenery modifies enclosure, comfort, and pedestrian experience, microclimatic simulation quantifies its impact on air temperature, vapor flux, and thermal recovery, species-level analysis reveals differentiated metabolic performance within the biotic flow.

Importantly, GI is not presented in this dissertation as a universal solution or as a substitute for UM analysis. Instead, it functions as a modifier of metabolic flows. Where GI is continuous, well-distributed, and appropriately configured, metabolic pressures such as heat accumulation, cooling demand, and exposure to environmental stress are reduced. Where GI is scarce, fragmented, or poorly integrated, these pressures intensify and become spatially concentrated. In this sense, GI does not define urban metabolism, but it reveals how metabolic processes are regulated, amplified, or constrained by spatial configuration.

Finally, Spatial equity is not reduced to greenery, and UM is not explained solely through ecological elements like GI. Cities are shaped by governance, land value, infrastructure, and social processes that extend beyond the scope of GI. However, because GI interacts directly with different flows and is highly sensitive to spatial and socio-economic conditions, it becomes an effective diagnostic entry point for understanding how metabolic systems operate unevenly in practice.

5.3 From Microclimate to Metabolic Performance

Through the integration of ENVI-met simulations, microclimate is shown to function as a measurable outcome of how urban form, material configuration, and very largely by GI with how it regulates energy, water, and air flows within the city.

The results presented in subchapters 4.2 and 4.3 provide that localized temperature patterns, heat accumulation, and cooling potential are strongly shaped by the spatial distribution and its materials, in addition to the quality of GI. Neighborhoods with higher continuity canopy, more green lots, or permeable surfaces consistently exhibited lower pedestrian-level air temperatures, while areas dominated by asphalt, or fragmented greenery showed intensified heat stress. These patterns were not abstract or theoretical, they were directly measured through microclimatic simulation and experienced by residents, as reflected in survey responses and walkability indicators in subchapter 4.3.

There also shows how small interventions can generate disproportionately large effects. The ENVI-met scenarios demonstrate that the initial reduction of asphalt coverage and compact green pockets produced the most significant temperature reductions in Amman neighborhoods focusing both on materials flow and GI.

Further interventions yielded diminishing returns, this finding highlights that microclimate operates as a sensitive metabolic indicator, capable of revealing critical thresholds where urban design decisions have the greatest impact on energy regulation and thermal comfort.

areas that cool effectively through vegetation and spatial configuration also tend to exhibit lower energy demand for artificial cooling, improved pedestrian comfort, and stronger alignment between environmental conditions and daily urban use. In this sense, microclimate becomes a bridge between biophysical performance and human-scale experience, an element discussed in the aims of the dissertation main UM gaps.

The findings also reinforce the importance of scale. City-wide climate data fails to capture the sharp contrasts observed between neighborhoods, where temperature differences of several degrees can occur within short distances.

microclimatic simulation is a helpful diagnostic instrument for urban metabolism. It enables planners to understand where cities are hot or cool, and why these conditions emerge and how targeted interventions can recalibrate metabolic performance while having GI as one of its main elements in its simulation tool.

5.4 Spatial Inequality Position within Urban Metabolism

This dissertation demonstrates that Spatial equity emerges from how the effects of these metabolic processes (income of flows and outcomes) are distributed across neighborhoods. It also points towards when GI is well integrated, metabolic pressures are moderated, and environmental conditions align more closely with everyday urban use. Where it is absent we can notice burdens, such as heat stress, pollution exposure, and increased energy demand in this sense, equity is not treated as an external social concern but as a spatial expression of metabolic performance.

The neighborhood-scale analysis presented in Chapter 4 show that metabolic performance varies sharply between districts within the same city, even when overall city-wide indicators appear moderate or stable. In Amman, for example, neighborhoods with higher land value exhibited stronger biota performance, higher walkability performance, lower thermal stress in microclimatic simulations, more waste bins, lower traffic and higher pedestrian comfort.

By interpreting these patterns through an UM framework, spatial inequality becomes legible as an outcome of how metabolic benefits and burdens are distributed.

Comparative analysis across cities in the last subchapter 4.4.2 further reinforces this interpretation. The Disparity Ratio analysis demonstrates that cities with lower GI inequality tend to exhibit more coherent metabolic functioning, while those with sharp socio-spatial gradients show signs of metabolic stress. Even though it is done only on a 3-city scale which still might need more verification, the early provided signs show that high disparity values indicate environments where metabolic benefits are concentrated in select areas, leaving other neighborhoods to absorb disproportionate environmental burdens.

By analyzing GI alongside microclimate, material surfaces, and pedestrian experience, the dissertation demonstrates how inequity is embedded in the physical organization of the city, which aligns with understanding the indirect flows as gaps within UM earlier explained in the dissertation, but also positions questions like, Instead of asking whether a city is metabolically efficient, it becomes necessary to ask where that efficiency is produced and who benefits from it. This in addition to using GI to understand it and examined at a smaller scale reveals that sustainability outcomes are inseparable from spatial distribution and focuses on how UM should be assessed with accountability for inequity.

Importantly, this research does not suggest that GI defines spatial justice, or that spatial justice defines UM. Rather, GI operates as a visible and measurable proxy (or can be imagined as a probe) in which it can give us an understanding of how inequalities become apparent and finally spatial justice is then an expression of all the incomes and outcomes interconnection and imbalances within our large metabolic system.

5.5 Methodological Contributions, Limitations and Possibilities

This subchapter reflects on the methodological contributions from the results discussed in chapter 4, while later acknowledging limitations and outlining future possibilities

5.5.1 Methodological Contributions

The value of the developed framework is demonstrated by the specific diagnostic insights each method yielded. Table 10 summarizes these contributions, showing how tools like street-view profiling or neighborhood-scale assessment revealed distinct layers of metabolic performance often missed.

Table 10.

Methodological contributions of the dissertation and their linkage to Chapter 4 results

Methodological Component	Chapter	What it Reveals in Summary	Methodological Contribution
Street-Scale Metabolic Profiling (SVI)	4.1	Revealed variation in perceived greenery, enclosure, comfort at street level, invisible to aerial metric	Demonstrates how human-scale perception can be operationalized within UM
Microclimatic Simulations	4.2	Quantified the thermal consequences of urban form, and GI configuration. Showcasing how species flow performance varies	Extends UM analysis with measurable microclimatic performance, also frames GI as an active, metabolic crossflow rather than generic green cover
Neighborhood-Scale Metabolic Assessment	4.3	Test metabolic performance on district scale masked by city-wide averages	Demonstrates the necessity of neighborhood-scale UM for diagnosing spatial disparities
Spatial Justice Analysis	4.4	Linked GI distribution and metabolic stress to socio-economic gradients	Shows spatial equity reflects how metabolic benefits and burdens are distributed within systems.

These methods from chapter 4 operate as diagnostic tools, each revealing a different dimension of urban metabolic performance. They demonstrate that UM can be meaningfully interpreted when environmental processes, spatial configuration, and human experience are examined and at different scales. The complexity of such flows combined in around 7 in many literature references are immense, in which relations between GI, the 7 major flows and Spatial justice as an indirect flow are under continuous analysis in Amman.

5.5.2 Limitations

First, UM is an inherently complex and multi-dimensional concept, encompassing a wide range of interconnected flows and criteria. Cities can be analyzed through dozens of metabolic indicators, many of which extend beyond the focus of this research. This dissertation deliberately concentrates on GI and spatial equity as influential dimensions of urban metabolism. While this focus enables depth and clarity, it also means that the framework is just a partial sector of the full spectrum of metabolic processes operating together within cities.

The role of GI is highly context dependent. In hot-arid and Mediterranean climates, such as Amman, GI plays a particularly critical role in thermal regulation. In contrast, cities with abundant vegetation or different climatic conditions may exhibit different relationships between GI, microclimate, and metabolic performance. While the position of GI as a crossflow component within UM remains conceptually valid, its relative influence and measurable impact may vary significantly across geographic and climatic contexts.

The dissertation proposes spatial justice as an internal dimension of metabolic performance, emerging from the analysis rather than being imposed as a predefined assumption. While the results consistently indicate relationships between GI distribution, metabolic stress, and spatial justice, the connection should be understood as contextually emergent rather than universally fixed. In some cities, spatial injustice may be more strongly driven by factors other than GI, such as housing, or economic structure. As such, spatial equity is presented here as a diagnostic lens rather than a single element.

Fourth, the operationalization of "people as a flow" represents one of the most challenging aspects of UM analysis. Human perception, comfort, and behavior are highly complex and often contradictory. Survey results and street-level observations revealed that even in areas with relatively good environmental conditions, perceptions varied significantly among residents. This confirms that people-related flows cannot be fully quantified through environmental indicators alone and remain partially subjective, culturally mediated, and temporally unstable.

Finally, the neighborhood-scale assessment developed in this research should not be interpreted as a replacement for city-scale UM analysis. City-wide assessments of inputs, outputs, and aggregate flows remain fundamental to understanding overall performance. The neighborhood scale instead complements this perspective by revealing spatial variation, localized stress, and inequitable distribution of metabolic benefits and burdens that city averages tend to obscure.

5.5.2 Future Possibilities

A key opportunity lies in the automation and scaling of street-scale analysis. The Street View–based methodology developed in this dissertation is well suited for integration with machine learning. Automating the classification of vegetation, surfaces, and street elements would enable rapid, large-scale metabolic audits across entire cities. Second, continued advances in urban climate simulation platforms offer potential for expanding microclimatic analysis beyond isolated neighborhoods. Future studies could integrate neighborhood-level simulations into district or city-wide models, allowing for comparative assessments across diverse urban forms and climatic conditions.

At the end in my opinion from the extended research done, the framework could be extended more into multi-city comparative research, applying the same diagnostic logic across a broader set of cities with differing climates, governance structures, and socio-economic conditions. Such an effort would allow for deeper understanding of how context shapes the relationship between Urban Metabolism, GI, and spatial equity. However, it would also require substantial interdisciplinary collaboration and data coordination. The dissertation opens pathways toward practice-oriented applications, including performance-informed guidance for planners and designers.

CHAPTER 6 – NEW SCIENTIFIC FINDINGS

This chapter consolidates the original contributions of the dissertation into a series of formal theses. Each thesis presents a scientific finding that advances the theory and practice of UM explained after according to the studies, analysis and research done in addition to conclusions.

6.1 Thesis 1:

Urban Metabolism literature shows it largely operates at technical scales, limiting its ability to capture spatial and personal urban experience as a critical gap. The findings also demonstrate that applying UM at the neighborhood scales presented strengthens its diagnostic capacity by revealing human-scale and spatial inequalities masked by total averages.

This thesis is grounded in both, the structured literature review conclusion which is an essential part of the dissertation, and the empirical results developed across Chapters 4. The meta-analysis of highly cited Urban Metabolism studies demonstrated a persistent emphasis on material, energy, and quantified flows at city or metropolitan scales, with limited operationalization of spatial differentiation or lived experience (spatial and socio-economic dimensions). While this limitation has been hinted by scholars such as Kennedy, it has rarely been addressed.

This dissertation responds to that gap by shrinking the analytical scale rather than expanding flow complexity. Through neighborhood-level metabolic assessment in Amman presented in Chapter 4.3, the research demonstrates how metabolic conditions vary sharply within the same city unlike having one final average of incomes and outcomes of the city as a metabolic result.

The results in 4.3 show that neighborhoods with similar aggregate urban characteristics exhibit fundamentally different performances once spatial configuration, greenery, surface materials and pedestrian experience are examined. Districts that are adjacent to each other showcase different results when it comes to cleanliness, waste disposal, energy awareness, permeable surfaces, GI quality and distribution, NDVI, potential air temperature, walkability, air quality, traffic and goods distribution as a flow.

The findings show that spatial justice and its distributions are viewed on localized scales, showing heat stress, walkability deficits, and uneven access to GI. By integrating perceptual indicators, survey responses and neighborhood / district level analysis, essential for interpreting how metabolism functions for different urban populations.

The findings are operationalizing perceptual, spatial, and socio-economic dimensions which are limited in applications, alongside biophysical flows, extending Urban Metabolism from a system-level accounting framework into a spatially and socially legible urban sustainability tool.

6.2 Thesis 2:

Findings demonstrate that street profiling like Street View Imagery extends Urban Metabolism to a lived perception level by capturing spatial, vertical, and material dimensions (ratios) of urban environments that are invisible to top-down methods. Since the findings also show measurable environmental performance and subjective human perception do not always align in a paradoxical relation, aiding diagnostics for experiences in everyday urban life.

This thesis builds on the development of the Street-Scale Metabolic Profiling method using Street View Imagery. Traditional Urban Metabolism approaches rely on aggregated, top-down indicators that quantify biophysical flows but overlook how these conditions are perceived on the ground. These traditional flows, which are the basics of UM and undeniably core and important methods, can also integrate human perception, which is a very complex subject.

The complexity is presented in the findings and results of subchapters 4.3 and 4.4 where survey results revealed a counterintuitive pattern: in higher income neighborhoods with relatively more developed GI and cleaner streets reported dissatisfaction with greenery and cleanliness. Conversely, in low-income, GI-deprived neighborhoods, residents expressed satisfaction, despite objectively poorer conditions.

This thesis demonstrates that people as a flow is a multidimensional concept, incorporating both quantitative urban metabolic measurements and subjective resident perception. Therefore, it cannot be understood solely through physical metrics, perception, expectation, and context play a decisive role in how metabolic conditions are experienced.

Street-scale metabolic profiling does not resolve this paradox, but it makes it visible and analyzable. By aligning perceptual conditions with measurable spatial characteristics, the method provides Urban Metabolism with a missing diagnostic layer. In summary, there is a link between biophysical performance and lived experience. In doing so, it strengthens the capacity of Urban Metabolism to address spatial justice and human-centered sustainability without replacing or undermining its quantitative foundations.

6.3 Thesis 3:

Through my application of high-resolution microclimatic simulations in Amman and a few in Budapest, I establish that urban climate as a main UM flow can be transformed from a passive, analyzed flow into a diagnosable and actively designable component of the urban metabolic system that is proactively engineered.

The thesis results are grounded in the extensive analysis of UM flows and climates direct responsive relation to spatial design, surface materials, and GI configuration since GI is a main element of this dissertation. This is also verified throughout the ENVI-met simulations conducted in Amman subchapter 4.2.1 microclimatic simulations in 2 neighborhoods showcasing different interventions, and subchapter 4.3 with 4 neighborhood simulations, in addition to a small interventional simulation done in Budapest in subchapter 4.2.3.

Climate has always been treated as a fundamental flow in UM, yet it is often examined at broad scales through meteorological or climatological studies, leaving neighborhood- and street-level microclimates insufficiently analyzed. The results prove that we can proactively engineer the atmospheric conditions of city blocks by quantifying how specific choices directly recalibrate thermal flows and energy demand from a metabolic perspective.

Rather than treating climate as a static external input, the simulations quantified how specific interventions, such as reducing asphalt coverage, introducing courtyard typologies, or adding green pockets, unbuilt areas, adding greenery rows and certain numbers of trees, alter air temperature, heat stress, and cooling demand. The results demonstrate that form or green infrastructure directly shape climatic flows, making them diagnosable and designable components of the urban metabolic system. By integrating microclimatic simulation into Urban Metabolism, this research strengthens the framework's capacity to link spatial design choices with energy, comfort, and resilience outcomes.

These findings validate microclimatic simulation as an indispensable diagnostic tool for urban metabolism. Just as material flow analysis measures energy or waste, simulation allows climate flow to be quantified in response to design interventions.

6.4 Thesis 4:

My repeated ENVI-met simulations across Amman's neighborhoods demonstrate that the microclimatic outcomes of specific spatial interventions provide consistent results that are reusable and verifiable within the same urban and climatic context (Amman's neighborhoods), these results function as prescriptive guidance for evidence-based design and investments.

This thesis mainly focuses on the ability to create prescriptive guidance and evidence-based interventions that are verified and reusable throughout adjacent neighborhoods is derived from repeated ENVI-met experiments conducted in subchapter 4.2.1, showcasing adjacent neighborhoods in Amman under comparable and near exact morphological and climatic conditions. Throughout 40 comparable simulations, interventions such as asphalt reduction, courtyard typologies, and green space insertion produced nearly identical temperature reductions across sites, confirming that outcomes were not incidental.

While the research does not claim universal transferability across climates, it demonstrates that within a defined urban and climatic context, simulation results can be reproduced and used predictively.

Since Urban Metabolism aids in identifying spatial hotspots and translating diagnosis into targeted intervention, this finding shifts microclimatic simulation from a descriptive or exploratory tool into a prescriptive planning instrument. Within the Amman context, ENVI-met simulations can support locally grounded design guidance, enabling planners to link specific spatial configurations to predictable metabolic outcomes. In this way, microclimatic modeling directly contributes to improving metabolic flows, particularly climate, energy demand, and human comfort, through evidence-based decisions.

Beyond intervention predictability, the simulations also reveal the presence of latent metabolic reserves within dense urban environments. As demonstrated in higher-performing neighborhoods in Amman (e.g., Zone B in Section 4.3) and in the institutional garden case of the Budafok Cemetery (Section 4.2.3), underutilized spaces such as courtyards, vacant plots, and institutional landscapes possess significant untapped cooling potential. When strategically activated through targeted GI interventions, these spaces can measurably enhance local microclimate performance, reinforcing the role of micro-scale spatial adjustments in recalibrating broader urban metabolic conditions.

6.5 Thesis 5:

According to my simulation results, strategic approach targeting high impact areas based on evidence provides optimal urban intervention. For example: asphalt mitigation outperforms a blanket policy, where the first removal has huge thermal benefits, and further reduction produces smaller gains.

This thesis is extremely important for sequencing urban interventions within constrained planning and resource contexts like Amman, in which gaining the best metabolic benefit for the least amount invested in resource constrained cities is essential.

This thesis is derived from a series of ENVI-met simulations presented in Section 4.2.1 where several asphalt-reduction scenarios were tested in Amman, Jordan across six intervention scenarios per neighborhood (totaling 12 simulations) within 150x150 blocks,

By establishing the concept of the 'Diminishing Returns Threshold' for asphalt mitigation, a key principle where multiple asphalt-reduction scenarios were tested in Amman. The results consistently showed that the first approximately 8% reduction of asphalt coverage produced the largest decrease in near-surface air temperature, the finding emphasizes on the intervention and not the quantitative percentage (The number is specific for the context and will vary in another geographical contexts), while further reductions resulted in progressively smaller thermal gains which had a lower value. This confirms that urban microclimatic response is not linear and that intervention alone does not guarantee proportional benefit.

Rather than advocating for extensive or indiscriminate asphalt removal, the findings emphasize the importance of strategic, phased interventions focused on thermally critical surfaces such as parking areas, wide traffic corridors, and exposed intersections. Within the arid context of Amman, this approach allows municipalities to prioritize locations where limited investments can achieve the greatest metabolic effect, particularly in reducing heat stress and cooling demand. In contrast, interventions involving courtyard buildings or conversion of empty lots into green zones displayed near-linear benefits, with each incremental increase in green surface translating into measurable improvements in neighborhood-scale microclimate. This finding also highlights that intervention type matters: while some strategies (green lots, courtyards) can be scaled proportionally, asphalt mitigation requires careful, strategic planning to maximize impact.

In summary, this research provides an evidence-based framework for tactical urbanism, demonstrating that the effectiveness of microclimatic interventions depends not only on the type of strategy but also on the scale and sequence of implementation. By quantifying the Diminishing Returns Threshold for asphalt and contrasting it with linear responses in other interventions, this thesis offers practical guidance for strategic, flow-oriented urban planning, enhancing the metabolic performance of neighborhoods while ensuring efficient use of resources.

6.6 Thesis 6:

Green Infrastructure functions as a crossflow mediator within urban metabolism, and its spatial distribution reveals how metabolic benefits and burdens are allocated (equity) especially in scarce cities, connecting the overlapping relation of GI, UM and spatial justice as an internal dimension of metabolic performance.

This thesis is derived from the integrated results presented across Chapters 4.1, 4.2, 4.3, and 4.4, where GI was consistently used as an element through which multiple urban metabolic flows intersect and become spatially legible. Rather than functioning as a single environmental layer, GI simultaneously influenced microclimate regulation, surface temperature, water behavior, pedestrian comfort, and biotic performance. This multi-scalar influence positions GI as a mediating structure between otherwise separate metabolic flows. The relationship or synthesis between GI and UM can also be seen in the neighborhood-level metabolic diagnosis in Amman (Chapter 4.3) which demonstrates that variations in GI quality and continuity correspond directly with differences in climate exposure, walkability, and overall metabolic performance.

Crucially, the spatial distribution of GI revealed clear patterns of metabolic equity and inequity in Amman. High-performing metabolic conditions were not evenly distributed across the city but were concentrated in neighborhoods with higher land value and favorable planning regulations. This finding confirms that equity does not operate outside the metabolic system, rather, it is expressed through how metabolic benefits and burdens are spatially allocated. GI thus functions as both a diagnostic indicator, revealing where metabolic stress accumulates, and a corrective instrument through which flows can be recalibrated.

While the distribution of GI might not be the same in all cities, its distribution nevertheless gives an indication of spatial injustice, and in that spatial justice is a crucial part of the regulating framework and implications of UM flows, where GI is only a small part of, the distribution of different UM flows like energy, water, and other flows when assessed can provide an essential indicator of spatial justice in a city, and in the case of Amman, an arid city with scarce greenery, GI shines as a UM flow for this exact specific case, indicating inequity.

6.7 Thesis 7 (This Finding is related and compliments Thesis 6)

Tree species within Green Infrastructure function as differentiated metabolic agents, whose selection influences the efficiency and side effects of urban metabolic flows, particularly in arid and resource-constrained urban contexts. (cooling performance, water demand, air quality, carbon, and long-term resilience)

This thesis builds on microclimatic simulations and thesis 6 position on GI and UM, conducted within the dissertation, and explained in chapter 4.3.2. Rather than treating urban trees as a homogeneous green layer, the research demonstrates that different species exhibit distinct metabolic behaviors, producing varied impacts on cooling, evapotranspiration, water consumption, and air-quality-related flows.

The contribution does not claim universal novelty in recognizing species differences, because this is well established in ecological and forestry literature. Its contribution lies instead in operationalizing species choice within an UM framework, linking tree selection directly to measurable metabolic outcomes and urban design decisions. In arid contexts such as Amman, where water scarcity and heat stress intensify trade-offs, inappropriate species selection can make metabolic burdens worse.

By framing species selection as a matter of metabolic performance instead of aesthetics or survivability or even shade. This thesis supports evidence-based GI planning in the science of UM which is not discussed often. It complements the broader GI–UM–equity framework by showing that not only the distribution of GI matters, but also its internal composition, reinforcing the need for context-sensitive, flow-aware landscape decisions.

6.8 Thesis 8

In the context of Amman, governance frameworks and building regulations condition the spatial potential of some metabolic flows (like biota, climate and air quality), shaping environmental performance and spatial inequality. These practices systematically influence Green Infrastructure distribution, thermal exposure and thus the metabolic balance.

This thesis is derived from the combined analysis of zoning regulations, neighborhood morphology, and metabolic performance outcomes presented in Chapters 4.3 and 4.4. The findings show that governance mechanisms, such as zoning classes, density limits, setback requirements, and surface allocation play an important role in determining metabolic flows performance.

In Amman, lower density zones with larger setbacks and higher proportions of unbuilt land structurally allow for greater GI integration, improved thermal regulation, and enhanced pedestrian comfort. This does not mean all urban metabolic flows are better, in fact the complexity of urban systems might mean better waste management in denser zones, which have because of the zoning codes limited open-space requirements with less impervious surfaces, restricted vegetation, and heat exposure. From these regulations the contrasts are born, reflecting regulatory conditions embedded in the planning system of Amman.

The research does not claim that governance alone determines metabolic performance, nor that these findings are universally transferable. Rather, it demonstrates that within Amman's climatic, socio-economic, and regulatory context, planning frameworks act as a conditioning layer that amplifies or constrains the effectiveness of GI and other metabolic interventions. Governance therefore functions as an indirect but influential determinant of how environmental benefits and burdens are distributed across neighborhoods.

By empirically linking regulatory structures to measurable differences in microclimate, GI distribution, and lived environmental conditions, this thesis positions planning policy as an internal component of urban metabolic performance rather than an external administrative factor.

CHAPTER 7 – SUMMARY

This dissertation sets out to examine how Urban Metabolism can be spatialized and operationalized through its relation to GI to better understand environmental performance, lived urban conditions, and spatial inequality. Responding to conclusions and some scholars critique of Urban Metabolism as overly aggregated and technically focused, the research tested a multi-scaled diagnostic tool that integrates street-level observation, neighborhood-scale metabolic assessment, microclimatic simulation, and spatial equity analysis.

A key contribution of the work lies in positioning GI as a crossflow analytical lens within Urban Metabolism, rather than as a standalone environmental asset. Across the studies in Amman and the comparative analysis included in the dissertation, GI showed its connection to metabolic flows, including climate regulation, energy demand, water processes, biotic performance, and pedestrian experience. Neighborhoods with higher-quality and better-configured GI consistently exhibited improved microclimatic conditions, greater pedestrian comfort, and stronger alignment between environmental performance and everyday urban use.

At the same time, the research came to understanding that confirming GI alone does not guarantee sustainability or equity. Its distribution closely mirrors socio-economic gradients, mostly within Amman and in some international cases examined.

In the arid context of Amman, where GI is scarce and climatic stress is high, its presence or absence becomes a particularly strong indicator of localized metabolic performance. Where GI is fragmented or inaccessible, metabolic pressures such as heat stress, reliance on artificial cooling, and environmental discomfort accumulate disproportionately. This finding indicates that questions of spatial equity are embedded within urban metabolic processes, as they reflect how environmental benefits and burdens are unevenly distributed across urban space. In summary spatial equity emerges from the spatial organization of metabolic flows.

An important outcome of the dissertation is the demonstration that Urban Metabolism cannot be fully understood without attention in the beginning to spatial scale and configuration. While city scale analysis remain essential and original for understanding inputs and outputs, they tend to obscure localized variation in exposure, comfort masked by total numbers. By shifting the analytical focus toward streets and neighborhoods, the research reveals how metabolic processes are experienced unevenly across space, and how urban form, surface materials, and GI shape these conditions in everyday life.

Methodologically, the dissertation advances Urban Metabolism by demonstrating the value of human- or neighborhood-scale diagnostic tools and by analyzing the relation of UM-GI-Equity.

The tools used, Street-scale metabolic profiling using pedestrian-level imagery made it possible to capture vertical greenery, enclosure, surface composition, and perceptual exposure that are systematically missed by top-down datasets. Surveys with perception and people’s opinions. High-resolution microclimatic simulation further contributed by operationalizing climate as a diagnosable and design-responsive metabolic flow at the neighborhood scale. Rather than treating climate as a passive background condition, ENVI-met simulations demonstrated how spatial configuration, surface materials, and GI interventions recalibrate thermal conditions in measurable ways.

Taken together, the findings reinforce a core conclusion of the dissertation: UM, GI, and spatial equity are not separate analytical domains, but overlapping dimensions of the same urban system. Urban Metabolism provides the framework for understanding flows, GI acts as a spatial mediator with flows, even part of biota as a flow, and equity describes how the benefits and burdens of these flows are distributed across neighborhoods. This relationship is especially visible on the neighborhood scale, where differences in form, regulation, and access translate directly into everyday environmental experience. Each element can spot malfunction in the other in different ways and on different scales, it is even more evident in certain cities, depending on the available resources, cultural context, economy and even climate.

The dissertation does not claim universal metrics or predictive models applicable across all cities, nor does it present GI as the only regulator of UM. Instead, it contributes a transferable methodological logic: a way of combining existing tools (traditional UM tools) with street-level observation, microclimatic simulation, neighborhood-scale metabolic assessment, and spatial analysis, to diagnose urban conditions in a manner that is spatially explicit, human-centered, and sensitive to local context. In this sense, the work positions Urban Metabolism not as a closed technical system, but as a flexible analytical framework capable of informing more nuanced, equitable or just, and context-aware urban planning answering concerns of any quantitative gap addressed in the earlier literature review.

In conclusion, this research demonstrates that advancing urban sustainability requires moving beyond aggregate efficiency toward an understanding of where, how, and for whom metabolic processes operate, by spatializing UM through GI as an important element, in human scaled neighborhoods.

The dissertation provides both conceptual clarification and practical insight into how cities like Amman, facing climatic stress and resource constraints, can better align environmental performance with lived urban conditions in addition to better understanding into the complex relation of UM flows being direct and indirect like equity and perception.

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APPENDIX A: OVERVIEW OF DOCTORAL PUBLICATIONS

Table A1.
Presents the doctoral publications throughout my academic study years, their location or ties to the dissertation, relevance and source

No.	Publication Title	Direct Relevance to Dissertation	Location in Dissertation
1	Balancing Urban Metabolism (LOV 2023)	Foundation of meta-analysis, quantitative-qualitative divide	**Chapter 4.1, Thesis 1**
2	Sustainable Urban Planning Concepts (GU Conf 2023)	Theoretical framework development	**Chapter 2.1, Literature Review**
3	Consumption of Cities (Tájökológiai kihívások)	Urban metabolism conceptual foundation	**Chapter 2.4, Theoretical Framework**
4	Zöld infrastruktúrafejlődése (4D journal 2024)	Adaptive Reuse, Circularity & Metabolism, Green infrastructure methodology development	**Chapter 2.4, (2.4.2), Thesis 2**
5	SVI Analysis (Fábos Conference)	Street View Imagery methodology	**Chapter 4.2.1, Thesis 10**
6	Temperature as Urban Metabolic Indicator (Elsevier,Urban Climate)	Core ENVI-met simulation methodology	**Chapter 4.2.2, Theses 3-5**
7	Metabolic Streetscapes (Springer/Nature, Scientific Reports)	Street-level urban metabolism framework	**Chapter 4.3.1, Theses 7-8**
8	Exploring the Interplay of GI and Urban Flows (Fábos Conference)	Policy-spatial analysis	**Chapter 4.3.2, Regulatory Analysis**
9	People, intentions and our behavioral impacts on design decisions (ECLAS 2023)	People as a flow, Foundation of meta-analysis, quantitative-qualitative divide	**Chapter 4.1, Thesis 1**
10	Institutional Gardens as Metabolic Assets (LAND, MDPI)	Microclimatic Budapest applications	**Chapter 4.3.4, Thesis 11**
11	Aqueducts to Asphalt (Transylvania Conference)	Water as a flow, sustainable water solutions, Amman historical flow analysis	**Chapter 2.5, Amman Context**
12	Spatial justice as an indicator of Urban metabolism Nature, Scientific Reports, Under Review)	Spatial justice metrics development, Equity dimensions	**Chapter 4.2.4, Spatial Justice**
13	Microclimate & Tree Species (LAND, MDPI)	Species-specific metabolic analysis	**Chapter 4.2.3, Thesis 9**

APPENDIX B: INTRODUCTORY DEFINITIONS

This glossary provides definitions and context for academic terms and concepts that are not mentioned in chapter 1.5 as key definitions. As this research explores the complex intersections of urban metabolism, green infrastructure, spatial justice, and microclimatic analysis, it employs specialized terminology from multiple disciplines critical for understanding the discussions presented.

These terms have been selected based on their relevance to the dissertation's core themes and methodologies, including the analysis of urban flows, the diagnostic application of green infrastructure, and the examination of metabolic inequalities.

Metabolic Lock-in

The phenomenon where long-lasting infrastructure systems for energy, transport, and water dictate resource flows for decades, creating path dependency in urban development. It can be simply put that it’s a situation where a city is “locked” into a specific or unsustainable way of operating its incomes and outcomes.

Reference: Kennedy, C., et al. (2011). "The study of urban metabolism and its applications to urban planning and design." Environmental Pollution

Found in: Chapter 2.3.1 in the relation between GI and UM.

Sustainability and Economic Frameworks:

Circular Economy

An economic system aimed at eliminating waste and the continual use of resources through recycling, reusing, and sustainable design, primarily focused on material loops and production cycles.

- **Reference:** Ellen MacArthur Foundation (2015). Towards a Circular Economy
- **Found in:** Chapter 2.4.2, discussed in the context of adaptive reuse projects like De Ceuvel and Schoon Schip translating metabolic thinking into circular urbanism.

Cradle-to-Cradle (C2C)

A design philosophy challenging industrial "cradle-to-grave" models by proposing continuous cycles of "biological nutrients" and "technical nutrients" that eliminate waste.

- **Reference:** McDonough, W. & Braungart, M. (2002). Cradle to Cradle: Remaking the Way We Make Things
- **Found in:** Chapter 2.4.2, referenced within the discussion of metabolic and circular principles in adaptive reuse

Doughnut Economics

A conceptual framework visualizing a "safe and just space for humanity" between social foundations and ecological ceilings, providing an ethical compass for urban development.

- **Reference:** Raworth, K. (2017).
- **Found in:** Chapter 4.4.2, mentioned as a conceptual reference for Amsterdam's metabolism

Urban Sustainability

The practice of developing urban environments that meet current needs without compromising future generations' ability to meet theirs, balancing economic, social, and environmental dimensions.

- **Reference:** Campbell, S. (1996). "Green Cities, Growing Cities, Just Cities?" Journal of the American Planning Association
- **Found in:** 1.1.1, positioned as a goal that Urban Metabolism (UM) serves as an urban sustainability tool just like the previous definitions above it.

Political Ecology and Justice Frameworks

Political Ecology

An analytical framework examining the power relations and socio-political structures that shape environmental conditions and resource access, providing the critical lens for understanding metabolic inequalities, the relationship between it and the resources of the city, in addition to our social structures is analyzed by Heynen.

- **Reference:** Heynen, N., Kaika, M., & Swyngedouw, E. (2006). In the Nature of Cities: Urban Political Ecology
- **Found in:** Chapter 2.1.3 & 2.2.2.

Spatial Justice

The equitable distribution of urban resources, services, and opportunities across space, serving as both an ethical principle and analyzed in relation to UM's incomes and outcomes.

Reference: Soja, E. W. (2010). Seeking Spatial Justice, Harvey, D. (2008). "The right to the city."

Found in: Chapter 1.1.2 & 1.5.1 and continued until the end as a core, interconnected dimension of the study and its relationship with UM.

Quantitative-Qualitative Divide

The divide in urban metabolism scholarship between technocratic flow accounting and socio-spatial justice considerations, introduced in this research.

- **Reference:** Documented through metal analysis in Chapter 4.1
- **Found in:** Chapter 2.2.1, addressed in the literature review.

Perception-Reality Paradox

By explaining the difference between the objective conditions and subjective resident perceptions, revealing the complex dimension of "people as a flow."

- **Reference:** Original findings from integrated survey and spatial analysis
- **Found in:** Chapter 4.4.1.4, identified in the survey results from Amman's zoning analysis

Urban Climate and Environmental Terms

Urban Heat Island (UHI) Effect

The phenomenon where urban areas experience significantly higher temperatures than their rural surroundings is due to human activities and modified land surfaces.

- **Reference:** Oke, T.R. (1982). "The energetic basis of the urban heat island." Quarterly Journal of the Royal Meteorological Society
- **Found in:** Chapter 2.3.1 & 4.2.1,

Carbon Sequestration

The process of capturing and storing atmospheric carbon dioxide, performed by urban vegetation through photosynthesis and biomass accumulation, serving as a key metabolic function.

- **Reference:** Nowak, D.J., & Crane, D.E. (2002). "Carbon storage and sequestration by urban trees in the USA." Environmental Pollution
- **Found in:** Chapter 2.3.1, 4.2.2 as part of the outputs of ENVI-met simulations and analyzed in the species-specific metabolic assessment.

CO_2 Flux

The rate of carbon dioxide exchange between urban surfaces/vegetation and the atmosphere, measured in $mg/m^2 \cdot s$, indicating the carbon metabolism performance of urban systems.

- **Reference:** Grimmond, C.S.B., et al. (2002). "Local-scale fluxes of carbon dioxide in urban environments: Methodological challenges and results from Chicago." Environmental Pollution
- **Found in:** Chapter 3.2.2 & 4.2.2, listed as a key output of ENVI-met simulations and analyzed in the species-specific metabolic assessment.

Vapor Flux

The rate of water vapor transfer from surfaces and vegetation to the atmosphere through evapotranspiration, measured in g/kg·m·s, representing the water metabolism of urban systems.

- **Reference:** Oke, T.R. (1987). Boundary Layer Climates
- **Found in:** Chapter 3.2.2 & 4.2.2, listed as a key output of ENVI-met simulations and analyzed in the species-specific metabolic assessment.

Evapotranspiration

The combined process of water evaporation from surfaces and transpiration from plants represents a critical cooling mechanism in urban metabolic systems.

- **Reference:** Grimmond, C.S.B., & Oke, T.R. (1991). "An evapotranspiration-interception model for urban areas." Water Resources Research
- **Found in:** Chapter 2.3.1, described as a key process through which GI influences the climate and water flows of a city.

Methodologies and Analytical Tools

Material Flow Analysis (MFA)

A quantitative method to trace the input, stock, and output of materials in an urban system over time, allowing identification of resource inefficiencies and potential circularity.

- **Reference:** Brunner, P.H. & Rechberger, H. (2004). Practical Handbook of Material Flow Analysis
- **Found in:** Chapter 2.1.2 & 2.4.4, a foundational tool of UM.

Life Cycle Assessment (LCA)

A methodology to evaluate environmental impacts associated with all stages of a product, service, or system's life, from raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling.

- **Reference:** Finnveden, G., et al. (2009). "Recent developments in Life Cycle Assessment." Journal of Environmental Management
- **Found in**: 2.1.2 & 2.4.4

ENVI-met

A three-dimensional microclimate simulation software that models surface-plant-air interactions in urban environments, enabling high-resolution analysis of temperature, humidity, wind flow, and radiation.

- **Reference:** Bruse, M. & Fleer, H. (1998). "Simulating surface–plant–air interactions inside urban environments with a three-dimensional numerical model." Environmental Modelling & Software
- **Found in:** Chapter 3.2.2, "Tool 2: Microclimatic Simulation (ENVI-met)" and Chapter 4.

Microclimatic Simulation

Computational modeling of localized atmospheric conditions at the neighborhood or building scale, capturing interactions between urban form, materials, vegetation, and meteorological factors.

- **Reference**: Arnfield, A.J. (2003). "Two decades of urban climate research: A review of turbulence, exchanges of energy and water, and the urban heat island." International Journal of Climatology
- **Found in:** the base used by the ENVI-met simulation throughout the studies.

Correlation Analysis

A statistical method measuring the strength and direction of relationship between two variables, used in this research to quantify connections between urban morphology and metabolic performance.

- **Reference:** Fisher, R.A. (1921). "On the interpretation of χ^2 from contingency tables, and the calculation of P." Journal of the Royal Statistical Society
- **Found in:** Chapter 4.3.3, used to describe the relationship between Biota scores and perceived walkability ("r=0.85").

Remote Sensing

The science of obtaining information about objects or areas from a distance, typically from aircraft or satellites, uses electromagnetic radiation to monitor urban and environmental changes.

- **Reference:** Lillesand, T.M., Kiefer, R.W., & Chipman, J.W. (2015). Remote Sensing and Image Interpretation
- **Found in:** Chapter 2.1.2 & 4.1.1, as part of the methods of UM

Normalized Difference Vegetation Index (NDVI)

A remote sensing metric quantifying photosynthetic activity by measuring the difference between near-infrared and red-light reflection, serves as an indicator for vegetative abundance and health.

- **Reference:** Tucker, C.J. (1979). "Red and photographic infrared linear combinations for monitoring vegetation." Remote Sensing of Environment
- **Found in:** Chapter 4.4.1 & 4.4.2, used as the primary biophysical data source for analyzing GI distribution across zoning codes and for the Disparity Ratio analysis.

Urban Morphology

The study of the physical form and structure of urban areas, including patterns, shapes, and spatial organization of buildings, streets, and open spaces.

- **Reference:** Kropf, K. (2017). The Handbook of Urban Morphology, Moudon, A.V. (1997). "Urban morphology as an emerging interdisciplinary field."
- **Found in:** Chapter 2.5.1, used to describe the fragmented fabric of Amman.

Potential Air Temperature (PAT)

The simulated air temperature in ENVI-met models representing thermal conditions unaffected by local humidity variations, used for comparative analysis of urban cooling interventions.

- **Reference:** ENVI-met documentation and scientific applications

- **Found in:** Chapter 4.2.1 & 4.2.3, presented as the key output metric in the results of all thermal simulation studies (e.g., Figures 12, 13, 27).

Leaf Area Index (LAI)

The ratio of total upper leaf surface area to ground surface area, a key parameter in microclimatic simulations determining shading capacity and transpiration rates of vegetation.

- **Reference:** Watson, D.J. (1947). "Comparative physiological studies on the growth of field crops." Annals of Botany
- **Found in:** Chapter 3.2.2, the physiological inputs for modeling tree species in ENVI-met.

Albedo

The measure of surface reflectivity, ranging from 0 (perfectly absorbing) to 1 (perfectly reflecting), significantly influencing urban heat absorption and radiative balance.

- **Reference:** Taha, H. (1997). "Urban climates and heat islands: albedo, evapotranspiration, and anthropogenic heat." Energy and Buildings
- **Found in:** Chapter 4.2.1.2, specified as a material property for local surfaces (asphalt, concrete, limestone) in the ENVI-met simulation setup.

Personal concepts and definitions used:

Metabolic Mis-selection

A condition where tree species or green infrastructure elements are chosen for short-term benefits while introducing long-term metabolic inefficiencies that undermine urban resilience.

- **Found in:** Chapter 4.2.2.1, introduced as the hypothesis driving the species-specific metabolic analysis.

Street Metabolism

Using street-level imagery to quantify the human-scale perception and composition of urban flows, bridging the quantitative-qualitative divide in UM studies.

- **Found in:** Chapter 4.1.

Disparity Ratio

A quantitative metric used in this dissertation by comparing green infrastructure distribution (via NDVI) between high-income and low-income neighborhoods to indicate metabolic stability.

- **Found in:** Chapter 4.4.2.2, (High Income NDVI / Low Income NDVI) for the spatial justice analysis.

Diminishing Returns Threshold

A principle identified in this dissertation where strategic, targeted interventions yield maximum metabolic benefits, beyond which additional investments provide progressively smaller returns.

- **Found in:** Chapter 4.2.1.4 & 5.5 Thesis 5, discussed in the context of asphalt reduction strategies and formalized as a key scientific finding.

Metabolic Return on Investment (MROI)

A concept suggested in this dissertation by evaluating the cooling benefit per unit of intervention, enabling cost-benefit analysis of urban metabolic improvements.

- **Found in:** Chapter 4.2.1.4, introduced in the discussion of strategic intervention sequencing for resource-constrained cities.

Green View Index (GVI)

A metric quantifying the percentage of greenery visible in street-level imagery, capturing the human-scale perception of green infrastructure that satellite-based indices miss.

- **Found in:** Chapter 4.1.2, described as the output of the Street Metabolism method.

Floor Area Ratio (FAR)

A zoning metric representing the ratio of a building's total floor area to the size of the parcel on which it is built, directly regulating urban density and development intensity.

- **Found in:** Chapter 4.4.1.2, used as a key calculated metric in the urban morphological analysis of Amman's zoning categories.

APPENDIX C: LITERATURE REVIEW

This appendix showcases the analyzed literature and publications chosen for the field of Urban Metabolism as mentioned in the Literature Review

Table C1.

Full classification of 41 influential Urban Metabolism publications, including authors, publication type, source, aspect representation, and citation count

No.	Title	Author	Year	Publication Type	Environ-mental Aspects	Spatial Aspects	Socio Economics Aspects	Citations, 2022 Google Scholar
1	In the Nature of Cities	Heynen, N.; Kaika, M.; Swyngedouw, E.	2006	Book, Routledge	No	Yes	Yes	1669
2	The Changing Metabolism of Cities	Kennedy, C.; Pincetl, S. Bunje, P.	2007	Journal, Environmental Pollution	Yes	Yes	Yes	1610
3	Urban Metabolism of Paris	Barles, S.	2008	Journal of Industrial Ecology	Yes	Yes	No	101

4	UM & Sustainable Development in Rotterdam	Tillie, N. et al.	2014	Report, IABR / Municipality of Rotterdam	Yes	Yes	No	101
5	Understanding Urban Metabolism	Chrysoulakis, N. et al.	2015	Book Springer	Yes	Yes	No	58
6	UM Planning Approaches	Pinho, P. et al.	2017	Journal Urban Ecosystems	No	Yes	Yes	15
7	Urban Metabolism: Review & Future Directions	Zhang, Y.	2017	Journal, Resources, Conservation & Recycling	Yes	No	Yes	164
8	Society, Energy, Materials in Paris	Barles, S.	2009	Journal of Industrial Ecology	No	Yes	Yes	318
9	General Approaches to Assess Sustainability	Baynes, T.	2011	Journal Environmental Modelling	Yes	No	No	137
10	UM: A Review of Recent Methodologies	Zhang, Y. et al.	2015	Journal of Cleaner Production	Yes	No	No	407
11	Renewable Energy & Circular UM	Ersoy, A.	2020	Book, Springer	Yes	No	No	172
12	Urban Metabolism in Asian Cities	Zhang et al.	2010	Report UN-Habitat	Yes	No	No	10
13	Urban Ecosystems & Energy Flow	Zhang, Y.	2013	Journal, Ecological Modelling	Yes	No	No	127
14	Environmental Implications of Circular UM	Zhang, Y.	2018	Journal of Cleaner Production	Yes	No	No	727
15	Urban Metabolism of Beijing Zh	Zhang et al.	2015	Journal of Industrial Ecology	Yes	No	No	722

	ang et al.							
16	Material Flow Analysis of Beijing	Tan, Z. et al.	2014	Journal of Cleaner Production	Yes	No	No	347
17	Energy & Exergy Flow in Cities	Chen, B.; Chen, G.	2011	Journal Ecological Modelling	Yes	No	No	167
18	Ecosystem Services & Flows in Cities	Haase, D.	2015	Journal Ecological Indicators	No	Yes	Yes	109
19	UM in Indian Cities	Singh, S. et al.	2017	Journal of Industrial Ecology	Yes	No	No	77
20	Review of Urban Energy Use	Kennedy et al.	2010	Journal of Industrial Ecology	Yes	No	No	227
21	UM of European Cities	Goldstein, B.; Birkved, M.; Quitzau,	2013	Journal of Cleaner Production	Yes	Yes	No	371
22	Infrastructure & UM Transitions	Newman, P.	2016	Journal Urban Studies	No	Yes	Yes	79
23	UM & Sustainable Development	Broto, V.; Allen, A.; Ratti, C.	2020	Journal Cities	Yes	No	No	28
24	Methodological Review of UM Studies	Resenberg et al.	2018	Journal of Cleaner Production	Yes	No	No	95
25	Energy Use in Chinese Cities	Cui et al.	2019	Journal Applied Energy	Yes	Yes	No	47
26	Metabolism of African Cities	Meinard et al.	2016	Report UNEP	Yes	No	No	4
27	Challenges in UM Sustainability	Lü et al.	2015	Journal of Environmental Management	Yes	No	No	108
28	Sustainable Urban Infrastructure	Fenner, R. et al.	2018	Book, Springer	Yes	Yes	No	20

29	Socio-economic Metabolism of Taiwan	Wang et al.	2019	Journal of Industrial Ecology	Yes	No	Yes	46
30	Energy & Material Flow Review	Decker et al.	2000	Journal of Industrial Ecology	Yes	No	No	6310
31	The Social Metabolism: A Socio-Ecological Theory	Fischer-Kowalski, M.; Haberl, H.	1999	Journal Regional Studies	Yes	No	Yes	700
32	Smart Urban Metabolism	Zhou et al.	2020	Journal Sustainable Cities	Yes	Yes	No	108
33	UM & Urban Transitions	Levine et al.	2018	Journal Urban Transitions	No	Yes	No	147
34	Metabolic Accounting of Cities	Li et al.	2017	Journal of Environmental Management	Yes	No	No	31
35	Governance & Urban Metabolism	Dijst, M.; Ziying, Y.	2013	Book Routledge	No	Yes	Yes	152
36	Construction Material Flows in Cities	Zhao et al.	2017	Journal Resources, Conservation	Yes	No	No	241
37	The Metabolism of Hong Kong	Newcombe et al.	1978	Journal	Yes	No	No	227
38	Urban Agriculture & UM	Dettlaff, W.	1997	Journal Land Use Polic	No	Yes	Yes	27
39	Metabolism of Cities	Newcombe et al.	1991	Journal of Environmental Management	Yes	No	No	110
40	UM & Circular Economy in China	Ren et al.	2014	Journal of Cleaner Production	Yes	No	No	117
41	Spatial Patterns in UM	Chen, G.; Qian, Z.	2018	Journal, Habitat International	Yes	Yes	No	79

APPENDIX D: SIMULATION METHODS CONFIGURATIONS

This appendix provides a summary of the primary simulation configurations presented in the Methods chapter (3), it shows the datasets and key quantitative elements that form the foundation of this dissertation's Microclimatic simulations and analysis. The data is drawn from the core computational studies conducted mostly in Amman, Jordan, and one example in Budapest, Hungary, utilizing the high-resolution, three-dimensional microclimatic modeling software ENVI-met.

All microclimatic simulations were performed using ENVI-met. The model was used to quantify key metabolic indicators, including Potential Air Temperature (PAT), CO_2 flux, and vapor flux, under peak summer conditions to stress-test the urban fabric and proposed interventions.

The data sets are presented in numerical order depending on their position in the dissertation.

1. Temperature and GI as Metabolic Indicators. (spatial configurations study).

Table D1.

Showcasing the Configurations for "Spatial Configurations" (Amman) explained in the methodology subchapter 3.2.2 and later simulated in results of subchapter 4.2.1

Parameter	**Configuration Details**
Study Focus	Quantifying thermal impact of Green Pockets, Courtyard Blocks, and Semi-Superblocks.
Simulation Date	1 July 2024
Analysis Time	12:00 PM (midday peak heating)
Total Simulation Time	24 hours (incl. spin-up), With focus on the first 2 hours from 12:00 PM (Peak heating period)
Weather File	Energy Plus Weather (EPW) Amman
Wind Speed/Direction	2.5 m/s at 10m height, 315° (Prevailing NW)
Initial Relative Humidity	30% (characteristic of arid summer midday)
Initial Air Temperature	34.5 °C (from EPW data)
Soil Model	Loamy soil
Grid Resolution (Dx, Dy, Dz)	1m, 1m, 1m (for high-resolution analysis of urban form)
Pavement Albedo	0.18 (Standard for Amman's gray concrete/asphalt)

2. Tree Species Metabolic Performance in Arid Climates.

Table D2.

Showcasing the Configurations for "Tree Species as Metabolic Agents" (Amman) explained in the methodology subchapter 3.2.3 and later simulated results in subchapter 4.2.2.

Parameter	**Configuration Details**
Study Focus	Comparing metabolic performance of Melia azedarach, Olea europaea, and Ceratonia siliqua.

Simulation Date	1 July 2024
Analysis Time	12:00 PM (midday peak heating)
Total Simulation Time	24 hours (incl. spin-up), With focus on the first 2 hours from 12:00 PM (Peak heating period)
Weather File	Energy Plus Weather (EPW) Amman
Sectional Cut location	Around 1.6 M Height (Human Height Focused)
Initial Relative Humidity	30% (characteristic of arid summer midday)
Initial Air Temperature	34.5 °C (from EPW data)
Wind Speed / Direction	2.5 -3.5 m/s at 10 M, NW/315
Soil Model	Loamy soil
Grid Resolution (Dx, Dy, Dz)	Scenarios A&B: 1m, 1m, 1m, Scenario C: 3m, 2m, 2m

Table D3.

Species specific parameters and values used in the ENVI-met simulation for "Trees Species as Metabolic Agents" explained in the methodology subchapter 3.2.3 and later simulated results in subchapter 4.2.2.

Parameter	**Melia azedarach**	**Olea europaea**	**Ceratonia siliqua**
LAI	3.5	2.1	2.8
Albedo	0.18	0.18	0.18
Transmittance	0.40	0.25	0.30
Emissivity	0.95	0.95	0.95
Canopy Height	7 M	5 M	9 M
Leaf Type	Deciduous	Evergreen	Evergreen
Leaf Size	0.15 m2	0.1m2	0.12 m2
Stomatal Conductance	280	160	140

These species-specific parameters are what allowed the simulation program to provide results. It is stored as the default within the program depending on the standards available but was also investigated and crosschecked from different sources and references in the publication *Land* 2025, *14*(8), 1566.

Table D4.
Spatial configuration, grid resolution, and buffer allocation for each ENVI-met simulation scenario.

Scenario	**ENVI met Dimensions X*Y*Z**	**ENVI met grid size Dx, Dy, Dz**	**Domain Size**	**Buffer**	**% Domain Width**
Scenario A	30 × 30 × 30	1M, 1M, 1M	20 × 20 m	7–10 m	35- 50 %
Scenario B	50 × 20 × 50	2 M, 2 M, 2 M	60 × 20 m	10 m	12–17%

Scenario C	50 × 50 × 50	3 M, 2 M, 2 M	150 × 150 m	3 m	~2%

These are the specific dimensions and grid sizes used in the simulation program for the provided results, in what is called the spatial domains showcasing 3 scenarios in different scales:

- Scenario A (Plot): 20 x 20 m area.
- Scenario B (Street): 60 x 20 m area.
- Scenario C (Neighborhood): 150 x 150 m area.

3. Neighborhood Level Metabolic Diagnosis.

Table D5.

Showcasing the Configurations for "Neighborhood Metabolic Analysis" (Amman) explained in the methods subchapter 3.2.3 and simulated in results of the subchapter 4.3

Parameter	Configuration Details
Study Focus	Quantifying thermal impact in 4 districts
Simulation Date	1 July 2024
Analysis Time	12:00 PM (midday peak heating)
Total Simulation Time	24 hours (incl. spin-up), With focus on the first 2 hours from 12:00 PM
Sectional Cut location	Around 1.6 M Height (Human Height Focused)
Initial Relative Humidity	30% (characteristic of arid summer midday)
Initial Air Temperature	34.5 °C (from EPW data)
Soil Model	Loamy soil
Grid Resolution (Dx, Dy, Dz)	2m, 2m, 2m (optimized for larger neighborhood domain)
Pavement Albedo	0.18 (Standard for Amman's gray concrete/asphalt)

4. Institutional Gardens (Budapest).

Table D6.

Showcasing the Configurations for "Institutional Gardens" (Budapest), the simulations are presented in subchapter 4.2.3

Parameter	Configuration Details
Study Focus	Microclimatic regulation of Budafok cemetry
Simulation Date	Representative hot summer day (July) (2025)
Analysis Time	12:00 – 14:00 (Peak heating period)
Total Simulation Time	24 hours (incl. spin-up), With focus on the first 2 hours from 12:00 PM
Weather File	Energy Plus Weather (EPW) file for Budapest
Initial Air Temperature	22°C (Night) to 34°C (Day) range

Wind Speed/Direction	315° (Prevailing NW)
Sectional Cut location	Around 1.6 M Height (Human Height Focused)
Initial Relative Humidity	30% (characteristic of arid summer midday)
Initial Air Temperature	34.5 °C (from EPW data)
Soil Model	Loamy soil (40% sand, 40% silt, 20% clay)
Grid Resolution (Dx, Dy, Dz)	Cemetery: 8m, 10m, 2m
Pavement Albedo	0.35 (Light concrete graves) / 0.10 (Dark concrete paths)

APPENDIX E: RESULTS AND SUPLLEMENTARY DATA

This appendix provides supplementary and needed data presented in the results chapter (4), it shows some datasets, criteria, images used in analysis, and survey results.

E1. Neighborhood Level Metabolic Diagnosis.

This section introduces the neighborhood-level metabolic diagnosis framework, detailing the evaluation criteria which is basically a smaller scale of the original criteria used to analyze metabolic flows, and scoring technique used to assess urban flows across biota, climate, goods, people, waste, water, and energy

Table E1.

Introducing the Criteria and scoring technique followed

Flow	**Criteria**	**Assessment Technique (Score out of 3)**	**Score 1**	**Score 2**	**Score 3**
Biota	Type of flora and fauna	Ecological evaluation regarding adaptability	Minimal drought / heat resistance	Moderate drought or heat resistance	High drought or heat resistance
	General design	Design based analysis	Basic design, limited	Functional design, moderate	Innovative design, highly effective
	biodiversity variety	Ecological analysis and percentage/ratio evaluation	Low biodiversity ratio	Moderate biodiversity ratio	High biodiversity ratio
	Connectivity	Ecological analysis regarding green corridors	Limited connectivity	Some connectivity, but with gaps	Extensive connectivity
	Maintenance strategies	Efficiency and sustainability assessment	Maintenance is inefficient	Maintenance is somewhat efficient	Low maintenance, highly efficient
	Adaptation to seasons	Seasonal planting strategies and invasive species	Poor adaptation	Moderate adaptation	Excellent adaptation
Climate	environment temperature	Measurement of street and surroundings temperature and reflective elements	High temperatures, low comfort	Moderate temperatures, some discomfort	Low temperatures, comfortable for pedestrians

	Heat Reduction Elements	Assessment	Few or no Heat Reduction	Some heat reduction elements present	Abundant heat reduction
	Building Height	Analysis based on Jan Gehl analysis.	Buildings height poor shading	Mixed heights, some shading	Optimal shading element
	Street Orientation	Sun exposure analysis	Poor orientation, excessive sun	Moderately oriented or optimized	Excellent orientation/ shade
	Microclimate Creation	Assessment	Minimal efforts	Moderate modification	Comprehensive modification
Goods	Street Vendors	Environmental impact and obstruction design analysis	High disruption, poor hygiene	Moderate or some disruption	Minimal waste, well-managed
	Sustainable Delivery Systems	Use of bike couriers, electric vehicles assessment	Predominantly fossil fuel vehicles, high	Mix of fossil fuel and some sustainable vehicles	Predominantly sustainable vehicles, low
	packaging-waste	Reduction initiatives assessment	High levels of single use, no reduction	Some initiatives, partial reduction	Comprehensive eco-friendly packaging
	Traffic/pollution effects	Traffic and pollution effects analysis	Significant congestion	Some strategies mild congestion	Well-plan, minimal congestion
People	Population density	Density impact on street congestion and usability	High density and overcrowdness	Moderate manageable density	Low density with optimal street use
	Pedestrian flow/comfort	Design based analysis	Narrow sidewalks, obstructed	Adequate sidewalks, some seating areas	Wide sidewalks, no obstruction
	Public safety	Lighting, visibility, security	Poor lighting, visibility, security	Adequate lighting, moderate visibility	Excellent lighting, visibility, security
	Accessibility for all	Ramps, tactile paving analysis	Limited or no accessibility	Some accessibility features present	Comprehensive accessibility
	Social interaction	Evaluating social interaction	Few or no social interaction spaces	Some social interaction spaces	well-designed social spaces
	People stress	Gallup world ranking for emotions	no greenery, traffic & stress levels	Moderate greenery, stress levels	low stress related factors
Waste	Street cleaning schedules	Schedule and frequency evaluated	Inconsistent schedules	Regular but infrequent cleaning	well-coordinated schedules
	Public littering awareness	Survey	Low awareness, high littering	Moderate awareness/ littering	High awareness, minimal littering

	Waste segregation	Survey	Limited segregation	Some segregation systems in place	Comprehensive segregation
	single-use plastics	nearby shops evaluated	High usage of single-use plastics	Moderate reduction efforts	Significant reduction efforts,
	Waste control infrastructure	Design analysis	Few bin points, poorly maintained	Close to adequate number of bins	Adequate bins and well-maintained
Water	Water Management Elements	permeable pavements, rainwater harvesting, drought combating design	Predominantly impermeable surfaces	Partial implementation of permeable surfaces	Extensive use of permeable well-integrated systems
	Floodwater Street Elements	Bioswales, rain gardens design analysis	Absent or minimal floodwater management	Presence of some bioswales, rain gardens	Comprehensive floodwater management
	Water Usage and Efficiency	water conservation methods in the city	Predominant use of traditional irrigation	Partial adoption of water-efficient systems	Extensive use of efficient water systems
	Greywater Recycling	Design analysis	No greywater recycling systems	Limited greywater recycling initiatives	Comprehensive recycling systems
Energy	Renewable energy sources	Efficient street lighting, solar panels, public transportation energy usage	Traditional lighting, high energy consumption	Partial use of energy-efficient lighting	Comprehensive use of energy-efficient lighting
	Street furniture	Assessing Benches, kiosks solar powered etc.	No energy-efficient street furniture	Some energy-efficient furniture	Widespread use of efficient furniture
	Smart grid integration	Assessing smart grid integration in the city	No smart grid integration	Partial smart grid integration	smart grid real-time monitoring
	Energy awareness	Survey	No awareness	Basic energy consumption	Comprehensive energy awareness

Resident Survey:

A structured survey of 320 residents (approximately 80 per neighborhood), around 160 were conducted mostly online using Google forms on the 20th of September 2024, all survey results were checked and verified by Scientific Reports an open-access scientific journal published by Nature Portfolio, presented in *Street-level urban metabolism as a tool for mapping urban flows in Amman's neighborhoods*, published (Tuffaha & Sallay, 2025). The questions are focused on perceptions of cleanliness, thermal comfort, walkability, and primary urban challenges.

The following are the survey questions deployed across four neighborhoods in Amman (Downtown, Jabal Amman, Sweifeyeh, Tla' Al-Ali).

Survey Questions:

1. What is your age category?

- Under 24
- 25-34
- 35-54
- 55+

2. Which location or area fits your residence?

- Downtown
- Jabal Amman
- Al Sweifeyeh, 7th circle
- Tla' Al-Ali
- Other (Please specify): ________________

3.Do you feel the people in your neighborhood are aware of street cleanliness and throwing trash correctly?

- Yes, the majority does
- Some people do
- No

4.When it comes to waste segregation (Recycling), is your neighborhood aware and active towards it?

- Yes, the majority does
- Some people do
- No

5. Regarding Energy Awareness, are there efforts and public awareness to use energy-efficient tools like solar ene+5rgy?

- Yes, the majority does
- Some people do
- No

6. In your neighborhood, which of these is the biggest problem? Solving it could improve your neighborhood drastically.

- Lack of green areas or vegetation

- Climate control and extreme weather
- The people lack interaction (no correct interaction zones or methods)
- Wastes, cleanliness
- Water flooding and management, water shortage
- Increased Traffic
- Street vendors
- High energy costs, lack of sustainable energy

7. Check the category that needs development to improve your local street and the daily lives of the locals.

- Increase walkable area
- Climate control and extreme weather mitigation.
- Add street elements (like seats), and interaction zones.
- Recycling bins and waste disposal awareness
- Water flooding, management & shortage
- Improve parking spaces, car/people relationship, reduce traffic
- Add energy-efficient systems like solar power

8. On average, how many steps or Km's do you walk per day?

- 0-3000 (Under 2.5km)
- 3000-6000 (2.5km-5km)
- 6000-10000 (5km-8km)
- 10000+ (8km+)
- I don’t keep track

Survey results in figures:

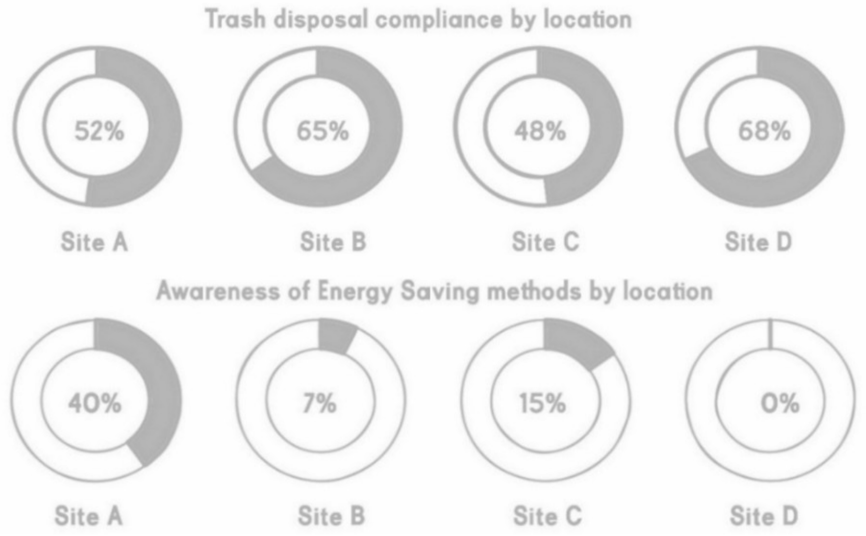


Figure E1. Graphs displaying survey results of the trash disposal and energy awareness through location A–D**.**

Figure E2. Graphs displaying survey results of the steps walked per day through locations A–D.

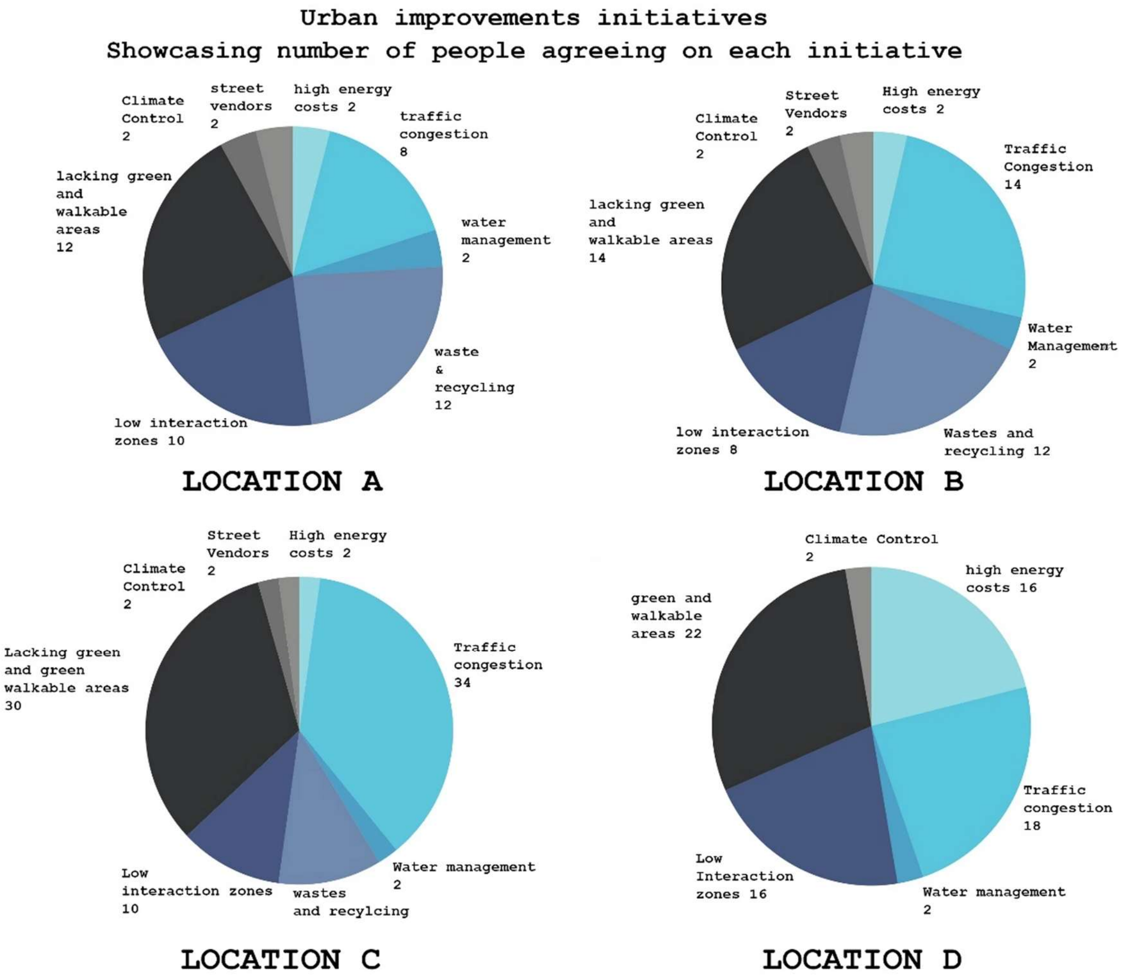


Figure E3. Urban improvement initiatives showcasing survey results from location A–D.

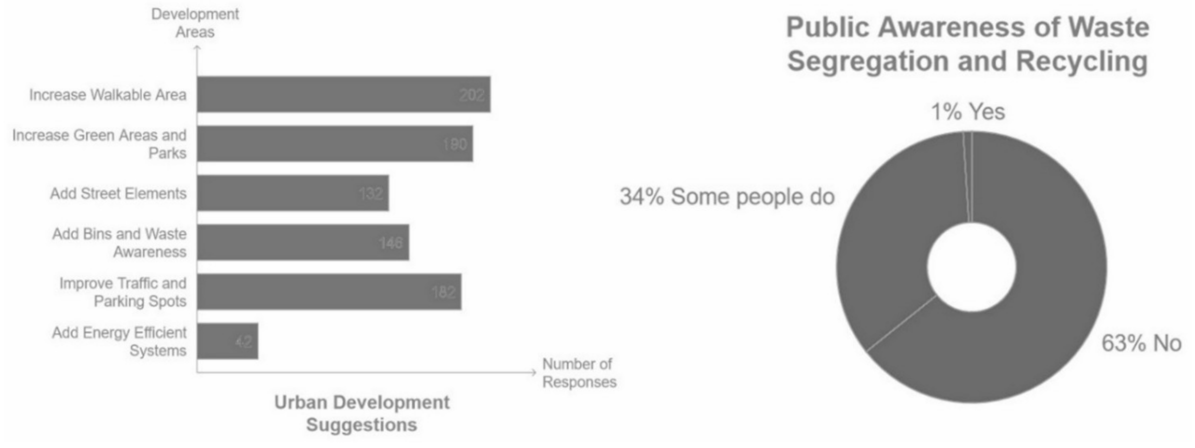


Figure E4. Urban development suggestions and people's awareness regarding recycling answers from A–D.

Statistical Analysis:

A multivariate regression analysis was performed to identify causal relationships. It confirmed that the Biota Score (greenery) was the strongest positive predictor of walkability ($\beta = 0.69$, $p <$

0.001), while the Goods Flow Score (traffic congestion) was a significant negative predictor ($\beta = -0.58$, $p = 0.007$).

Multivariate Regression Analysis ("Street-Level Urban Metabolism" Study)
A multivariate linear regression was applied to identify causal relationships between metabolic flows and pedestrian walkability, controlling for socio-economic variables.

- **Dependent Variable:** Walkability Score (standardized 10-point scale).
- **Independent Variables:**
    - Biota Score (10-point scale)
    - Goods Flow Score (traffic congestion, 10-point scale)
    - Climate Score (ENVI-met temperature deviation)
    - Income Level (survey-derived ordinal scale: 1 = low, 5 = high)

Table E2.

Multivariate Regression Results for Walkability Predictors

Variable	Coefficient (β)	Std. Error	p-value	95% Confidence Interval
Biota Score	0.69	0.12	<0.001	[0.48, 0.90]
Goods Score	-0.58	0.18	0.007	[-0.89, -0.27]
Climate Score	-0.21	0.09	0.061	[-0.39, 0.02]
Income Level	0.33	0.15	0.043	[0.06, 0.60]
R^2	0.82			

Biota Score: A 1-point increase in biota score corresponds to a 0.69-point increase in walkability ($p < 0.001$), confirming greenery's critical role.

Goods Flow: A 1-point increase in traffic congestion (lower goods score) reduces walkability by 0.58 points ($p = 0.007$).

- Biota is the strongest predictor of walkability ($\beta = 0.69$, $p < 0.001$).
- Goods flow (traffic congestion) significantly reduced pedestrian comfort ($\beta = -0.58$, $p = 0.007$).

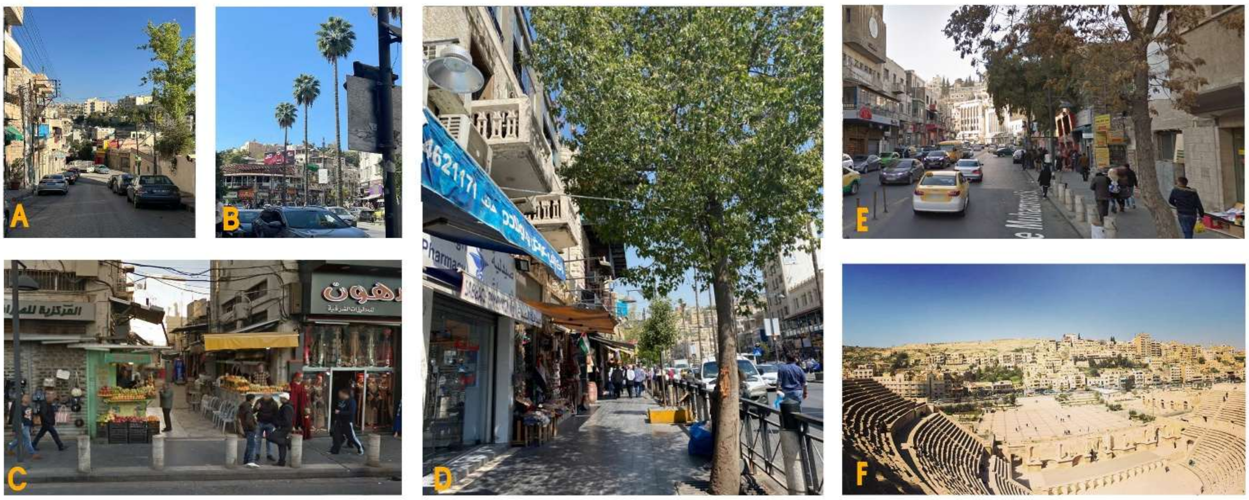
General images from site analysis and research:

Throughout the study each district A, B, C AND D are analyzed using several criteria mentioned. This appendix contains several important images showcasing, the condition and some analysis results in each district which can help understand the process of analysis on a neighborhood scale that is followed.

1.District A, Downtown, Amman, Jordan.

In order to understand each district's overall atmosphere in more detail, these are representative street-level views from District A (Downtown Amman).

Each lettered image illustrates characteristic urban typologies within the district with its exact location on the figure E6, highlighting variations in width, building enclosure, atmosphere.



(Photographs A, B, D and F taken by the author (Anas Tuffaha) in 2023, Photographs C and E obtained from Google Street View (© Google, 2023), accessed via Google Maps in 2023, available at https://www.google.com/maps/. Imagery was used for academic, non-commercial purposes in accordance with Google's Terms of Service.)

Figure E5. Showcases images and photographs of the chosen Site A in the anaylsis.

Full extent of District A, including vegetation distribution coverage.

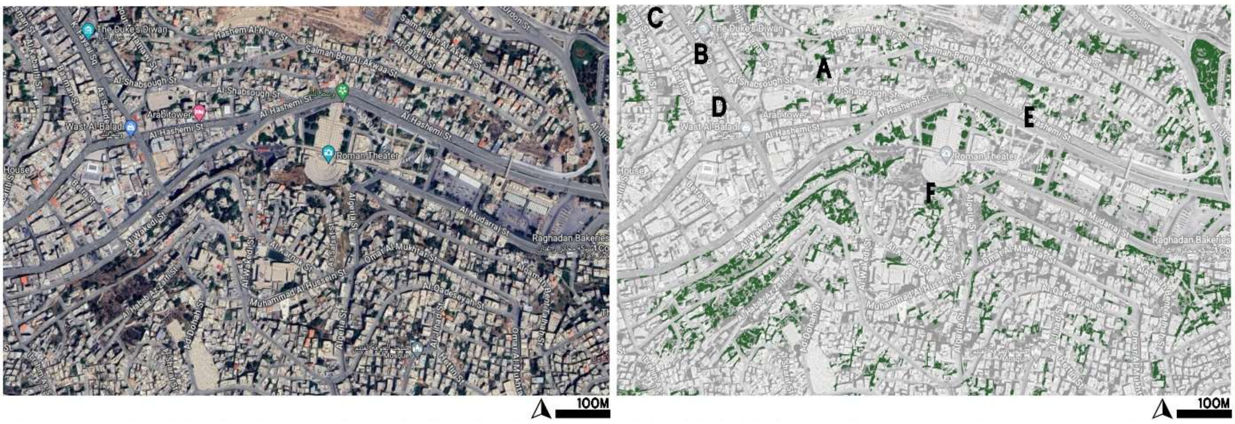
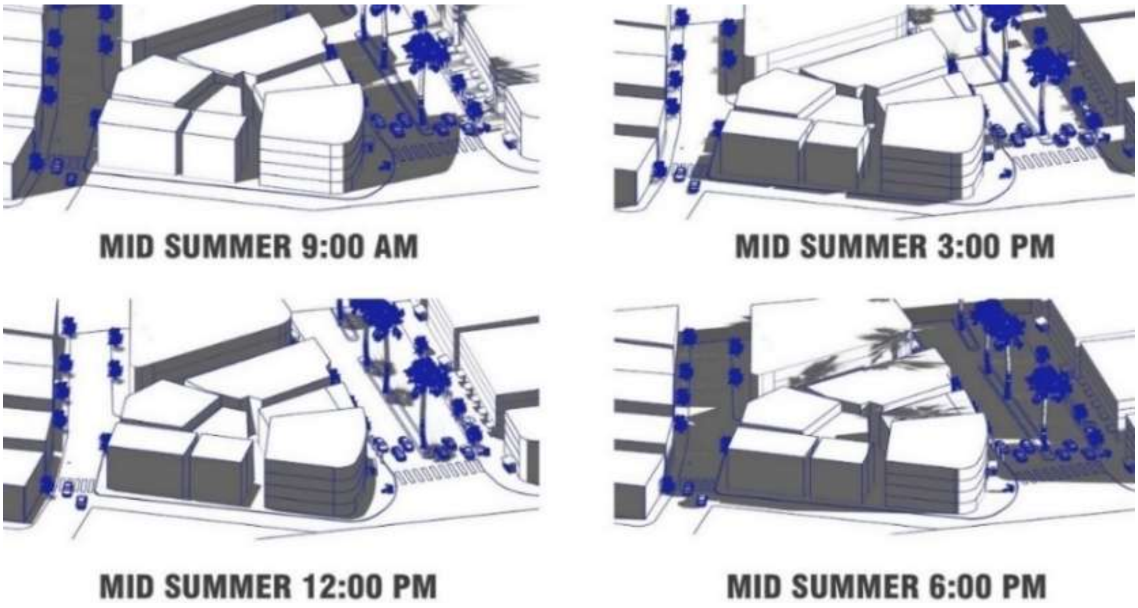


Figure E6. Downtown sample google earth aerial photo, followed by the green areas presented in green.

Another method for analysing the model was a three-dimensional models of selected central Downtown blocks as seen below, focusing on building heights, street widths, and spatial proportions.The model was used to examine shading patterns, enclosure ratios, and solar exposure in relation to street orientation during summer conditions at different times of the day.


MID SUMMER 9:00 AM

MID SUMMER 3:00 PM

MID SUMMER 12:00 PM

MID SUMMER 6:00 PM

Figure E7. The sample area presented in different hours of the day, showcasing shade,heights, and exposure. (3D models were created by Anas Tuffaha).

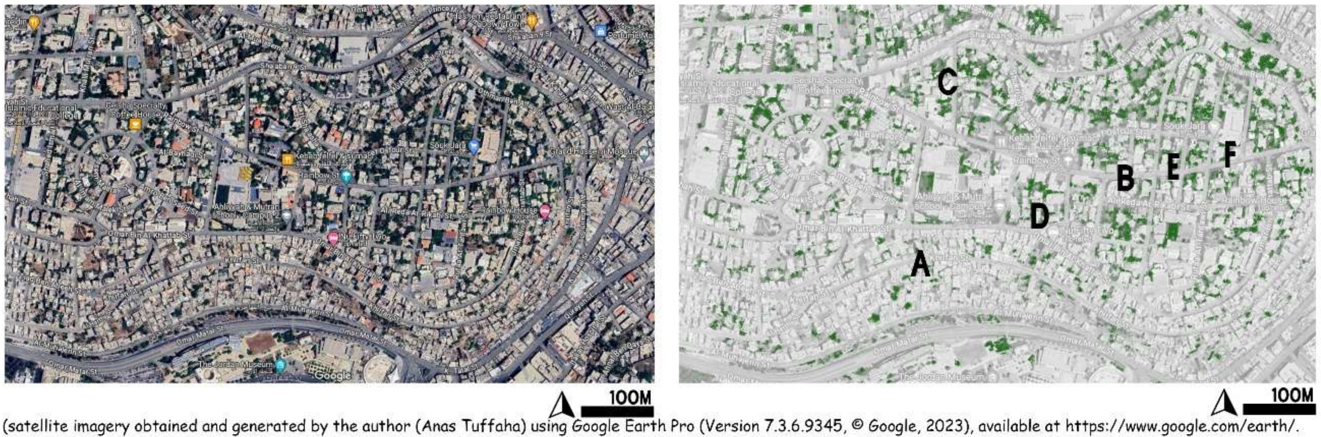
District B, Jabal Amman, Amman.

Views from District B as presented above showcasing the overall neighborhood atmosphere characterized by lower heights, wider streets and more touristic areas in addition to walkable neighborhoods.

(Photographs D & C taken by the author (Anas Tuffaha) in 2023, Photographs A, B, E and F obtained from Google Street View (© Google, 2023), accessed via Google Maps in 2023, available at https://www.google.com/maps/. Imagery was used for academic, non-commercial purposes in accordance with Google's Terms of Service.)

Figure E8. Showcasing images obtained and collected of Site B.

Full extent of District B, including vegetation distribution coverage, in addition to the alphabets showcasing the street images in the figure above (E8).



(satellite imagery obtained and generated by the author (Anas Tuffaha) using Google Earth Pro (Version 7.3.6.9345, © Google, 2023), available at https://www.google.com/earth/. Imagery was edited for academic visualization purposes using Adobe Photoshop CC 2015 (Version 16.0, © Adobe Inc., https://www.adobe.com/). Used in accordance with Google's permissions guidelines (http://www.google.com/permissions/geoguidelines/attr-guide.html).)

Figure E9. Site B google earth aerial photo, followed by the green areas presented in green.

Three-dimensional models of the selected district blocks as seen below, focusing on building heights, street widths, and spatial proportions.The model was used to examine shading patterns, enclosure ratios, and solar exposure in relation to street orientation during summer conditions at different times of the day.


Mid Summer 9:00 AM

Mid Summer 3:00 PM

Mid Summer 12:00 PM

Mid Summer 6:00 PM

Figure E10. The sample area presented in different hours of the day, showcasing shade,heights, and exposure.

Zone C, Sweifeyeh, 7th circle, Amman:

Views from District C as presented above showcasing the overall neighborhood atmosphere characterized by more commercial atmosphere, higher traffic and car use and 4-5 buildings storeys.

(Image obtained from Google Street View (© Google, 2023), accessed via Google Maps in 2023, available at https://www.google.com/maps/. Imagery was used for academic, non-commercial purposes in accordance with Google's Terms of Service.)

Figure E11. Showcases Site C images collected and obtained by the author. (Anas Tuffaha).

Full extent of the district showcased in 3d, showing the relation with the sun path to show the relation during summer conditions at different times of the day. in addition to heights, street widths, and spatial proportions.The model was used to examine shading patterns, enclosure ratios.

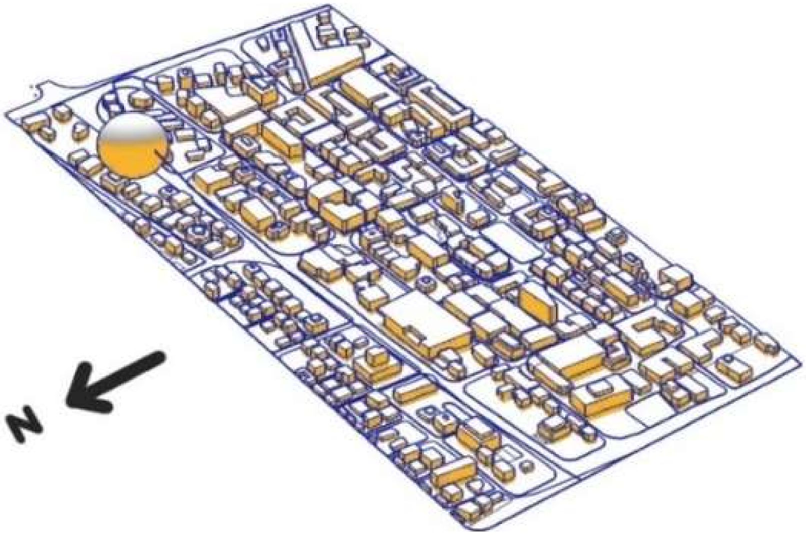


Figure E12. A simulation of the relation between building orientation and the sun.

Site D, Tla' il-Ali, Amman:

Views from District D as presented above showcasing the overall neighborhood atmosphere characterized by mostly residential areas, wide streets, thin pathways, low accessibility and dense areas.

(Image obtained from Google Street View (© Google, 2023), accessed via Google Maps in 2023, available at https://www.google.com/maps/. Imagery was used for academic, non-commercial purposes in accordance with Google's Terms of Service.)

Figure E13. Marked images around Site D presenting the overall atmosphere.

Images taken at the district showcasing a common issue at the neighborhoods pathways and pedesetrian walkways being blocked and limited in access giving Inaccessibiilty issues.

Figure E14. blocked path throughout site D showcasing blockage of trees and unfixed paves.

The last image from this method showcases the ENVImet simulations for the central zones of each district showcasing the potential air temperature and overall thermal distribution.

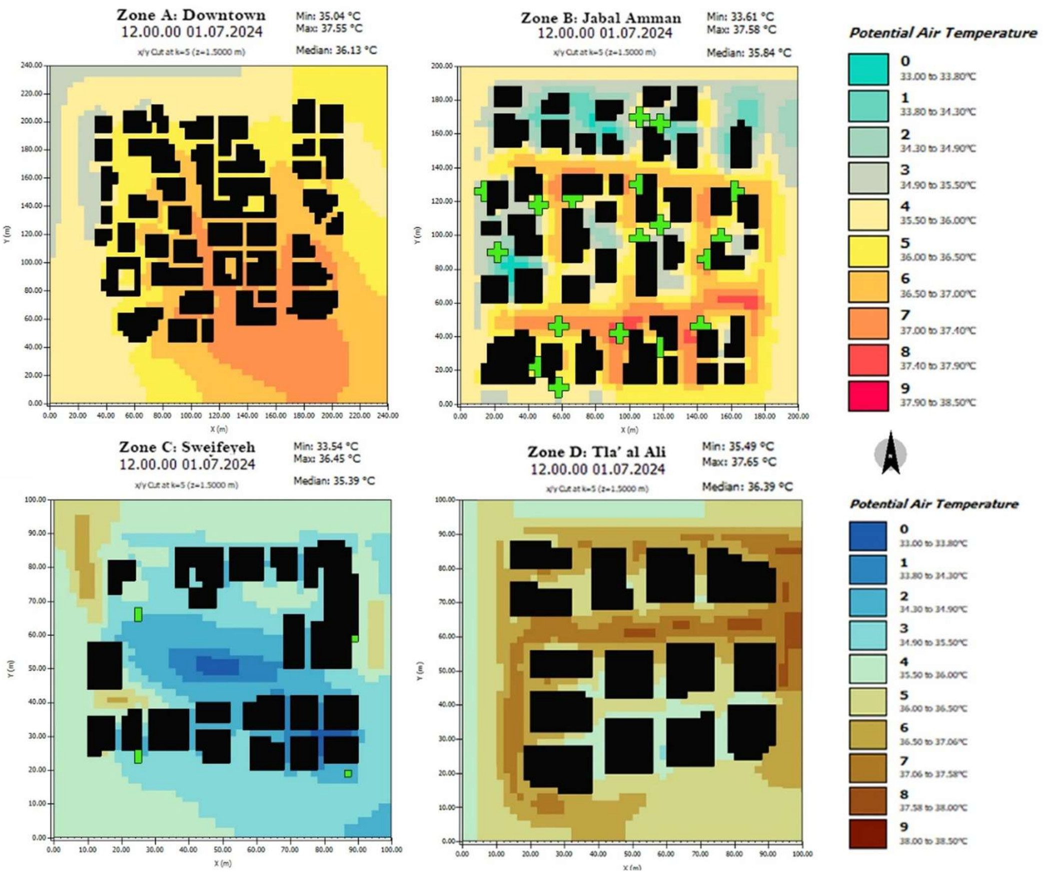


Figure E15. Presents the ENVI-met simulations for the blocks within the 4 neighborhoods.

E2. Latent GI as a Metabolic Reserve (Institutional Gardens)

This section of the appendix refers to the results chapter 4, more specifically 4.2.3 showcasing the small simulations using ENVI met that were done in Budapest's institutional gardens. The simulation results were shown in chapter 4, and below are the original and proposed conditions of the cemetery.

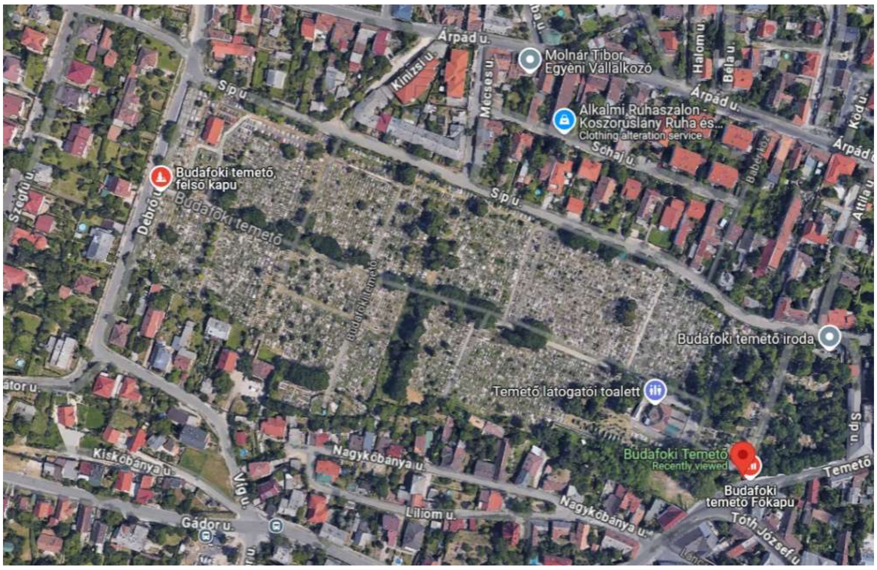


Figure E16. Showcases the Budafok Cemetery condition without any edits to the tree species, as named in the study "Current Status"

Figure E17. Showcases the Budafok Cemetery with additional tree species for the simulation as named the "Planned Status"

Results of the Full Simulations in addition to the mixture of components in each institutional garden (My focus was more central to the cemetery as part of the team):

Table E3.

Showcases the Simulation results in Temperature for both the Current and Planned status part of the study.

	Péterfy Sándor Street Hospital		**National Centre for Spine Hospital**		**Budafok Cemetery**	
	Current status	Planned status	Current status	Planned status	**Current status**	**Planned status**
Land area	22,637 m^2	22,637 m^2	23,170 m^2	23,170 m^2	**22,637 m^2**	**22,637 m^2**
Buildings	39%	39%	17%	17%	**39%**	**39%**
Paved surfaces	41%	32%	48%	34%	**41%**	**32%**
Vegetation-covered surfaces	20%	29%	35%	48%	**20%**	**29%**
Canopy coverage	15%	30%	35%	51%	**15%**	**30%**

Table E4.

Showcases the Simulation results on the PAT (Potential Air Temperature), in the original and planned condition of the Cemetery.

Original Condition	**Planned Condition**		**Maximum PAT Values in a Given Area**		
	Min. PAT values	Max. PAT values	Min. PAT values	Max. PAT values	

Budafok Cemetery	31.09 °C	34.13 °C	30.18 °C	32.00 °C	−2.13 °C

E3. Zoning Codes, Land Value, and Fabric of Amman

This section of the appendix refers to the results chapter 4, more specifically 4.4.1 showcasing the building classification codes, land values, names and locations of the areas analyzed in addition to results regarding NDVI analysis, density, and total calculated areas.

Table E5.

Classification zones, building codes and insights into income and wealth through land valuation zoning

Land by price Category	**Land Valuation (JOD, USD, EURO/sqm)**	**Building Code**	**Areas**
Zone 1 - High-value	500, 640, 710	A, B (Special Cases)	Abdoun, Dabouq, Al-Thahir
Zone 2 - Mid-value	250, 315, 350	C, occasional B	Tla' Al-Ali, Shmeisani
Zone 3 - Low-value	100, 130, 140	D, occasional C	Abu Alanda, tbrbour

Table E6.

Synthesized Urban Morphology and Perception Data by Zone

Aspect	**Zone 1**	**Zone 2**	**Zone 3**
Building Heights (m)	9m (2 floors + roof)	16m (4 floors)	
Setbacks	5m front/back, 4 M sides	4m front/back, 3 M sides	3m front/back, 2.5 M sides
NDVI Value	0.129	0.065	0.046

Results of High-resolution simulations regarding 100mx100m scenarios for each zone:

Table E7.

Showcases the Calculation and analysis results in each zone

Metric	**Zone 1 (High-Value)**	**Zone 2 (Mid-Value)**	**Zone 3 (Low-Value)**
Total Units	28	67	76
Total Built Area (m²)	2,800	6,700	7,600
Green Space (m²)	1,500	750	500
Unbuilt Area (m²)	5,700	2,550	1,900
Total Residents	168	536	608
Population Density (res/m²)	0.0168	0.0536	0.0608
Floor Area Ratio	0.28	0.67	0.76

Green Area per Person (m²)	8.93	1.40	0.82

E4. Spatial Justice as a Metabolic indicator

This paper is currently under second review by the editors in Nature (Scientific reports), I present its important data sets and information that can be needed for chapter 4.4.2 which includes NDVI and collected data for Amman, Cairo and Amsterdam. The method was as follows:

1. Grouping by Income: For each city, the six socio-spatial zones were grouped into three primary income categories: High, Mid, and Low.
2. Calculating Mean NDVI by Income Bracket: The average MEAN NDVI value was calculated for the two zones within each income category (e.g., the mean of 'High income, low density' and 'High income, high density' provides the 'High Income NDVI' for the city).
3. Computing the Disparity Ratio: To provide an intuitive measure of the gap between the most and least advantaged groups, a High-to-Low Income Disparity Ratio was calculated for each city using the formula:

   Disparity Ratio = High Income NDVI / Low Income NDVI
   A ratio of 1.0 indicates perfect equity. A higher ratio indicates a greater level of spatial injustice, quantifying how many times greener the high-income areas are compared to the low-income areas.

NDVI Metrics by Socioeconomic Typology in Amman

Table E8.

NDVI metrics in different locations by socioeconomic typologies in Amman

Socioeconomic Zone	Mean NDVI	STD	NDVI Range	NDVI Max	NDVI Min	Median	PCT90	location
High income, low density	0.1798	0.0905	0.6075	0.5934	0.0141	0.1790	0.2937	https://maps.app.goo.gl/bmJ7kKBnVtPmk3SK6
High income, high density	0.1511	0.0935	0.7702	0.7299	0.0403	0.1346	0.2743	https://maps.app.goo.gl/u7UWboY5PKcUCJYWA
Mid income, low density	0.1695	0.0815	0.5435	0.5362	0.0073	0.1648	0.2773	https://maps.app.goo.gl/yuRCBsACR6wmrDgw7
Mid income, high density	0.1177	0.0626	0.4770	0.4384	0.0386	0.1064	0.2773	https://maps.app.goo.gl/JLdGaNTcG3cppwUK8

Low income, low density	0.1181	0.0406	0.4020	0.3945	0.0075	0.1159	0.1705	https://maps.app.goo.gl/tFAoCHc3rpjFXvrd8
Low income, high density	0.0941	0.0600	0.5344	0.4838	0.0506	0.0786	0.1727	https://maps.app.goo.gl/8BwYiTFQ19xBcAjM7

NDVI Metrics by Socioeconomic Typology in Cairo

Table E9.

NDVI metrics in different locations by socioeconomic typologies in Cairo

Socioeconomic zone	**Mean NDVI**	**STD**	**NDVI Range**	**NDVI Max**	**NDVI Min**	**Median**	**PCT90**	**Location**
Low income, high density	0.0941	0.0606	0.6732	0.6638	-0.0094	0.0766	0.1498	https://maps.app.goo.gl/U2YydcAk5NkqhtMJ9
Low income, low density	0.1048	0.0700	0.6503	0.6707	0.0204	0.0799	0.1874	https://maps.app.goo.gl/Kc76h82W85EkKidv6
Mid income, low density	0.1325	0.2158	1.0339	0.7201	-0.3138	0.1148	0.4369	https://maps.app.goo.gl/3ZTLVnmn8VNUuFdB9
Mid income, high density	0.1675	0.1154	0.6765	0.6874	0.0109	0.1309	0.3274	https://maps.app.goo.gl/6TKz1GpYJhxrxqNaA
High income, high density	0.2720	0.1547	0.7059	0.7350	0.0290	0.2491	0.5004	https://maps.app.goo.gl/TjMMm4x5vyYZB45v8
High income, low density	0.2622	0.1441	0.7172	0.7459	0.0287	0.2444	0.4698	https://maps.app.goo.gl/yEAvJ4EkvRqvgMjZ8

Table 2. NDVI metrics in different locations by socioeconomic typologies in Cairo.

NDVI Metrics by Socioeconomic Typology in Amsterdam

Table E10.

NDVI metrics are organized by socioeconomic typologies in Amsterdam

Socioeconomic zone	Mean NDVI	STD	NDVI Range	NDVI Max	NDVI Min	Median	PCT90	Location
Low income, high density	0.4446	0.2160	0.9047	0.8749	-0.0299	0.4320	0.7478	https://maps.app.goo.gl/ktiaRKUXw4xnFRsH9
Low income, low density	0.3794	0.2104	0.8299	0.8326	0.0026	0.3401	0.6968	https://maps.app.goo.gl/up42arwYCGTB2jhMA
Mid income, high density	0.2994	0.1790	0.8595	0.8024	-0.0570	0.2484	0.5914	https://maps.app.goo.gl/yU15YC3DW9c7Pwxo7
Mid income, low density	0.4301	0.1908	0.9165	0.7899	-0.1265	0.4161	0.6958	https://maps.app.goo.gl/EiHVrHCSgfZrrcMM6
High income, high density	0.4319	0.1924	0.8854	0.8394	-0.0461	0.4135	0.7072	https://maps.app.goo.gl/Gu3wL8KyrqyU3F6S7
High income, low density	0.4727	0.2176	0.9830	0.8779	-0.1051	0.4691	0.7779	https://maps.app.goo.gl/WvHwaF3KYTntD1py8

Disparities ratio:

Table E11.

Social disparity ratio calculated from income ranges on all locations

City	High income NDVI	Mid income NDVI	Low income NDVI	Disparity Ratio (High: Low)
Amman	0.1655	0.1436	0.1061	1.56
Cairo	0.2671	0.1500	0.0995	2.68
Amsterdam	0.4523	0.3648	0.4120	1.10

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