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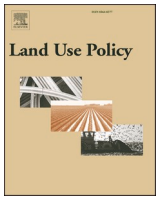

Characterizing informality in urban resource management: Towards an integrated framework of urban metabolism and informal flows

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ABSTRACT

Urban resource management demands greater efficiency to address the growing challenge of resource use in cities. Urban Metabolism (UM) is a fundamental approach that quantifies energy, water, and material flows within urban environments, providing a foundation for policy development. However, UM often overlooks informal flows—unregulated resource processes that play a significant role in many regions, particularly in developing countries, operating outside the oversight of public institutions. This paper addresses two primary objectives. First, it offers a structured characterization and holistic definition of informality, analyzing its diverse forms across water, energy, waste management, food production, and mobility sectors. Second, it introduces an expanded UM framework that integrates informal flows. This approach has the potential to help policymakers with a comprehensive tool to address resource management challenges more inclusively by including these informal systems. Key findings highlight three significant policy implications: integrating informal and formal systems is complex, hence this requires flexible and adaptive regulatory frameworks; the exacerbation of social injustices through informal flows and inequalities—especially concerning access, affordability, and gender disparities—underscoring the need for targeted, equity-focused policies; and the human-centric nature of informal systems, emphasizing the importance of engaging informal actors in policy development and land-use planning. The expanded UM framework fosters the creation of transparent, equitable, and effective policies that, in theory, can bridge the gap between formal and informal systems, enhancing resource governance, social equity, and sustainable urban development.

1. Introduction

Urban population growth, climate change effects, and limited availability of resources are pushing cities to become more resource efficient (Wang et al., 2023; Williams, 2019). To improve overall resource use, scholars have developed assessment methodologies to quantify and track how cities use their resources. One of them is the Urban Metabolism approach (UM), a popular method that quantifies energy, water, and material inflows and outflows. UM is widely adopted as it is useful in empirically measuring resource use and allowing policymakers to translate results into tangible strategies that reduce resource consumption and mitigate their associated emissions (Goldstein et al., 2013; Newell et al., 2019; Perrotti, 2020). UM focuses on systematically examining resource flows within urban systems, which are subject to formal governance and are quantitatively documented through data pertaining to both flows and stocks (Guibrunet and Sánchez Jiménez, 2023; Zhang, 2013). UM serves as a valuable instrument for the assessment of ecological constraints within an urban setting, particularly concerning the intricate exchange of resources between the city and its surrounding hinterland. Nonetheless, contemporary methodologies employed in the field of urban metabolism exhibit a notable limitation in their scope as they are primarily configured to investigate the formalized aspects of a city. These methodologies, predominantly reliant on official statistics and reports, tend to disregard all activities and material flows existing outside the purview of state monitoring (Guibrunet and Arnés, 2022; Otero Peña et al., 2022).

Using resources in an informal way is widespread across sectors, including water, energy, waste management, food production, and mobility. For instance, informal water systems serve approximately 30–60 % of the urban population in the Global South (Ahlers. et al.,

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2014). Furthermore, an estimated 1.1 billion people lack formal access to electricity, relying on informal means for its provision (Stephan et al., 2018). In waste management, informal channels in cities play a substantial role, managing 15–20 % of waste in most developing countries, surpassing the contributions of formal channels (United Nations Human Settlements Programme (Ed.) (Ed.)., 2010).

Given the prevalence and spread of informal flows, it becomes necessary to characterize them across sectors and better understand their role within the resource accounting of cities to enable policy-makers to pursue more transparent resource management policies in cities (Acevedo et al., 2021; Christ et al., 2016). This research aims to fill this gap by first developing a holistic definition of informality, characterizing informal flows across sectors, and then by developing an expanded UM framework integrating these informal flows.

The concept of informality emerged in the 1970s to understand the migration processes of rural people seeking urban employment opportunities (Alsayyad, 2004). The term was coined by Hart, referring to informal employment in Ghana, with a clear distinction between formal and informal employment and whether labor is recruited permanently or not (Hart, 1973). Informality was then seen as an activity at the periphery of societies, among the urban poor, where individuals rely on their entrepreneurial acumen to recreate their work opportunities (McFarlane and Waibel, 2012). The concept of informality was initially applied in the context of the informal economy. It is characterized by the lack or inadequate enforcement of formal structures, such as legal statutes and regulations. (Bosch Mossi and Maloney, 2007). This lack of formal oversight gives rise to several consequences, including scenarios of unprotected workers, excessive regulation, low productivity, unfair competition, evasion of the rule of law, underpayment or nonpayment of taxes, and work conducted “underground” or in the shadows (Perry et al., 2007). Direct attention to informality is primarily evident in SDG 8.3.[1]

Market globalization and liberalization broke urban and rural divides and gave rise to new forms of informality beyond lower-income communities (Roy and AlSayyad, 2004). This work allowed breaking the schism between formal and informal by expanding the meaning of informality as being interconnected with the formal sphere (Chen, 2006; Soto, 2000). Roy brings a compelling definition by moving beyond this dichotomous view, realizing that informality is constantly shifting “between what is legal and illegal, legitimate and illegitimate, authorized and unauthorized” (Roy, 2005, p. 80). Informality has become a new mode of urbanization, a process of urban transformation, and a space of different transactions connecting different economies. Today, the field of informality is expanding beyond economic and urban planning. When formal infrastructure fails to deliver needed quantities and qualities of resources, communities develop informal “workarounds, resistance and collective self-provisioning for vital resources and services” (London et al., 2021, p. 120). The informal practices are present in different sectors of water, energy, waste management, food production, and mobility.

2. Material and methods

The research methodology is structured into three main phases: Iterative Literature Review, Comparative and Thematic Analysis, and the development of an Expanded Material Flow Analysis (MFA). These phases work synergistically to build a comprehensive understanding of how informal flows interact with formal urban metabolism (UM) frameworks across various resource sectors, such as water, energy, waste, transportation, and food.

2.1. Iterative literature review

The literature review follows a structured, multi-step approach adapted from Acevedo and Perrotti (2024) to systematically identify, screen, and analyze existing research on informal resource flows within the context of UM.

2.1.1. Search strategy and keywords

A comprehensive literature search was conducted using Scopus, recognized as one of the most extensive and comprehensive databases for peer-reviewed academic research (Baas et al., 2020). The search was performed on September 12th, 2024, utilizing the following Boolean search string:

(TITLE-ABS-KEY (informal* AND decentralized) OR TITLE-ABS-KEY (informal* AND "small scale") OR title-abs-key AND informal*) AND TITLE-ABS-KEY (water OR energy OR biomass OR waste OR food OR " food production" OR mobility OR transportation) AND PUBYEAR $>$ 1999 AND PUBYEAR $<$ 2025 AND (LIMIT-TO (LANGUAGE, "English"). This search yielded 491 documents, which were then subjected to a systematic screening and selection process to ensure that only relevant studies focusing on informal flows in various sectors were included.

2.1.2. Screening and selection process

The screening and selection process involved several stages (see Fig. 1). The initial sample of 491 documents was first filtered based on document type, retaining only articles, conference papers, and reviews. This step reduced the sample to 402 papers. The remaining papers were subjected to a second-level review, which involved a detailed screening of titles, abstracts, and keywords. This step specifically aimed to identify case studies that focused on urban resource flows within informal systems, ensuring relevance to the study’s objectives. As a result of this targeted review, 72 papers were selected for further in-depth analysis.

In the third stage, an in-depth screening was conducted, focusing on papers explicitly addressing the three critical phases of resource flows: Input, Process, and Output. This step narrowed the selection to 61 papers for a more comprehensive analysis. Finally, these papers were evaluated based on their relevance to specific resource sectors (such as water, energy, and food), the complexity of the systems described, and the inclusion of factors like decentralized systems, informal governance, and land use implications. The final selection consisted of 61 papers, which were used as the foundation for the next study phase.

2.2. Comparative and thematic analysis

Following the literature review, the study employed two analytical approaches: Comparative Analysis and Thematic Analysis.

2.2.1. Comparative analysis

In this phase, different case studies and sectors are compared side-by-side, focusing on the informal characteristics identified during the literature review. The aim is to highlight commonalities and differences between informal systems across the sectors, paying close attention to the complexities, scale, flexibility, and associated socio-environmental challenges, including justice, insecurity, and gender disparities. This allows for a cross-sectoral understanding of how informal systems operate and interact with formal systems.

2.2.2. Thematic analysis

Following the comparative analysis, a thematic analysis is conducted

[1] SDG 8.3 advocates for the promotion of policies that foster productive activities, the creation of dignified employment, entrepreneurship, creativity, innovation, and the encouragement of formalizing and expanding micro-, small-, and medium-sized enterprises, including facilitating access to financial services. However, indirectly, numerous other SDGs concerning poverty (SDG 1), gender equality (SDG 5), equity (SDG 10), institutions (SDG 16), and partnerships (SDG 17) hold relevance to informality. Programs aimed at gradually formalizing the informal economy stand to contribute significantly to the advancement of these interconnected SDGs.

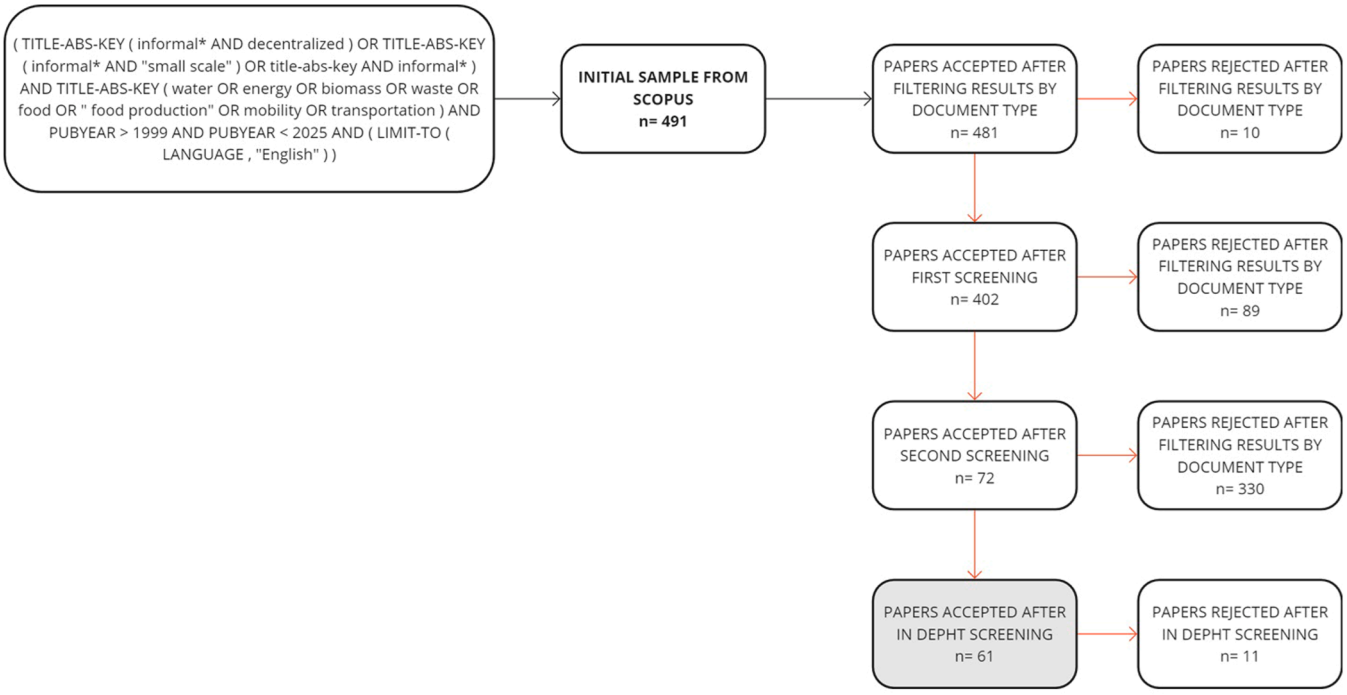

Fig. 1. Diagram of systematic literature review criteria.

to identify recurrent themes in the data. This involves grouping findings into categories like "complexity," "small scale and decentralized," "flexibility and adaptability," and "injustice and insecurity." Each theme is explored in depth to extract key patterns and insights. The thematic analysis helps synthesize sector-specific findings into overarching themes that characterize informal resource flows and their policy implications.

2.3. Expanded Material Flow Analysis (MFA)

This phase incorporates the findings from the iterative literature review into an Expanded Material Flow Analysis (MFA). The MFA framework, adapted from Voskamp et al. (2017) provides a structured approach for mapping and analyzing the flow of resources through informal systems within the broader urban metabolism framework.

The MFA process consists of three key phases:

1. Input: Identifies the entry point of resources into the informal system, which could include local sources or external imports.
2. Internal processing and use: Describes how resources are handled, transported, treated, or transformed within the system.
3. Output: Focuses on the final destination of resources after processing, including disposal, reuse, recycling, or export.

2.3.1. Integration of informal flows into MFA

The Expanded MFA is designed to capture the unique characteristics of informal resource flows. Drawing on the framework developed by Choueiri et al. (2022a), which analyzed informal flows within the water-energy nexus, the MFA is adapted to reflect informal flows across sectors such as water, waste, energy, and food production. The Life Cycle Assessment (LCA) concept is also integrated into this analysis to trace the resource life cycle in informal systems, offering a more nuanced understanding of how informal flows interact with formal UM frameworks.

This research phase seeks to map the interdependencies between formal and informal systems, highlighting the challenges and opportunities posed by integrating informal resource flows. The analysis also emphasizes the potential of informal systems to contribute to urban sustainability despite their operation outside formal regulatory frameworks.

2.3.2. Application of the MFA framework

The application of the Expanded Material Flow Analysis (MFA) framework allows for a more comprehensive integration of informal resource flows into the broader context of urban metabolism. As illustrated in Fig. 2, the framework systematically incorporates the informal inputs, processes, and outputs identified in the literature review, providing a holistic view of resource flows that are often overlooked in traditional MFA models.

Using case studies from various sectors such as water, energy, waste, food production, and mobility, the Expanded MFA framework establishes clear pathways for analyzing how informal systems operate in parallel with or alongside formal urban systems. The framework highlights the role of informal actors, decentralized networks, and alternative supply chains in influencing the overall resource metabolism of cities.

3. Results and discussion

3.1. Comparative analysis of urban resource management strategies in global regions

Table 1 (see Annex 1) showcases the prevalence of formal and informal systems across different urban sectors and regions. In the water and wastewater sectors, informal practices are prevalent in Southeast Asia, Africa, and South America. Informal water provision is common in peri-urban areas where formal infrastructure is lacking, and systems like water trucks, boreholes, and unregulated networks are widely used (Schwartz et al., 2015a; Kacker and Joshi, 2012). These systems often contribute to inadequate water quality and unsustainable water management. Additionally, informal wastewater disposal, where untreated waste is discharged into rivers, exacerbates environmental degradation (Chivenge et al., 2024). Across these regions, 70 % of the analyzed cases within the water and wastewater sectors demonstrate informal practices.

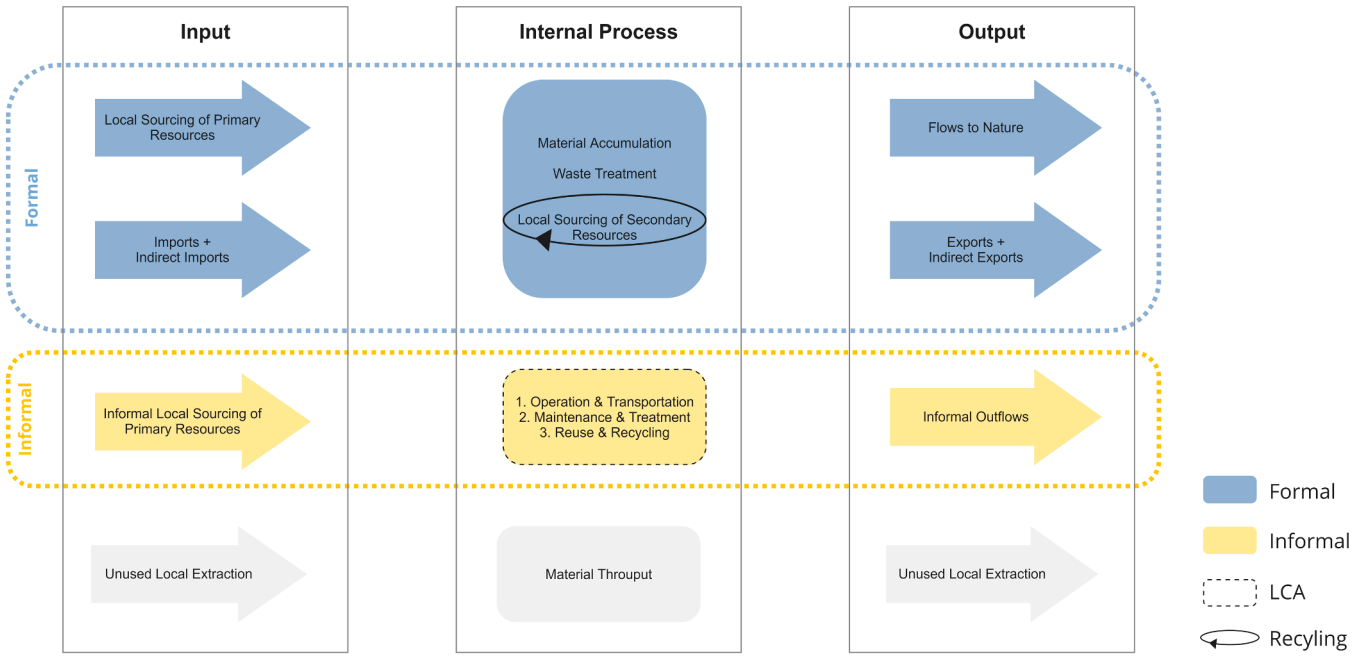

Fig. 2. Expanded MFA integrating formal and informal flows.

In the energy sector, informal practices are common across developing regions such as Sub-Saharan Africa, South America, and Southeast Asia. Decentralized renewable energy systems, including biomass and solar energy, operate informally, with renewable energy sources like wood, coal, and paraffin being common inputs. These systems often lead to health risks such as indoor air pollution and carbon monoxide poisoning (Hoefsloot et al., 2020; Baruah and Enweremadu, 2019; Fonseca and Schlueter, 2013). Approximately 70 % of the cases in the energy sector rely on informal systems.

Similarly, the waste management sector in Sub-Saharan Africa and Southeast Asia exhibits a strong presence of informal systems. Informal collection and recycling processes dominated by scavengers and small-scale operators often involve uncollected household waste and unsanitary conditions, resulting in negative environmental consequences such as air pollution from burning waste and water contamination (Ambastha and Aich, 2019; Bruce and Storey, 2010; Imam et al., 2008). About 75 % of cases in these regions rely on informal waste management systems.

In the food systems sector, informal practices are similarly dominant in Sub-Saharan Africa and South Asia. Small-scale vendors and informal markets are common mechanisms for food distribution, exposing communities to health risks such as foodborne diseases, particularly where informal food vendors operate without proper regulations (Ghosh and Kumar, 2021; Mathaulula et al., 2016). Roughly 70 % of food sector cases in these regions involve informal practices.

The main differences between formal and informal flows manifest in resource acquisition, utilization, and disposal methods. In the energy sector, formal systems rely on regulated utilities, whereas informal practices involve unregulated sources such as biomass and decentralized renewable energy (Longe, 2020; Nabukalu and Gieré, 2020). Formal systems employ structured collection services in waste management, while informal practices rely on open dumping and waste picking (Pakasi et al., 2024; Villa et al., 2022). In food systems, formal supply chains contrast with informal street vendors and local markets, which are more prone to health risks (Ghosh and Kumar, 2021; Mathaulula et al., 2016). Similarly, formal systems use piped networks and regulated wells in water management, whereas informal practices involve unregulated extraction and direct discharge into water bodies (Chivenge et al., 2024; Joshi et al., 2023; Schwartz et al., 2015a).

3.2. *Thematic analysis: Informality characteristics in different sectors*

As informality expands into multiple sectors, a range of descriptors is used to characterize it, but a holistic definition that integrates these descriptors remains absent in the literature. The analysis of informality characteristics (Descriptors, Challenges, and Actors) across various sectors, as summarized in Table 2 (see the complete analysis of informality characteristics across various sectors in Annex 2), reveals consistent patterns and nuanced variations in diverse domains. In the literature review we identified descriptors that outline these characteristics: Complex, Small Scale and Decentralized, and Flexible and Adaptable. These descriptors demonstrate common themes across sectors, highlighting the multifaceted nature of informality within different societal spheres. Informal actors, such as individual vendors, waste pickers, and decentralized service providers, play a critical role in shaping these systems, operating in spaces where formal systems often fall short. Policy implications focus on integrating these actors into formal frameworks, ensuring resource management approaches to account for informal contributions and challenges while promoting more inclusive and sustainable urban policies.

The "Complex" descriptor illustrates the elaborate interaction between formal and informal structures, blurring the demarcation lines and emphasizing the coexistence of these systems within each sector. This complexity is a recurrent theme across sectors, indicating the pervasive nature of informality in different operations. Furthermore, the "Small Scale and Decentralized" aspect elucidates the localized, often individualized nature of informal operations within these sectors. This characteristic emphasizes the diverse, decentralized networks and individual actors contributing to informal activities, evident in various sectors, further underlining informality's dynamic and varied nature. "Flexible and Adaptable" further underscores the agility and adaptability inherent within informal systems across sectors. This adaptability allows for responsive and versatile operations, adjusting to varying circumstances and demands, a key feature that transcends sector boundaries.

In examining challenges, particularly the identified issues of "Injustice and Insecurity" and "Gender Inequalities," a consistent narrative emerges. These challenges are prevalent across various sectors, indicating the universality of these societal concerns within informal operations. The presence of injustice and insecurity reflects a broader socio-

economic disparity, impacting different sectors. At the same time, gender inequalities persist as a prevalent issue, revealing disparities and limitations faced by women within these informal systems.

The descriptors are elaborated further below, focusing on the human aspect behind informal flows.

3.2.1. *Complexity*

Informal systems are complex and deeply entangled with formal ones, a dynamic widely recognized in the study of resource consumption (Roy, 2005). It is particularly difficult to distinguish between formal and informal systems in the water sector, as they often exhibit a continuum of characteristics (Misra, 2014). These systems can be interlinked and interdependent; for instance, formal systems might incorporate informal configurations, such as unregulated water pricing and maintenance, while informal systems may adopt formal governance mechanisms (Ahlers et al., 2013). In some instances, actors such as mafia members strategically blur the boundaries between formal and informal domains to navigate both public and private sectors, demonstrating the fluidity between the two spheres (Cheng, 2014). Formal and informal water systems are frequently connected through networks of actors from different public and private sectors, operating within the same socio-political structures (Schwartz et al., 2015a). Water services can be co-produced through everyday negotiations, where informal water providers are not entirely independent from the state. These providers protect their interests and profitability by maintaining social relationships and cooperation with formal systems, highlighting the interdependence of these networks (Dagdeviren and Robertson, 2011). Formal and informal systems can be understood as a meshwork where actors operate in both spheres, using hybrid identities to make services more appealing and accessible (Dakyaga et al., 2023; Cheng, 2014). In the energy sector, similar dynamics exist. The management of certain resources, such as coal, often shifts between formal and informal practices. Coal's social and political value enables it to move from a basic material to a valuable commodity that various actors exploit across both formal and informal channels (Baruah and Enweremadu, 2019). Informal charcoal production, trade, and consumption in Africa further demonstrate the socio-ecological complexity of these systems, which are shaped by political, ecological, and historical factors (Nabukalu and Gieré, 2020). The value chain of fuelwood similarly involves formal and informal activities, with formal processes focusing on collection and price-setting while informal networks manage transportation and trade (Cholez and Trompette, 2020). In the waste sector, informal waste management systems involve complex negotiations, particularly among waste pickers who determine access to valuable waste materials. The competition for access to high-value resources can lead to transgressive and violent behavior among waste pickers, further complicating the system (Makina and Lawhon, 2022). In cities such as Dar es Salaam, informal waste collection and recycling involve complex networks of scavengers, intermediaries, and small processing facilities that negotiate their roles within the broader waste management system (Bruce and

Table 1
Summary of Informality Characteristics in Different Sectors.

Sectors/Characteristics		Water	Energy	Waste	Food Production	Mobility	Policy Implications
Descriptors	**Complex**	• Continuum & fluidity between formal-informal characteristics. • Interlinked and interdependence of both systems. • Meshwork of public and private actors. • Operations through similar socio-political structures.	• Management shifts between formal and informal systems. • Social and political drivers for access. • Mix of activities between both systems. • Socio-ecological complexities	• Complex negotiations between both formal-informal sources leading to transgressions.	• They operate in unregulated spaces and are closely tied to local economies and food security.	• Paratransit composed of formal and informal types of transportation systems	• Policies may disrupt existing socio-economic relationships. • Policies may improve access to informal sources. • Integrating informal collection systems into the formal ones.
	Small Scale & Decentralized	• Decentralized networks • Individual vendors • Mobile or sedentary	• Self-constructed infrastructure through the grid or local distribution systems.	• Individuals' pickers • Enterprises • Decentralized facilities	• Individual vendors • Urban food systems (farms and gardens)	• Individual drivers and their vehicles	• Decentralized is an opportunity to extend the service to disconnected areas.
	Flexible & Adaptable	• Flexible service and adaptable rates	• Adaptable to local demand and fuel availability	• Adaptable to waste volumes	• Flexible to consumer needs.	• Adaptable to seasonal changes and demands	• Flexible and adaptable services can fill service gaps.
Challenges Identified	**Injustice & Insecurity**	• Affordability disparities in lower-income households • Exposure to lower water quality	• Social equity and inclusion • Energy affordability and poverty • Indoor air pollution	• Precarious jobs • Exposure to health hazards, including e-waste burning. • Disproportionate impact on women	• Improving food security • Precarious jobs • Health hazard exposure from pollution	• Job safety • Increased competition due to bureaucratic procedures	• Informal sources are not criminalized but offer safer and more affordable services
	Gender inequalities	• Gendered disparities	• Women being exposed to indoor air pollution from wood burning	• Inequities on health impacts	• Empowerment of women to own businesses		• Policy instruments to tackle disproportionate health and social burdens through safer technologies and work environments
Actors behind flows		• No state actors • Entrepreneurs • Community leaders	• Community leaders	• Individual collectors	• Individual street vendors	Individual street vendors	• Participatory platform for co-production of services

Storey, 2010). The mobility sector similarly reflects the complexity of informal systems through the concept of paratransit, a term used to describe transportation systems that operate between formal and informal networks. These systems encompass a range of services, from those that are regulated and follow a fixed schedule to those that operate more haphazardly with unfixed rates and routes (Alimo et al., 2022; Del Mistro and Behrens, 2015). The complexity of the paratransit system arises from the various actors involved and their negotiations within informal networks and urban governance (Salazar Ferro et al., 2013).

The complexity of informal systems presents significant challenges for policymakers. Due to their interlinked and hybrid nature, policies that attempt to formalize informal practices may disrupt existing socio-economic relationships or overlook informal actors' role in providing essential services. For instance, informal water providers often fill gaps left by formal systems and policies that seek to eliminate informal systems without adequate formal alternatives, which may exacerbate resource insecurity for vulnerable populations (Cheng, 2014; Schwartz and Sanga, 2010). In the energy sector, informal networks provide essential access to fuel and energy, particularly in low-income areas where formal infrastructure is absent (Baruah and Enweremadu, 2019). Efforts to regulate these systems must be sensitive to the socio-ecological context and ensure they do not further marginalize communities that depend on them (Nabukalu and Gieré, 2020). Similarly, in the waste and mobility sectors, policies that recognize the role of informal actors and seek to integrate them into formal systems rather than exclude them may be more effective in achieving sustainable urban development (Bruce and Storey, 2010).

3.2.2. Small-scale and decentralized

While all the sectors employ the term small scale to refer to informal systems, some refer to single individuals, others describe decentralized small networks. In the water sector, informal providers take different forms and shapes, ranging from decentralized (spaghetti) piped networks to individual vendors, either mobile or sedentary, such as water vending machines and kiosks or pushcarts and tanker trucks (Botton and Blanc, 2016). In the energy sector, small-scale informal systems are decentralized and self-constructed infrastructure (Fonseca and Schlueter, 2013; Hoefsloot et al., 2020). They consist of the generation and consumption of energy from renewable energy such as hydropower, solar panels, or solar home systems (Baruah and Enweremadu, 2019) or the use of traditional coal, charcoal briquettes, or wood (Longe, 2020; Nabukalu and Gieré, 2020). Distribution happens at a small scale through connections to the local grid or local distribution systems (Fonseca and Schlueter, 2013). In the waste sector, the term small-scale refers to individual waste pickers, collectors, or enterprises involved in the extraction of e-waste materials from open dump sites or streets (Fu et al., 2020; Hoang et al., 2023; Kahhat et al., 2022; Kinally et al., 2022), recyclables such as plastic waste (Bruce and Storey, 2010; Pakasi et al., 2024), or decentralized composting facilities that include solid and food waste (Ghosh and Kumar, 2021). In the field of food production, informal food businesses either focus on street vendors pushing food carts (Hockerts, 2017)or small-scale urban food systems such as individual vendors or urban farms (Blekking et al., 2017; Mathaulula et al., 2016). In mobility, small transportation refers to minibusses, motorcycle taxis, or decentralized car-sharing networks (Alimo et al., 2022; Hockerts, 2017; Kerzhner, 2024).

The recognition of small-scale and decentralized systems as crucial components in sectors like water, energy, and waste is essential for policy design. For instance, decentralization offers opportunities to extend services to underserved populations in peri-urban and informal settlements, where centralized systems fail (Acevedo de los Ríos et al., 2023; Kinally et al., 2022). Policymakers should focus on the formal inclusion of small-scale service providers through tailored regulations that ensure service reliability while avoiding overregulation that could stifle their flexibility and adaptability (Nabukalu and Gieré, 2020). Furthermore, providing incentives for innovation in decentralized systems, such as grants for solar energy or waste recycling initiatives, could help build more resilient infrastructure in underserved regions (Ghosh and Kumar, 2021).

3.2.3. Flexible and adaptable

The term flexibility has been used across sectors. In the water sector, scholars mainly focus on the cost flexibility of the informal services (Ahlers et al., 2013; Braimah et al., 2018; Kacker and Joshi, 2016) and their adaptability to local needs and fluctuating demand. In the energy sector, flexibility relates to meeting local demands based on fuel availability (Fonseca and Schlueter, 2013; Hoefsloot et al., 2020; Longe, 2020), emphasizing the adaptability of services to market demand. For example, in the waste sector, studies focus on adjusting to changing waste volumes and needs (Kahhat et al., 2022). Similarly, in the food sector, flexibility pertains to meeting consumer needs (Blekking et al., 2017; Mathaulula et al., 2016). The mobility sector focuses on the flexibility in responding to seasonal changes and fluctuating demands (Hockerts, 2017).

The adaptability of informal systems, particularly in sectors like waste management and energy, demonstrates their potential to fill service gaps left by rigid, formal systems. Urban planners and policymakers should adopt integrated frameworks that promote the coexistence of both formal and informal systems, recognizing the ability of informal providers to adapt to changes in demand (Bano et al., 2022; Muñoz-Erickson et al., 2021). By fostering collaborations between formal institutions and informal providers, cities can better respond to fluctuating resource needs without destabilizing the existing infrastructure (Hoang et al., 2023). Additionally, adaptive governance structures are essential to ensure that informal systems can be scaled up or modified in response to the evolving needs of urban populations (May, 2022).

3.2.4. Injustice and insecurity

Experts in various sectors emphasize the impact of informal systems on justice and security in different ways. Some discuss issues in access in terms of services, affordability, and health, while others point out the benefits of informality in allowing communities access to a service and a resource. In the water sector, affordability disparities that impact disproportionally lower-income communities are emerging concerns (Ahlers et al., 2013; Bhatt, 2014; Botton and Blanc, 2016; Dakyaga et al., 2023; Joshi et al., 2023; Schwartz et al., 2015b; Schwartz and Sanga, 2010), with a focus on injustices in poor communities or slums (Braimah et al., 2018; Dagdeviren and Robertson, 2011; Rahmasary et al., 2021) or insecurities due to unreliable service and exposure to lower water quality (Collignon and Chaponniere, 2011; Kacker and Joshi, 2012, 2016; Liddle et al., 2016; Spencer and Guzinsky, 2010). A few authors focus on the insecurities of the informal water providers (Basu and Main, 2001; Schaub-Jones, 2008). In the energy sector, we see a focus on access inequalities, affordability, and the high cost of informal service (Baruah and Enweremadu, 2019; Fonseca and Schlueter, 2013; Hoefsloot et al., 2020; Longe, 2020). Others discuss exposure to indoor air pollution from wood burning, which can sometimes disproportionately impact women (Cholez and Trompette, 2020). In the waste sector studies highlight the precarious work of waste pickers and legal risks implications (de Wit, 2010; Fu et al., 2020; Hoang et al., 2023; Imam et al., 2008; Jayasinghe et al., 2019; Kristanto et al., 2022), and their exposure to higher health risks (Bruce and Storey, 2010; Jai Singh Rathore, 2020; Kahhat et al., 2022; Katusiimeh et al., 2013; Villa et al., 2022), impacting more disproportionately women (Ghosh and Kumar, 2021; Pakasi et al., 2024). In the food production sector, while the informal sector allows for achieving food security, this comes at a cost of vendors that face precarities and insecurities in their working conditions (Blekking et al., 2017; Mathaulula et al., 2016). In the transportation sector, safety issues are discussion points (Alimo et al., 2022) including competitive challenges stemming from bureaucratic procedures (Kerzhner, 2024).

Addressing the injustices inherent in informal systems requires an intersectional policy approach that recognizes the vulnerabilities faced by marginalized communities. Governments should focus on improving the regulatory frameworks to ensure that informal service providers are not merely criminalized but are supported to offer safer and more affordable services (Alter Chen et al., 2002). Policies should aim to formalize informal services without removing their accessibility to low-income populations, ensuring that essential services remain equitable (Kahhat et al., 2022). Additionally, improving the legal protections for waste pickers, water vendors, and informal energy providers can mitigate health risks and enhance working conditions (Pakasi et al., 2024).

3.2.5. Gendered services

Some authors highlight the disproportionate gendered impact where women face inequitable conditions and are exposed to higher health risks. In the water sector, women face higher barriers to accessing water systems, resulting in gendered disparities (Ahlers et al., 2013; Basu and Main, 2001; Van Koppen et al., 2007). In the energy sector, women are exposed to inequitable health impacts from indoor pollution from wood and charcoal burning (Baruah and Enweremadu, 2019; Cholez and Trompette, 2020). Moreover, roles are inequitably distributed in terms of energy collection (Longe, 2020). In the waste sector, highlight the significant involvement of women in the field (Ambastha and Aich, 2019), and the inequitable health impacts on women (Pakasi et al., 2024). The studies on food production show how work opportunities have a positive impact on women's employment and empowerment (Kerzhner, 2024).

Informal systems frequently involve women as key actors, particularly in sectors like waste management and energy provision. Policies should aim to reduce the disproportionate health and social burdens faced by women in these sectors. For instance, policymakers can introduce safer technologies and work environments that directly address the hazards of indoor air pollution from biomass energy (Albadra et al., 2020). Additionally, policies should focus on empowering women by formalizing their roles within the sector, providing access to financial resources, legal rights, and improved working conditions (Acevedo De-los_Ríos et al., 2024). Recognizing women's pivotal role in informal systems and integrating them into formal policy frameworks can foster greater gender equity in resource management.

3.2.6. Actors in informal resource systems

The idea of power with a nuanced concept of governance (Swyngedouw, 2005) is present in different sectors. The importance of the people behind those systems is evident in the different sectors.

In the water sector, informal water providers can be referred to as none-state actors (Ahlers et al., 2013). In some cases, they act as entrepreneurs (Kacker and Joshi, 2012; Schaub-Jones, 2008), in other cases they create a sense of community or become community leaders (Botton and Blanc, 2016; Fuchs et al., 2020; Hussain and Chaves, 2023; Liddle et al., 2016; Maryati et al., 2018, 2022; Rahmasary et al., 2021; Spencer and Guzinsky, 2010; Van Koppen et al., 2007). This sense of community is also present in the energy sector (Baruah and Enweremadu, 2019; Hoefsloot et al., 2020). The term community or network is also present in the waste sector (Bruce and Storey, 2010; de Wit, 2010; Pakasi et al., 2024), with a focus on individual collectors or pickers (Ambastha and Aich, 2019; Fernando and De Silva, 2024; Fu et al., 2020; Hoang et al., 2023; Katusiimeh et al., 2013; Rahmasary et al., 2021; Villa et al., 2022). Similarly, the food and mobility sectors highlight individual street vendors (Blekking et al., 2017; Mathaulula et al., 2016) or transport operators (Alimo et al., 2022; Hockerts, 2017; Kerzhner, 2024).

Acknowledging the crucial role of informal actors in resource management systems is vital to creating policies that bridge the formal-informal divide. Policy initiatives should focus on enhancing the legitimacy of informal actors while incorporating them into city-wide governance frameworks (Chaskin and Abunimah, 2002). This could involve creating participatory platforms where informal providers, community leaders, and local governments can collaborate on the co-production of services, especially in the water, waste, and energy sectors (Faldi et al., 2022). Moreover, providing legal frameworks that protect informal workers' rights and establish mechanisms for conflict resolution between formal and informal actors can strengthen the resilience of urban resource systems (Tucker and Anantharaman, 2020).

3.2.7. Informal flows and implications for land use and spatial planning

The spatial distribution of water sources, infrastructure, and users is fundamental for effective and sustainable water management in informal settlements (Ahlers et al., 2013). Informal settlements often occupy floodplains or marginal land, areas not suited for formal infrastructure development, leading to a complex coexistence between formal and informal systems (Basu and Main, 2001). Informal water providers often utilize communal or unregulated spaces, affecting urban land use planning (Schaub-Jones, 2008). In cities like Maputo and Dar es Salaam, the narrow streets and rugged topography of informal settlements further complicate formal water service provision (Dakyaga et al., 2023; Botton and Blanc, 2016).

In other cases, informal systems are deeply integrated into formal networks. For example, in Manila, informal water providers coexist with formal utilities, with boundaries between the two systems often blurred (Cheng, 2014). In Accra, informal water vendors operate on communal land without formal regulation, complicating municipal efforts to integrate these services into broader infrastructure projects (Jambadu et al., 2024). Similarly, informal water systems utilize available land in Tanzania's peri-urban areas but often conflict with formal urban planning (Nganyanyuka et al., 2014). These informal water networks impact formalization and present challenges for integrating informal settlements into city-wide land use plans. In many informal settlements, energy provision involves using land for renewable energy projects or fuel sources like biomass and charcoal. In South Africa and Uganda, informal energy production, mainly charcoal, leads to deforestation and land degradation (Nabukalu and Gieré, 2020; Baruah and Enweremadu, 2019). Informal energy production depletes natural resources and affects rural and peri-urban landscapes, contributing to environmental challenges. In Madagascar, the informal trade of second-hand batteries for energy use impacts land use by requiring space for storage, repair, and resale in both rural and urban areas (Cholez and Trompette, 2020).

Decentralized energy systems, such as those observed in South America, repurpose communal spaces for solar or wind power installations, affecting local land use patterns (Fonseca and Schlueter, 2013). In rapidly growing cities, informal energy systems often occupy urban fringes or unregulated spaces, leading to land allocation and environmental sustainability conflicts.

Waste management in informal settlements presents significant land use challenges. Informal waste collectors and processors often use underutilized urban land or communal spaces for sorting and processing waste, contributing to land degradation and pollution (Pakasi et al., 2024). In Mumbai, for example, informal waste systems operate in narrow streets and alleys, leading to conflicts with formal land use policies and efforts to redevelop slum areas (de Wit, 2010).

Similarly, in Jakarta and other Southeast Asian cities, informal waste segregation near landfill sites creates environmental hazards and complicates urban planning (Fernando and De Silva, 2024). In Harare, decentralized wastewater treatment systems require dedicated land for treatment plants, which can lead to land use competition and environmental restoration efforts (Chivenge et al., 2024). Informal systems in these areas often operate on land that is not recognized by formal planning authorities, exacerbating land use conflicts.

Informal transportation systems also have significant land use implications. In cities like Kampala, informal minibusses and motorcycle taxis (boda-bodas) use roadsides and public spaces, contributing to urban congestion and complicating formal transport planning

(Kerzhner, 2024; Alimo et al., 2022). These transport systems often compete with formal infrastructure for space, creating challenges for city planners who must accommodate both formal and informal modes of transportation.

The operation of informal transport routes often involves the use of unregulated land, which can affect the development of formal transportation systems and contribute to haphazard urban growth (Hockerts, 2017).

Informal food vending also impacts land use, particularly in urban and peri-urban areas. In cities like Nairobi and Lusaka, street vendors occupy public spaces without formal recognition, leading to conflicts with urban planners and public health authorities (Blekking et al., 2017). The expansion of cities into peri-urban areas often displaces agricultural land, reducing access to fresh, locally produced food and threatening food security (Nenguda and Scholes, 2022). Informal food systems, such as street markets and urban gardens, utilize public land and open spaces, creating tensions with formal land use plans prioritizing urban development over food production.

The complexity of informal systems, particularly in relation to land use, presents significant challenges for policymakers. Land use policies must account for the realities of informal settlements, which often occupy spaces unsuitable for formal infrastructure. In the water sector, this means recognizing the role of informal providers in delivering services to underserved areas and integrating them into formal land use plans (Botton and Blanc, 2016; Ahlers et al., 2013). Policymakers should also consider the environmental impacts of informal energy production, particularly in rural areas, where deforestation and land degradation are significant issues (Nabukalu and Gieré, 2020). Integrating informal systems into formal land-use frameworks in the waste management sector can help reduce environmental hazards and improve urban planning (Pakasi et al., 2024). Addressing land tenure issues in informal settlements is also crucial, as uncertain legal status often prevents the formal integration of infrastructure, particularly in the energy and water sectors (Smit et al., 2017). By addressing these policy challenges, cities can better manage the complexities of informal systems and ensure more sustainable and equitable urban development.

3.2.8. Holistic definition of informality

The literature review shows that while Roy (2005) offers a comprehensive definition of informality, the concept has expanded into different sectors with distinct characteristics. This corroborates the necessity to develop a more holistic definition that reflects the diversity of characteristics across sectors. Based on this summary, we propose a new holistic definition of informal systems, specifically in the context of resource consumption and use. These systems are complex networks comprising different political actors operating simultaneously within formal and informal dimensions. Informal systems tend to be small-scale or decentralized networks that operate independently from centralized services, although they may occasionally intersect or connect with them. They can be flexible in modes and rates and adaptable to people's demands. However, informal systems can also lead to various socio-economic and environmental issues, including affordability, pollution, and health disparities. These impacts frequently affect marginalized communities, including lower-income populations and informal settlement residents. In some cases, these impacts can result in gender inequalities with disproportionate negative impacts on women. Finally, the human aspect is embedded in informality, as individual actors' social infrastructure and networks are behind the different sectors.

While this paper thoroughly reviews the definition of informality across disciplines and fields, future work should develop a more applied understanding of how informal resources are used and consumed from a quantitative perspective, with particular attention to measuring how these informal systems interact with formal systems in urban contexts.

3.3. Informality and expanded UM framework integrating informal flows

In this section, we adopt an applied approach to highlight the importance of integrating informal flows while accounting for urban metabolism, and we introduce an expanded MFA framework to analyze urban metabolism. Accounting for informal flows is challenging because of the complexity of collecting data on informal sources and estimating their flows (United Nations Economic Commission for Africa, 2008).

Utilizing this expanded MFA with a focus on the informal flows (see Fig. 3) facilitates a clearer picture of these flows, allowing a better understanding of resource consumption within the broader urban economy. This frame of reference can be used to enable policymakers to understand informal resources and develop more transparent and evidence-based policies to enhance resource management in cities.

Within the field of UM, Eurostat's Economy-Wide Material Flow Analysis (MFA) is one of the most used input-output UM assessment models (Voskamp et al., 2017) that accounts for (formal) resource flows and stocks in cities (Perrotti, 2020; Zhang, 2013). MFA models have evolved in the literature. Initial frameworks calculated resource flows and outflows without detailing internal resource processes (Krausmann et al., 2017). Recent research has addressed internal processes by incorporating stock-explicit and space-explicit dimensions into Material Flow Analysis (MFA) (Otero Peña et al., 2022; Wiedenhofer et al., 2019). This includes distinguishing between renewable resources and waste consumed internally, those that merely pass through the system, and those that are locally sourced (Zeller et al., 2019; Voskamp et al., 2017) (Fig. 4).

Fig. 3 further incorporates the land-use implications of informal flows, illustrating how activities such as waste sorting, decentralized energy production, and informal food vending require and reshape urban and peri-urban spaces. For example, waste sorting often occurs in unregulated areas, contributing to inefficient land use and localized environmental degradation, while decentralized energy systems in rural areas can alter traditional land-use practices. These insights highlight the critical role of integrating land-use considerations into resource management frameworks, ensuring that informal systems are included in urban planning to minimize conflicts and enhance sustainability.

Additionally, some scholars have explored the integration of Urban Metabolism (UM) with informality. A review of the relevant literature reveals that UM has been utilized to assess the sustainability and resilience of informal urban areas (Bahers et al., 2020; Musango et al., 2020; Smit et al., 2017; Strydom et al., 2019). Other studies have employed societal metabolic processes to analyze and quantify informal economies (Pérez-Sánchez et al., 2019; Smit et al., 2019; Tejedor-Flores et al., 2017). Moreover, case studies have proposed strategies for integrating UM and informality, offering action-based solutions to address the challenges of these interlinked domains (Khalil and Al-Ahwal, 2021).

While these examples highlight the benefits of using UM in analyzing informal flows in cities, they fall short in providing a framework for accounting for these flows in UM. To specifically address the integration of informal flows in MFA, we adopt Voskamp et al. (2017)'s MFA model. First, we draw on the literature covered in the first section to detail the flows of every sector. However, our focus is on enhancing the MFA model by explicitly incorporating the within-system informal dimensions, and for this purpose, we leverage the concept of Life Cycle Assessment (LCA). Material Flow Analysis (MFA) and Life Cycle Assessment (LCA) share similarities regarding resource flows. Both methods incorporate raw material extraction and sourcing as input parameters while evaluating emissions as part of their output. Despite these commonalities, they diverge in several aspects. One significant distinction lies in their system boundaries: MFA primarily focuses on territorial systems, but methodological expansions also allow to quantify upstream flows related to traded products and so-called material footprints of consumption. This approach allows for the integration for the integration of upstream flows related to imported products (Eisenmenger et al., 2016). In contrast, LCA centers on individual

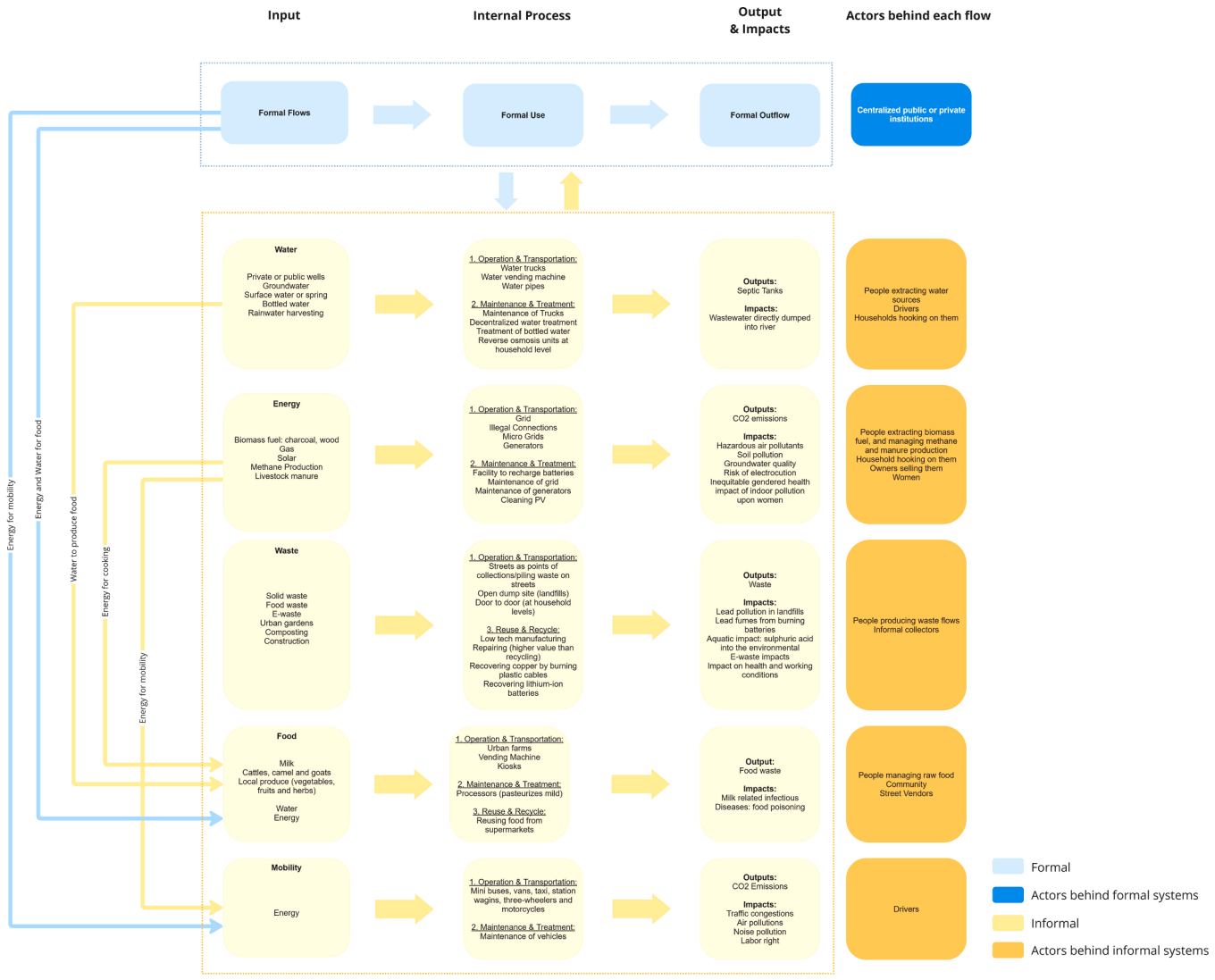

Fig. 3. Expanded MFA with a highlight on the informal flows.

services, assessing the resources utilized in their production processes (Bovea and Powell, 2016).

Additionally, LCA employs a detailed within-system process characterized by multiple steps (Goldstein et al., 2013). These detailed steps, as demonstrated in the analysis of informal water-energy nexus flows by Choueiri et al. (2022b), can be instrumental in integrating informal flows into an expanded MFA framework. It is noteworthy that while MFA is an effective accounting tool, it is critical to broaden its scope to encompass the social dimensions of informal resource flows.

Life Cycle Assessment (LCA) is widely used to evaluate environmental impacts across sectors. In the building sector, it serves as the standard for assessing carbon emissions from materials and comparing Construction and Demolition Waste (CRD) management strategies (Keena et al., 2023; Di Maria et al., 2018; Takano et al., 2015).

The expanded MFA includes formal and informal flows, along with unused extractions that pass through the system (Fig. 2). The classification of formal flow sub-categories is adapted from Voskamp et al. (2017). Building on this, Fig. 3 provides a detailed examination of informal flows across multiple sectors. The framework highlights three key features that align with the characteristics identified in the literature from the previous section. We find that informal systems are complex, and this is evident at two levels. First, formal and informal spheres are entangled. The framework shows that formal and informal interact where a resource can be extracted in the formal sphere but used internally in an informal way, generating informal outflows. An example is energy carriers that can be transformed formally but then used informally in the food production and mobility sectors. Another level of complexity is the interaction that happens among sectors. For example, informal water extraction can serve the water and food production sectors, or informal energy production can serve multiple sectors of energy, food production, and mobility. A second feature shows that while informal flows give access to basic services, they can engender further inequalities, leading to injustices and insecurities. We find that informal outflows lead to air, soil, and water pollution from raw sewage dumped into rivers, biomass produced in unmonitored and unsafe ways, the burning of e-waste to extract heavy metals, and the operation of old and polluting vehicles. These can result in health disparities for those who work in informal sectors and generally have a lower income. They can also result in gendered disparities by having a disproportionately negative impact on women working in informal sectors. The expanded framework finally highlights that the human aspect is transversal across sectors and stages. Informal flows are driven by individuals, such as the case of drivers of water tankers, waste pickers, street food vendors, or drivers of informal private cars, buses, and vans. In other cases, this can involve larger groups, including households hooking illegally onto water pipes, electrical grids, or communities running local urban farms.

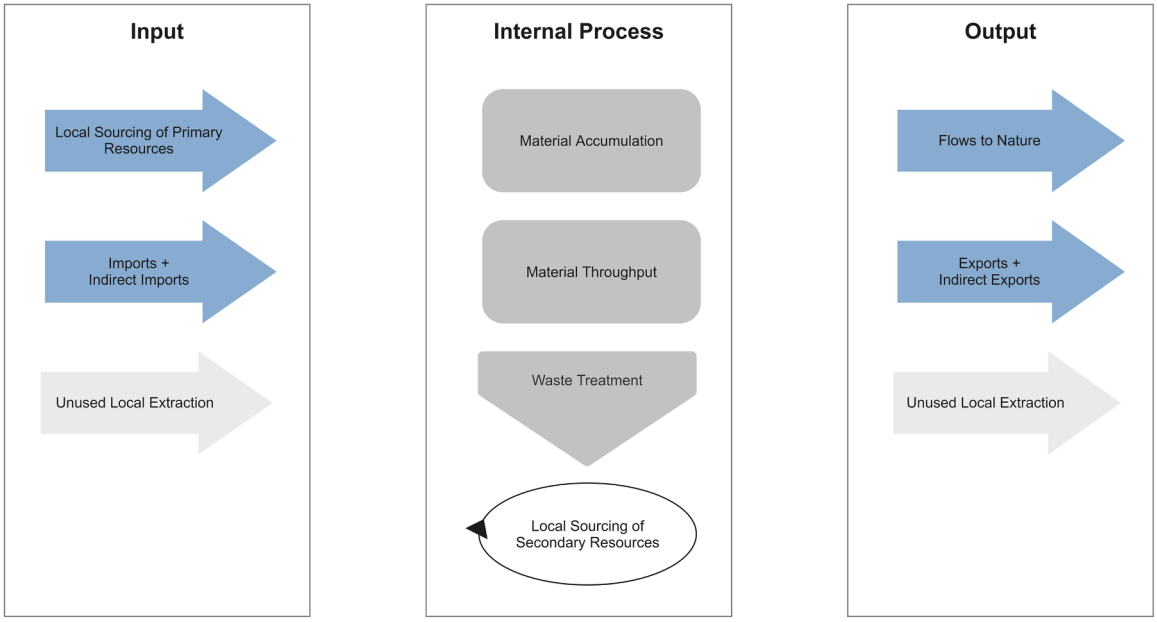

Fig. 4. MFA model showing resource input, internal process, and output, based on Voskamp et al. (2017).

4. Conclusions

In conclusion, this review underlines informality's significant and evolving role within urban resource systems. It addresses the critical gap in existing Urban Metabolism (UM) methodologies in fully capturing the dynamics of informal flows. Though a valuable tool for comprehending resource utilization in cities, the traditional Urban Metabolism approach continues to fall short in its ability to account for the complexities introduced by informal resource systems, particularly across different sectors. The presented literature review underscores that these informal flows operate within political, social, and economic realms, requiring an integrated policy response. This paper establishes that the proposed holistic definition of informality and the expanded UM framework contribute to a more comprehensive understanding of informal flows and their diverse manifestations across water, energy, waste management, food production, and mobility sectors.

The expanded framework, emphasizing the integration of informal flows, emerges as a crucial analytical tool for policymakers seeking to enhance transparency and efficacy in urban resource management. It helps policymakers to recognize the intersectionality of informal flows with land use, social justice, and environmental sustainability. This framework offers a nuanced perspective on resource consumption by recognizing the dynamic relationships between formal and informal systems and the cross-sectoral nature of informality. It provides a basis for developing targeted and contextually evidence-based policies addressing the challenges of informal resource utilization in urban contexts.

A key finding of this review is the significant impact of informal systems on land use in rural and urban areas. Informal activities, such as charcoal production in rural Sub-Saharan Africa, often lead to deforestation and land degradation. At the same time, decentralized renewable energy systems can repurpose communal or peri-urban spaces, altering traditional land uses. In urban areas, informal waste management operations frequently utilize unregulated spaces for sorting and processing, resulting in localized land degradation and conflicts with formal planning. Similarly, informal food and transportation systems compete for public spaces, underscoring the importance of integrating these practices into formal land-use planning. Such integration would mitigate land-use conflicts and promote sustainable and equitable urban development by leveraging the adaptability and resourcefulness of informal systems.

Three overarching characteristics of informal systems emerge from the holistic definition and applied framework. First, informal systems exhibit a high degree of complexity, are intricately linked to formal structures, and are interconnected across sectors. This interconnectedness necessitates a more holistic approach to resource management, considering the diverse and often integrated nature of informal and formal resource flows. Secondly, new evidence from the literature review highlights the diverse socio-environmental impacts of informality, particularly in terms of spatial injustice, inequitable access, and the environmental consequences of informal practices in peri-urban and marginalized areas. This emphasizes the need for a more equitable and inclusive resource management paradigm. Policymakers must recognize and address the disparities arising from informal practices to promote social and environmental justice. Finally, the human aspect, which emerged even more prominently in the new findings, remains a common thread transversal across sectors and stages in informal systems. Recognizing individuals' and community actors' fundamental role in formal and informal resource management is imperative for developing comprehensive and inclusive UM models.

Looking ahead, this paper advocates for future research that places a heightened focus on the human aspect within both formal and informal resource systems. This research must integrate the socio-political dimensions of informality, especially the role of community-led initiatives and local governance structures in shaping informal flows. Inclusivity in UM models should extend beyond quantitative assessments of resource flows to encompass the social dimensions, injustices, and insecurities associated with resource management. By bridging the gap between empirical resource measurements and the lived experiences of individuals engaged in informal resource practices, future research can contribute to developing more holistic and people-centered UM frameworks. Ultimately, the imperative lies in fostering resource management models that account for formal and informal flows and prioritize the well-being, equity, and empowerment of the individuals and communities shaping these interrelated urban resource systems.

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CRediT authorship contribution statement

Alejandra Acevedo-De-los-Ríos: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Daniela Perrotti:** Conceptualization. **Yasmina Choueiri:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

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

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.landusepol.2025.107472.

Data Availability

All data was shared in supplementary material

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