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REVIEW ARTICLE

A data framework for assessing nature-based solutions' contribution to the urban metabolism of informal settlements

Dorothy Julian Nalumu[1] · **Daniela Perrotti**[1] · **Elisabetta Rosa**[1]

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Abstract

Nature-based solutions (NBS) and their benefits in supporting ecosystems can improve city environmental planning, by providing a comprehensive approach to interact with complex urban social–ecological systems. For most African cities, NBS are significant to the residents of the informal settlements (IS), as their source of basic provision services amidst exclusion from municipal plans and services. Currently, there is little comprehensive data on their contribution to resource flows in the IS; yet, in most African cities, the highest share of the population lives in the IS. To address this gap, first, this paper provides NBS data framework to enable gathering, organising, and understanding the contribution of NBS to ecosystem benefits at the household and community level within the IS. The framework encompasses multiple infrastructural, social and ecological systems' 'determinants' of NBS benefits (or 'outcomes'). Second, it provides case studies illustrating NBS benefits and their contribution to resource flows. Then, discuss methods to analyse NBS contribution to metabolic flows within the IS. Finally, the key implications of the study are explored across theoretical, methodological, societal, and policy dimensions, emphasising the importance of understanding urban resource flows within the IS. The proposed data framework is designed to be broad and adaptable to various urban contexts, while also being sensitive to specific case characteristics and requirements. Also it aims to foster evidence-based NBS knowledge in IS to enable cross-learning among different cities. Lastly, the framework supports bottom-up, data-driven approaches to natural resource management and planning, contributing to the development of sustainable and inclusive cities in Africa.

Keywords Nature-based solution · Urban metabolism · Informal settlements · Data framework

Introduction

Global urbanisation trends have led to rapid city growth, which have stretched the ability of municipal agencies to provide adequate service infrastructures. In Africa, these trends are characterised by a notable increase in the population residing in informal settlements (IS) (United Nations 2019). The UN-Habitat (2012) defines IS as household dwellings that lack one or more of the following: secure tenure, adequate living spaces, durable housing, adequate sanitation, and improved drinking water. As per this study, IS are discussed as settlements outside formal urban planning and regulatory frameworks (Charmes 2012), and forms of entitlements not recognised by existing legal urban planning regimes (Dovey and King 2011). The rise of IS in urban areas has been driven by rural–urban migration, in search of improved social and economic prospects, and high birth rates (AlSayyad 2004; Mulligan et al. 2020; Roy et al. 2018). According to the United Nations' Sustainable Development Goals Report 2023 (United Nations 2023), approximately 1.1 billion people currently live in the IS representing about 30% of the global urban population. The report further projects that by 2050, nearly 3 billion people could be living in the IS.

These trends pose notable challenges to sustainable development, as highlighted by the United Nations Department of Economic and Social Affairs (UN-DESA 2024) and further supported by UN-Habitat (2020). Cobbinah et al. (2015) reported that neglecting to tackle the complexities associated

Handled by Vinod Tewari, Indian Institute of Management Bangalore, India.

✉ Dorothy Julian Nalumu
dorothy.nalumu@uclouvain.be

[1] Urban Metabolism Lab, Louvain Research Institute for Landscape, Architecture, Built Environment, 1060 Brussels, Belgium

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with IS can hinder sustainable urban development and exacerbate existing social and environmental issues. Moreover, inadequate public services (Rahman and Rahman 2020) are threat to the global sustainability agenda. Addressing these challenges is central to global policy frameworks, in particular, the Sustainable Development Goals (SDG) (UNDP 2015) in Africa. Among others SDGs, SDG 11 advocates for inclusive, safe, resilient, and sustainable cities, and is virtually linked to others (e.g. SDG3, health and well-being; SDG6-7, clean water/energy; SDG10 reducing inequality; SDG13, combat climate change and its impact). However, existing urban development strategies frequently overlook the ecological and metabolic dynamics of IS limiting their long-term sustainability (Smit 2019).

Nature-based solutions (NBS) and urban metabolism (UM) offer promising frameworks for addressing the environmental and socio-economic challenges of IS. In line with Cohen-Shacham et al. (2016, p. 2), NBS are defined as "actions to protect, sustainably manage, and restore natural or modified ecosystems, which address societal challenges". In an African context, they are referred to as actions that support and are supported by nature to address societal challenges (Diept et al. 2022). NBS can be understood as an umbrella concept for ecosystem-based adaptation and urban green infrastructure rooted in climate change mitigation and adaptation strategies (Pauleit et al. 2017). The definition of UM by Kennedy et al. (2007) "the total sum of the technical and socio-economic processes that occur in cities, resulting in growth, production of energy, and elimination of waste" is among the most widely used in literature. Recent UM studies provide conceptual frameworks to guide sustainable urban planning and design (Otero Peña et al. 2022; Perrotti 2019) and their link to NBS land uses and green infrastructure (Perrotti and Iuorio 2019). However, they have not effectively captured the social and ecological processes that exist in the IS. Therefore, this article adopts the definition provided by Currie and Musango (2017, p. 1265), whichdefines urban metabolism as “the complexity of socio-technical and socio-ecological processes by which flows of materials, energy, people, and information shape the city, services, and the needs of its populace, and impact the surrounding hinterland.” This definition is given priority because it conceptualises material flows in the context of African IS and offer methodological guidance. The NBS and UM approaches are reported to be valuable when planning for natural resource use in cities with high rates of IS (Nalumu and Perrotti 2024).

Furthermore, several studies on UM (Choueiri et al. 2025; de Souza and Torres 2021; Smit et al. 2017) highlight that IS are often excluded in metabolic analyses. This is due to lack of reliable data or official data are often poor, outdated, or entirely absent (Abass and Kucukmehmetoglu 2021). This data gap not only limits the inclusion of IS in UM assessments, but also constrains the understanding of resource flows in cities. Presently, many governments in Africa are struggling to address the historical and present challenges that push people to stay in the IS (UN-Habitat 2016; Simiyu et al. 2019). In the same line, Polese (2023) and Azunre et al. (2021) highlight the need to understand the potential role of IS in enhancing sustainability. Birtchnell et al. (2019) also pointed out that IS are wells of sustainable knowledge and highlighted a need to understand NBS contribution to resource flows. However, a significant barrier to such exploration is the lack of data. Our study is therefore motivated by the need to develop a data framework that can facilitate the collection of relevant and context-sensitive data on NBS contributions to UM in IS. Therefore, providing a data framework that can be used to gather data about NBS contribution to UM represents the main novelty of our work.

The UM approach is vital for understanding resource flows in IS, because it uses a bottom-up approach to collect and analyse data (Currie and Musango 2017; Smit et al. 2018). This is important, as top-down data is often unreliable or unavailable in IS which limits institutional access and official records. Similarly, NBS also rely on bottom-up methods for knowledge gathering (McEvoy et al. 2023; Wolff et al. 2023). In this context, NBS and UM are inherently intertwined: both emphasise participatory, place-based data practices that ensure effective understanding and application (Perrotti and Iuorio 2019; Perrotti and Stremke 2018). This shared orientation toward bottom-up knowledge gathering is what motivated this current study, especially in exploring how NBS can be leveraged to support sustainable UM in informal settings.

According to the UN-Habitat (2022) report on NBS initiatives found in the IS of Africa, a significant portion of urban residents in several African cities depend on NBS for some of their daily household needs such as water, energy, and food. IS are often located in or near green areas and natural ecosystems, which are environmentally sensitive and ecologically significant (Diep et al. 2022a). Inhabitants of IS often depend on nature for provisioning (fresh water, firewood), climatic regulating (e.g. flood mitigation, windbreaks), and socio-cultural (e.g. aesthetics, spiritual enrichment) benefits at the household levels. The report further recommended NBS data collection to foster sustainable development plans and strategies in the cities. Despite the promising NBS initiatives that exist in the IS, a critical gap remains, for lack of data and knowledge that frames the specific NBS contribution to the metabolic flows and how they enhance urban resilience by integrating social and ecological processes in the IS.

Based on the above considerations, the current article will contribute to NBS data knowledge and UM in IS. By providing a data framework that can be used by researchers and practioners, effective data-driven methodologies can

be fostered to enhance the implementation and scalability of NBS. The study aims to analyse the relevance of the data framework in gathering NBS knoweldge to UM at the household and community levels within IS. Moreover, the data framework explicitly considers the interplay of context-specific challenges, during NBS and UM data gathering by recognising the different types and characteristics of the IS. The findings are expected to bridge a gap in literature by providing a methodological understanding of NBS contributions to UM in IS.

Accordingly, three research questions (RQ) will be pursued, including: (1) How can NBS's contribution to UM be framed for wider use? (2) What data collection methods are most suitable for generating knowledge on NBS in the IS to support a comprehensive framework? (3) What are the policy implications of adopting a UM approach to analyse NBS contribution in the IS? Answers to the above questions, can foster efficient natural resource use and management, as well as towards achieving sustainable and inclusive cities in Africa.

The study is organised into the following sections. The first section entails the introduction of the study. The next section covers the methods used in the study. The result section outlines the identification of the main methods used to collect NBS data in the IS, a data framework for assessing NBS contribution to UM of the IS, a schematic representation of the data framework for assessing NBS contribution to UM, and examples of NBS initiatives and contribution to UM. The discussion section provides the implications of adopting the data framework to analyse social and ecological resource flows in the IS and the limitations of the study. Lastly, the final section presents the conclusion of the study.

Method

Introduction of the NBS data frame showing their contribution to the UM in the IS

The framework is adapted from Clark et al. (2022), and structured on multi-sector, transboundary, and social–ecological–infrastructural systems to facilitate, contextualise, analyse, and assess data from an intra-urban scale for broader use and interpretation. Therefore, we adapted the framework to contextualise, facilitate, and enable the collection and analysis of NBS data, and highlighted NBS contribution to resource flows in IS. The latter defined data framework as an anchor for systematically gathering, analysing, and informing multiple dimensions of system determinants and desired societal outcomes at the intra-urban scale (Clark et al. 2022). The framework comprises two structures which are "system determinants" and "ecosystem benefits". The system determinants show the complex interactions among social and ecological infrastructures in the built environment of the IS, for ecosystem benefits outcomes. The system determinants are categorised as follows: social actors and provisioning systems (S), ecological and natural systems (EN), physical infrastructural and provisioning systems (I), and urban form and design (U), all grouped as SENIU. On the other hand, the ecosystem benefit outcomes are also categorized as follows: environmental benefit (E); health (H), and subjective well-being (W), and economy and security (E), all grouped as EHWE to indicate NBS contribution to UM. Based on the above, we came up with the SENIU–EHWE framework focused on NBS and their contribution to the UM of IS, we replaced the desired societal outcomes with ecosystem benefits while retaining the EHWE categories. Additionally, the sub-categories of EHWE have been contextualised to align with the current study goal.

Clark et al. (2022)'s framework was selected as a base to our study for the following reasons: first, it is based on a bottom-up approach to categorise data collected at an intra-urban scale; second, it highlights the global and the urban level, physical and social provisioning systems determinants, which are fundamental to SDG; third, it provides a methodology to gather and analyse data from data-scarce places. Moreover, the seven key provisioning systems, food systems, energy, water, waste, building, and mobility, are presented (Clark et al. 2022) and can be interpreted to enable NBS data gathering to understand their contribution to UM in the IS. Moreover, the key provisioning systems listed above are also fundamental in the UM and NBS literature. Therefore, an understanding of system commonalities in terms of resource presentation (food, energy, water) and connected theme (IS) guided the different steps of the literature review.

The SENIU–EHWE data framework

The SENIU–EHWE data framework organised in this study is based on four levels: first is the SENIU of existing NBS and their EHWE; second, the data sub-category which is the generic way of organising data layers; third, the data layer which can be a variable of interest that could be used in models and scenarios; and fourth, data attribute which is the specific ways of representing or measuring a variable from a data layer to analyse and assess nature's contribution to resource flows in the UM (See Supplementary Material Fig. 1).

The interaction between the SENIU determinants and EHWE ecosystem benefits is central to understanding the contribution of NBS to UM in IS. SENIU categories shape how NBS are implemented and function to influence resource flows, governance structures, and infrastructure networks highlighted in Table 1. These determinants directly drive EHWE categories by regulating the extent to which NBS contribute to environmental stability, health outcomes,

Table 1 The structure of the SENIU–EHWE data framework

Level	Description	Categories	Sub-categories
1. System determinants	Factors shaping NBS implementation and resource flows in IS	**SENIU**: social, ecological, infrastructure, urban form	**S**: Social actors and provisioning systems (e.g. community networks, governance) **EN**: ecological and natural systems (e.g. environmental hazards, biodiversity) **I**: physical infrastructure and provisioning systems (e.g. water, energy, waste) **U**: Urban form and design (e.g. spatial patterns, historical development)
2. Data sub-categories	Thematic organisation of data layers	Derived from **SEIU** categories	Community networks, governance Biodiversity, climate risks Water, waste, energy services Building materials, urban patterns
3. Data layer	Specific variables used for assessment	Variables within sub-categories	Household head income, religious affiliation Flood risk, heat waves Waste collection points, gardens Roofing material, settlement age
4. Data attribute	Measured representation of variables	Quantitative and qualitative indicators	Percentage, frequency, spatial mapping
Level	Description	Categories	Sub-categories
1. Outcomes (benefits provided by local ecosystems)	NBS contributions to urban metabolism	**EHWE:** environmental, health, well-being, economy	**E**: environmental benefits (CICES classification: Regulation, Provisioning, Social–cultural benefits storage) **H**: health (e.g. disease reduction, mental health) **W**: subjective well-being (e.g. social cohesion, aesthetics) **E**: economy and security (e.g. job creation, food security)

social well-being, and economic security. For example, governance structures and social networks can enhance collective action for flood mitigation, leading to improved environmental regulation (E), while infrastructure investments can support urban gardens, boosting food security (E). Thus, the SENIU determinants operate as enablers or barriers that shape the realization and distribution of EHWE benefits, emphasising the need for integrated approaches that account for these interdependencies.

Description of new data sub-categories and layers used in the framework

This section describes the new data sub-categories and layers included in the data framework based on the literature. The additions enabled the data arrangement, to capture some concepts of NBS and UM about the IS. These additions are only found under the data categories of determinants, namely ecological and natural systems (EN), and urban forms and designs (U). On the other side of ecosystem benefits, the additions are found under environmental benefits (E). For the rest of the data categories that are not listed here, we maintained the sub-categories and layers used by Clark et al. (2022). This is because of their conceptual robustness and alignment with the analytical requirements of our study, i.e. offering an adequate structure for assessing NBS–UM interactions without necessitating further adaptation for the IS context.

Ecological and natural systems (EN) This aspect describes the physical systems of the natural environment. The sub-category of NBS characteristics was included. The layers to be considered in this sub-category include the reason for implementation, for better management (Hardoy et al. 2022; Hamel and Tan 2022; Gqomfa et al. 2022; Chhetri 2022), restoration, (Das et al. 2023; Adegun 2023; Diep et al. 2022a, b; Hardoy et al. 2022), or creation of new ecosystems. The second data layer captures the level of implementation, categorised based on the level of

benefit at the household (Das et al. 2023; Adegun 2023; Sagala et al. 2022; Twinomuhangi et al. 2021) or community level (Diep et al. 2022a, b, c; Thoms and Köster 2022; Ragheb and Barakat 2022).

Urban form and design (U) This category describes the physical form of the built environment. A new sub-category, historical formation, was added, drawing from Smit et al. (2017), with data layers including origin, age, scale, and size. Under the land use sub-category, additional layers were introduced: land use space for readjustment (open spaces) (Kharisma and Kaswanto 2021; Gqomfa et al. 2022; Adegun 2014; Hamel and Tan 2022; Miranda et al. 2016), zoning, location and boundaries, and distance from central business areas and landmarks (Diep et al. 2022a, b, c; Surya et al. 2020; Makuwira 2022). A new sub-category on legality and planning was also added, following Smit et al. (2017), distinguishing three types of IS: (1) Illegal unplanned, originally formal structures degraded by overcrowding and lack of maintenance (e.g. Adegun 2023; Das et al. 2023; Diep et al. 2022c; Ragheb and Barakat 2022); (2) Informal, illegal, unplanned, structures built without legal approval or planning (e.g., Diep et al. 2022a, b, c); (3) Informal, legal, planned, informal structures within formally planned layouts (e.g. Lizarralde et al. 2021; Muñoz Veloza et al. 2022).

Environmental benefits (E) Based on the Common International Classification CICES v5.1 (Haines-Young and Potschin 2010), three data sub-categories were introduced including provisioning, regulation, and social–cultural benefits.

A conceptual diagram linking NBS contributions to specific UM resource flows

Figure 1 visually represents the UM outcomes resulting from NBS. While the benefits of NBS are not always directly measurable as physical resource inputs or outputs, they significantly influence urban metabolic systems through indirect pathways. These fewer tangible impacts are crucial for achieving sustainable urban development. Arrows in Fig. 1 illustrate the interdependence among ecosystem benefits (e.g. green infrastructure reduces energy needs for cooling and heating, while urban gardens promote efficient resource use and reduce waste generation) through metabolic process. Additional arrows link these benefits to UM outcomes, emphasising how they collectively enhance urban systems, such as energy efficiency, climate regulation, and resource cycling. Ecosystem benefits from NBS improve resource flow optimisation through the efficient management and recycling of resources in urban areas. It is important to note that Fig. 1 refers to general urban areas, not specifically IS.

Search strategies

Figure 2 elaborates a synthesised view of the workflow that directed the various literature review steps aimed at

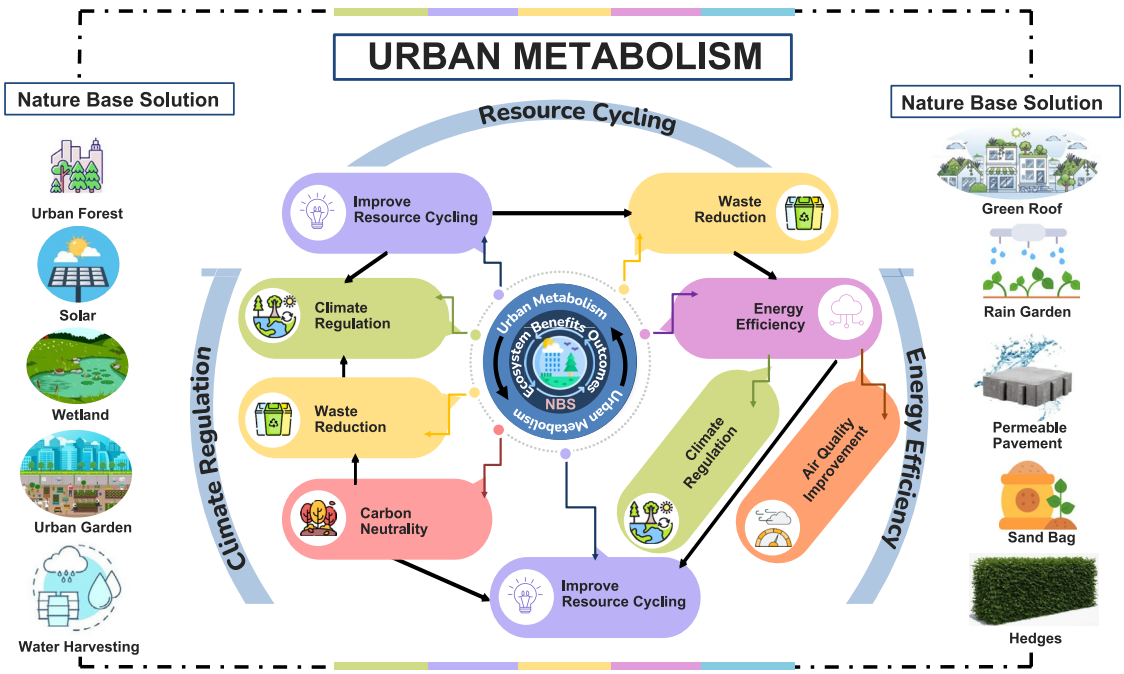


Fig. 1 The relationships of interdependency among the three main areas of contribution of NBS towards efficient and sustainable UM in IS

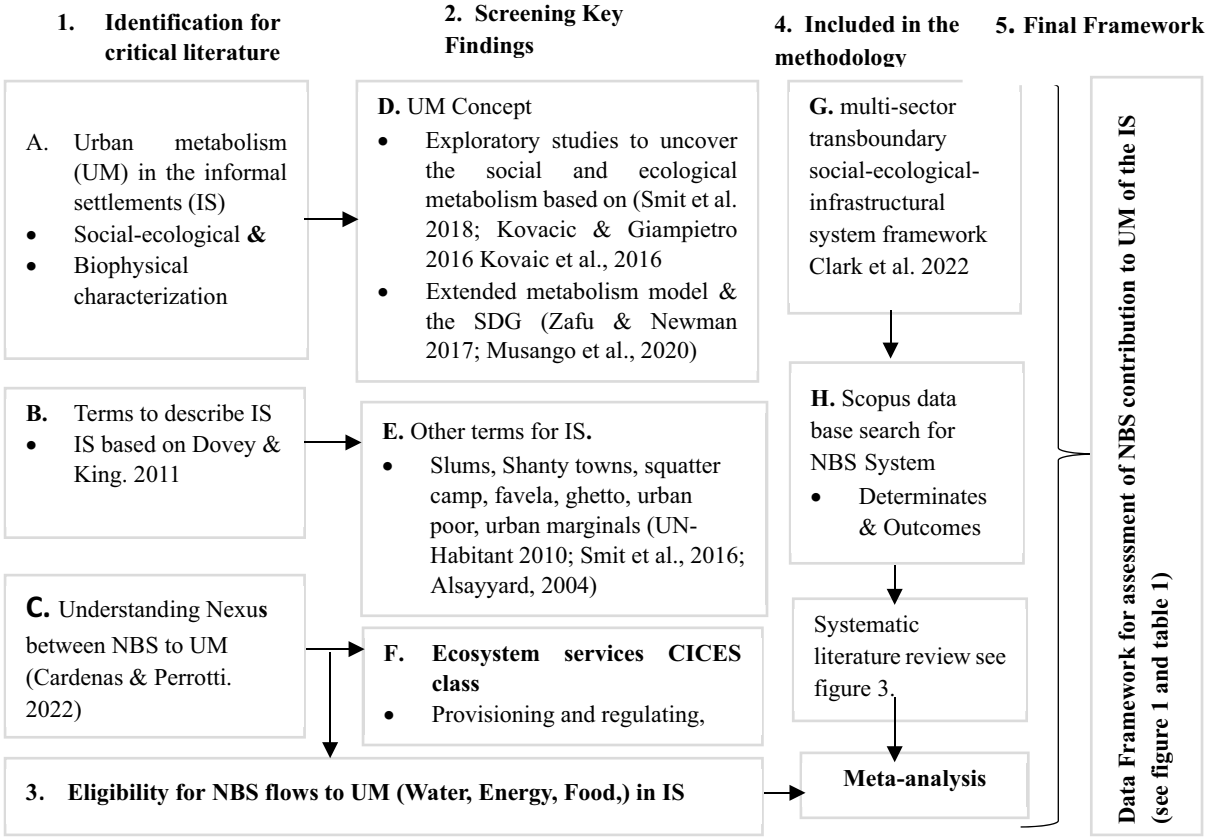


Fig. 2 Workflow for contextualising the data categories, data sub-categories, data layers, and data attributes of the data framework

contextualising the data categories, data sub-categories, data layers, and data attributes of the data framework. Four analytical steps were undertaken. Each step involved a review of existing literature in IS.

Commencing with studies on UM (see Fig. 2, sections A, and C), due to the limited literature on NBS and UM in the IS, an exploratory review was conducted to uncover the social and ecological metabolism by identifying commonalities and interconnected issues. For example, we identify common sources of basic provision services and how people get access to water, energy, and solid waste management. The review provided an understanding of nature's contribution to resource flows at the household level. The NBS contribution to resource flows such as water and energy housing materials was classified into three categories (provisioning, regulations and social–cultural benefits) (Haines-Young and Potschin 2010; Cardenas and Perrotti 2022). It guided our preferred reporting items for systematic reviews and meta-analyses detailed in the next section.

PRISMA search strategy

The study employed the Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) approach (Moher et al. 2009) to guide the methodological process and screen the literature from the databases. The PRISMA approach has been widely used by scholars in various disciplines and organisations for conducting high-quality systematic reviews and meta-analyses (Liberati et al. 2009; Basenach et al. 2023). Despite its strengths, the PRISMA approach has limitations, such as the inability to capture the results of continuous searches used in systematic reviews, which can compromise the quality of the studies conducted (Tao et al. 2011; Kahale et al. 2021). Furthermore, the PRISMA approach does not provide detailed guidance on how to conduct systematic reviews comprehensively. To overcome these limitations, the current study updated the list of literature used for analysis by including a snowballing technique. Snowballing involves reviewing the reference

lists of reviewed manuscripts to identify relevant references for the study. The process described in the "Inclusion and exclusion criteria" and "Data extraction, management, and analysis" sections of this paper also helped mitigate these weaknesses.

We searched through the SCOPUS database for relevant articles "Nature-based solution" OR ecosystem OR "Green (infrastructure OR area OR surface OR Space)" AND "informal settlement" OR slum OR shanty OR Ghetto OR Squatters (refer to section D, Fig. 1) to identify the NBS social and ecological flows contributing to the UM of the IS. To ensure the inclusion of all data about NBS in the IS, we employed synonyms related to NBS, such as “ecosystem”, “green infrastructure”, “ecosystem services”, and “ecological systems”, paired with IS (Africa, Asia, and South America), while considering their contribution to material flows in the IS. For example, "Ecosystem" AND "informal settlement," "Green infrastructure" AND "informal settlement" AND "Africa." Due to limited research on UM in the IS, the term "urban metabolism" was omitted from the search string, as most results were from the Global North and articles retrieved were manually screened to check for references to material flows.

Two Boolean searches were run. Search 1, conducted in December 2022, used the following string: "Nature-based solution" OR ecosystem OR "Green (infrastructure OR area OR surface OR Space)" AND "informal settlement" OR slum OR shanty OR ghetto OR squatters OR marginal OR urban poor, which resulted in 18,671 articles. However, screening of the results revealed that the inclusion of the terms “marginal” and “urban poor” reduced the relevance of the retrieved studies. Many articles using "marginal" referred to IS residents as marginalised patients in health-related research, while papers mentioning "urban poor" primarily discussed socio-economic conditions without engaging with natural resource management or material flows. These unintended associations weakened the focus on NBS and UM. To improve the specificity of our search, we refined the query by removing "marginal" and "urban poor," thereby reducing the number of unrelated results while retaining studies that directly addressed NBS in IS. This refinement allowed us to focus on literature that explicitly examined the role of ecological and social processes within IS, leading to a more relevant dataset for assessing material flows. By systematically refining our search strategy, we ensured that the retrieved studies were more aligned with the research objective to capture the intersection of NBS, ecological and social flows, and UM in IS contexts across the Global South.

Search 2, conducted in January 2023, used the following string: "Nature-based solution" OR ecosystem OR "Green (infrastructure OR area OR surface OR Space)" AND "informal settlement" OR slum OR shanty OR Ghetto OR Squatters, which resulted in 209 articles. Regarding retrieved results, 152 were journals, 15 were conference papers, 2

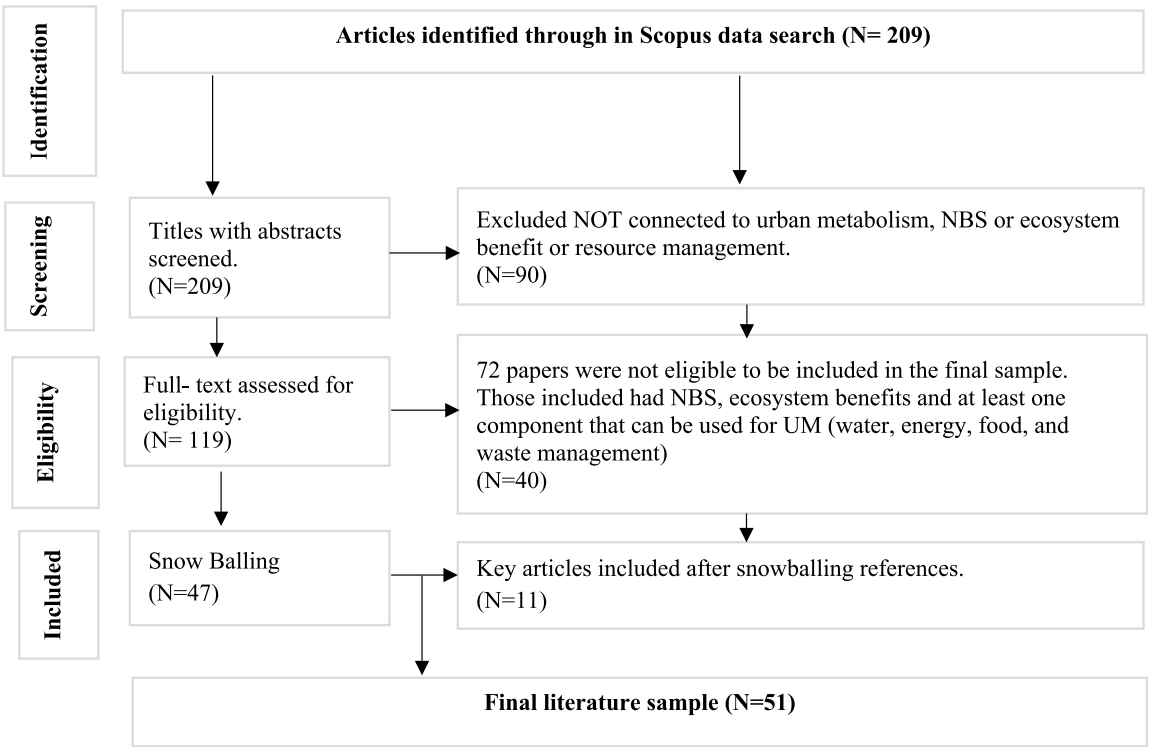


Fig. 3 PRISMA flowchart

book chapters, 2 scientific reports, 1 newsletter, and 1 from lecture notes. Figure 3 shows the steps taken for the inclusion and exclusion of data. Scopus Preview database was the best option because of our institutional ability to access data from Scopus Preview and we were very familiar with the database's interface and features. On the other hand, Scopus as a strong interdisciplinary coverage could capture a wide array of related literature relevant to this study (Baas et al. 2020).

Inclusion and exclusion criteria We reviewed all the retrieved 209 articles from our final Scopus preview search string and had 51 articles for full analysis. As such, a selection of studies that could provide information on determinants of NBS in the IS and their ecosystem benefits were analysed in an Excel spreadsheet (see supplementary material) to develop NBS SENIU–EHWE data framework to gather their contribution to UM. The criteria for inclusion of papers in the systematic analysis were as follows:

(1) Journal articles written in English focusing on NBS or natural resource use for societal benefits.
(2) Inclusion of at least one metabolic resource flow in the analytical framework presented in Fig. 1, section D, or related to natural resource use and management for ecosystem benefits. Exclusion criteria comprised (1) case reports, guidelines, and consensus opinions unrelated to natural resource use or management; (2) publications in languages other than English; (3) websites and meeting reports; and (4) articles with a general geographical focus and not focused on IS (for example, IS or GS is mentioned only in the discussion or conclusion section). Based on these criteria, we identified a final sample of 51 papers, as illustrated in Fig. 3. The content of each paper was categorised thematically to identify and organise data relevant to the study's objective. The identified data were then used to establish data subcategories, layers, and attributes for system determinants and ecosystem benefits, as outlined in Table 1. The quality of the eligible studies was assessed based on seven broad criteria, as described by Dos Santos and Beavan (2015). These criteria included the study's applicability to the review issue, study design, results transferability, and use of context to arrange findings, facilitating data collection on NBS contributions to UM of the IS in the GS, in a manner conducive to analysing their contribution within a social–ecological system approach.

However, there are some potential biases in data collection and literature inclusion, we acknowledge that restricting the review to English language journal articles may have led to the exclusion of relevant studies published in other languages, particularly those from regions where IS research is prevalent. This language limitation was mitigated by cross-referencing key findings with grey literature and regional reports where available. Additionally, while the focus on Scopus ensured access to a broad range of peer-reviewed publications, it may have introduced regional biases, as some locally published studies or non-indexed journals may have been overlooked. To minimise this, we incorporated search terms reflecting diverse regional terminologies for IS and NBS, ensuring the inclusion of studies from Africa, Asia, and South America. Furthermore, manual screening was conducted to verify that studies genuinely addressed material flows and ecosystem benefits in IS, reducing the risk of misclassification. These measures helped enhance the comprehensiveness and relevance of the dataset while acknowledging inherent limitations.

While the PRISMA approach provides a structured methodology for systematic reviews, its application in studies involving diverse terminologies referring to IS including slums, ghettos, and squatters presents unique challenges. One key limitation is the potential for terminological bias, as different disciplines and regions use varying terms to describe similar urban conditions. To address the limitations, we assessed abstracts and full texts for relevance to IS regardless of the specific terminology used, which helped to minimise the risk of terminological bias.

Therefore, NBS SENIU–EHWE data framework addresses the research questions by systematically organising data on methods for collecting NBS knowledge in IS, structuring NBS contributions to UM for broader application, and analysing the implications of a metabolism approach. It categorises studies based on methodologies used to capture NBS processes, enabling comparative analysis of data collection techniques. By integrating social, ecological, infrastructure, and metabolic dimensions, the framework provides a transferable structure for assessing NBS in IS. Additionally, it links NBS interventions with resource flows (e.g. water, energy, waste, green spaces), demonstrating their role in regulating material and energy exchanges. This metabolism-based approach highlights the functional benefits of NBS, reinforcing their importance in enhancing resilience, sustainability, and ecosystem benefits in IS.

Results

Figure 4 presents the case countries of the reviewed articles and indicates the distribution of publications on NBS and their contribution to UM. The results are highly uneven across regions, with South Africa (9) and Brazil (8) having the highest number of studies, followed by Indonesia (7). Other countries with moderate representation include India (4), Kenya (3), and Tanzania (3), while several regions, such

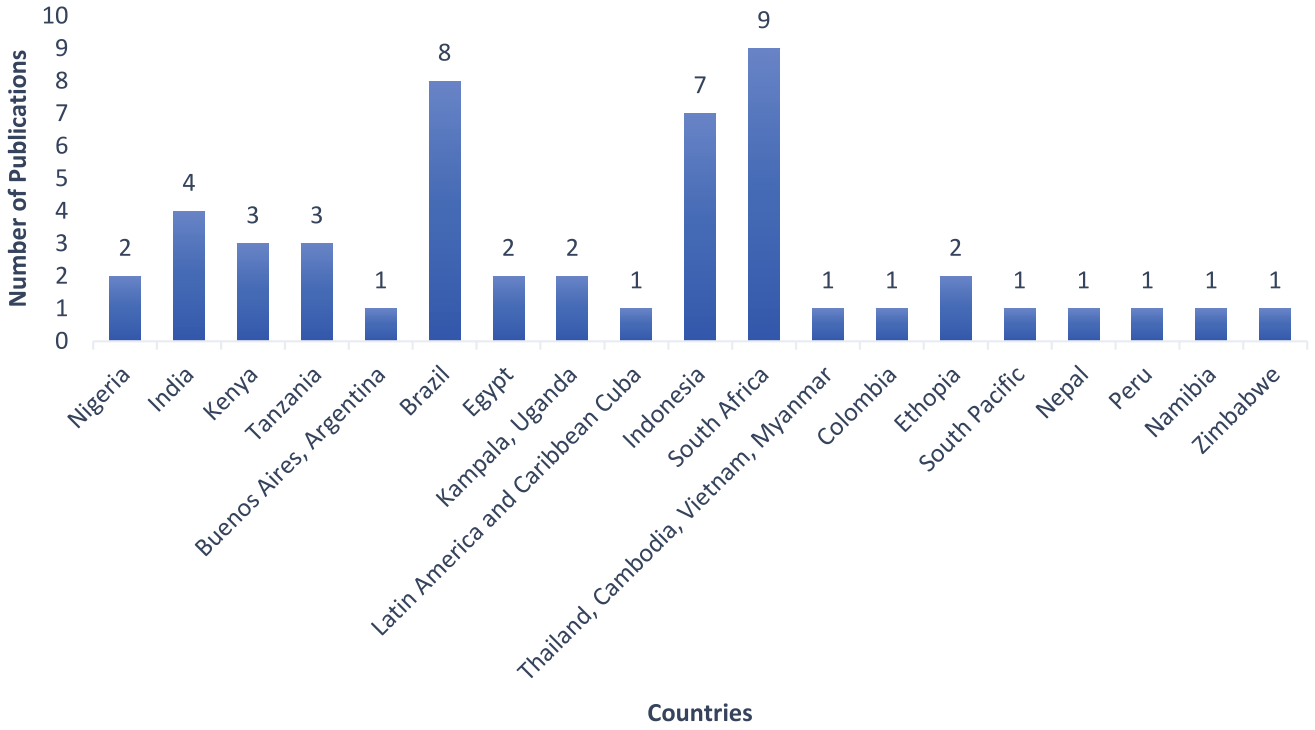


Fig. 4 Geographical focus of the study

as Uganda, Egypt, and Ethiopia, have limited but notable contributions (2 each). A significant number of countries, including Colombia, Nepal, Peru, Namibia, and Zimbabwe, have only a single publication. This geographic bias is particularly relevant to this study, which aims to develop a data framework applicable to IS in diverse urban contexts. The limited representation of many countries underscores the need for more inclusive research across different socio-ecological settings to ensure that NBS interventions and their metabolic contributions are not based on narrow or region-specific assumptions.

Identification of methods used to collect NBS data in the IS

Table 2 provides an overview of the frequency and diversity of research methods employed across the studies reviewed. The studies utilised both primary and secondary data sources to explore NBS knowledge in the IS domain. Among the reviewed papers, 25 studies exclusively relied on primary data, which was collected through various methods, including fieldwork surveys, interviews, observations, focus group discussions (FGDs), workshops, mapping, and other observational techniques. Additionally, 16 studies incorporated a combination of primary and secondary data sources. Finally, 10 studies based their findings solely on secondary data, through literature reviews. The specific data collection methods employed in these studies are further detailed in Table 2

The SENIU–EHWE data framework

This section is structured as follows: First, it provides an overview of each data category (SENIU and EHWE), supplemented with examples from selected references in Table 3. Next, Fig. 5 offers a schematic representation of the SENIU–EHWE data framework. Subsequently, the SENIU–EHWE data framework is detailed in Table 4, which also includes a comprehensive list of references for the data sub-categories and layers. Regarding the initial part of "Schematic representation of the SENIU–EHWE data framework for assessing NBS contribution to UM" and "Key variables of the SENIU–EHWE framework data sub-categories" which offers an overview of the data categories and layers, a few references are provided to present the results with the complete list of references available in Table 4. Thus, this introductory section provides a synopsis of the content presented in Table 4.

Schematic representation of the SENIU–EHWE data framework for assessing NBS contribution to UM

Figure 5 presents a schematic representation of the SENIU–EHWE data framework illustrating the complex interaction among ecosystem benefits (right panel), arranged into four categories: environment, health, subjective

Table 2 Methods used for NBS data collection in the IS

Research methods	Number frequency	Sources
Field survey/interview	6	Kharisma and Kaswanto (2021) Trundle and Organo (2023), Trundle (2020), Shackleton et al. (2015), Vollmer and Grêt-Regamey (2013), Jiusto and Kenney (2016)
Review	10	Ragheb and Barakat (2022), Adegun (2021), Hamel and Tan (2022), Becciu et al. (2020), Arcidiacono et al. (2017), Cavan et al. (2014), Miranda et al. (2016), Diep et al. (2019), Satterthwaite et al. (2020), Smit et al. (2018)
Review/fieldwork survey	14	Chhetri (2022), Muñoz Veloza et al. (2022), French et al. (2021), Mulligan et al. (2022), Adegun (2017a, b), Bunch (2016), Gopal and Nagendra (2014), Sandholz et al. (2018), Adegun (2019), Jiusto and Kenney (2016), Adegun (2017a, b), Akimolemiwa et al. (2018), Bredhauer (2016)
Mapping	1	Arcidiacono and Ronchi (2020)
Field survey/interview/observation/FGD/review	2	Hardoy et al. (2022), Diep et al. (2022c)
Field survey/interview/FGD	5	Diep et al. (2022a, b), Das et al. (2023), Twinomuhangi et al. (2021), Makuwira (2022), Wijesinghe and Thorn (2021), Adegun (2014)
Field survey, observation, FGD	1	Surya et al. (2020)
Household survey	1	Sarkar and Bardhan (2019)
Field survey/FGD	3	Stålhammar and Brink (2021), Lizarralde et al. (2021), Trimmer et al. (2020)
Workshop, FGD, surveys, interview observation	2	Juarez et al. (2008), Roy et al. (2018)
Field survey/interview/mapping	1	Adegun (2023)
Review/interviews/observations	3	Thoms and Köster (2022), Sagala et al. (2022), Gqomfa et al. (2022)
Field survey/mapping	2	Koroso et al. (2021), Birtchnell et al. (2019)
Total	51	

well-being, and economy and security. These are influenced by system determinants (left panel; organised into four categories: social actors and social provisioning systems; ecological and natural systems; physical infrastructure and food systems; urban forms and designs (SENIU determinants). Each Determinant and Outcome category consists of various sub-categories and layers indicated by dashed lines. Arrows show complex interconnections between system determinants and ecosystem benefits. NBS contribution to UM (bottom panel) is assessed across both determinants and outcomes.

Key variables of the SENIU–EHWE framework data sub-categories

Table 3 is a synopsis of key variables of the SENIU–EHWE data sub-categories framework and provides an overview of NBS contributions to UM in IS. SEIU determinants include social actors (S) supporting essential services, ecological and natural systems (EN) managing hazards, infrastructure (I) enhancing green and blue spaces, and urban form (U) addressing planning issues. EHWE benefits cover environmental (E) improvements in water cycles and air quality, health (H) through pollution reduction, well-being (W) via better living conditions, and economic (E) benefits like job creation. This framework highlights NBS as essential for resilience and sustainable development in IS by contributing to social and ecological resource flows.

Table 4 presents SENIU determinants and EHWE ecosystem outcomes benefits as the highest level of the structure and the basis for arranging NBS contribution to UM. It further presents data categories, sub-categories, and layers. Data attributes are specific ways of representing or measuring a variable from the data layer. Therefore, the data attributes for assessing NBS contribution to UM must be case specific. The attributes presented in are general, but case sensitive when analysing NBS contribution to metabolic flow (i.e. water, energy, food, or waste) in the IS.

Case examples of NBS initiatives and contributions to UM

The analysis revealed regulation and provisioning ecosystem benefits as NBS contribution to UM in the IS. Under regulation ecosystem benefits, temperature and humidity, hydrological cycle and water flows, and chemical composition of the atmosphere were indicated. Tree planting, and home and community gardens were mostly identified as NBS initiatives for temperature and humidity regulation. On the other hand, home and community gardens were mostly implemented as NBS initiatives for food provisioning. For water provisioning, rooftop rainwater harvesting is the most used NBS initiative to mitigate flash floods. Table 5 shows

Table 3 Key variables of the SENIU–EHWE framework data sub-categories

Categories	Sub-categories	Key findings	References
System determinants (SENIU)	Social actors and provisioning systems (S)	Social actors (households, NGOs, local governments, CBOs, international organisations) extend provisioning services like drainage, water, and waste management through NBS	Thoms and Köster (2022), Adegun (2023), Diep et al. (2022a, b), Hardoy et al. (2022)
	Ecological and natural systems (EN)	NBS enhance ecosystem restoration (tree planting, vegetated spaces, green roofs, gardens) and mitigate hazards (flash floods, heatwaves, landslides, windstorms)	Diep et al. (2022a, b), Lizarralde et al. (2021), Chhetri (2022), Trundle (2020), Hardoy et al. (2022), Cavan et al. (2014)
	Physical infrastructure and food systems (I)	NBS contribute to green/blue infrastructure (gardens, wetlands, parks) and address limited access to municipal services (sanitation, water, drainage)	Adegun (2023), Das et al. (2023), Diep et al. (2022a, b), Roy et al. (2018)
	Urban form and design (U)	Most IS are unplanned and informal; some undergo internal/external development with NBS integration	Smit et al. (2017), Diep et al. (2022a, b), Parikh et al. (2020), Hardoy et al. (2022), Surya et al. (2020)
Ecosystem benefits (EHWE)	Environmental benefits (E)	NBS provide regulatory (water cycles, air filtration), provisioning (food, water, fuel), and cultural (recreation, aesthetics, education) services	Trundle (2020), Roy et al. (2018), Diep et al. (2019), Adegun (2017a, b)
	Health (H)	Improved air quality, reduced health risks from pollution, and environmental hazards	Diep et al. (2022a, b), Hardoy et al. (2022), Ragheb and Barakat (2022), Juarez et al. (2008)
	Well-being (W)	NBS improve living conditions, reduce flood risks, and enhance overall quality of life	Adegun (2023), Diep et al. (2022a, b)
	Economic benefits (E)	NBS create jobs, strengthen community resilience, and provide cost-effective solutions for livelihoods and hazard mitigation	Hardoy et al. (2022), Stålhammar and Brink (2021), Surya et al. (2020), Arcidiacono and Ronchi (2020)

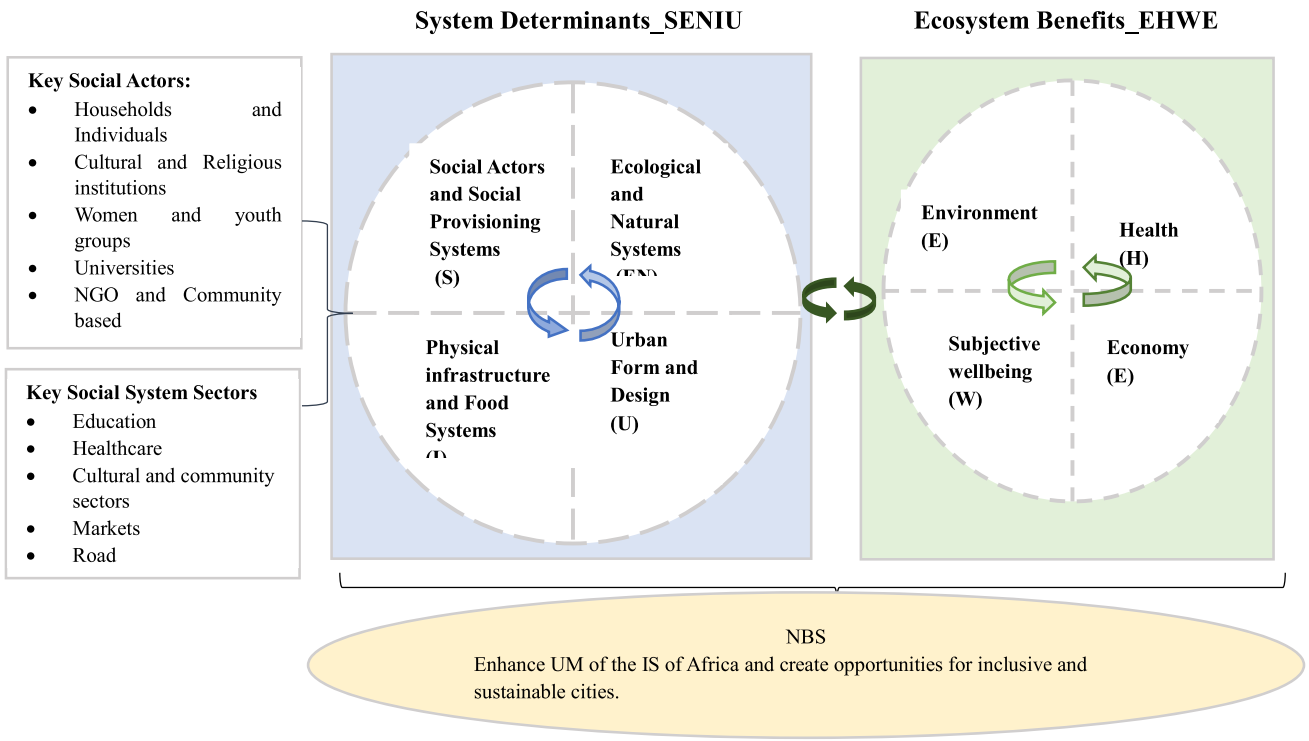


Fig. 5 Schematic representation of the SENIU–EHWE data framework for assessing NBS

examples of NBS initiatives and their contribution to UM through ecosystem benefits. South Africa tops the list with 14 examples from various cities, while Brazil and India each have 5 examples.

Cross-cutting themes among the case studies indicating NBS contribution to UM

The analysis of NBS in UM across case studies reveals key trends in resource flows within IS. Food and water provision emerge as the most widely implemented NBS, with home gardens and community gardens (frequency: 10 each) playing a crucial role in enhancing local food security across South Asia, Africa, Latin America, and small island states. Natural springs (12) and rooftop rainwater harvesting (3) are critical water management strategies, particularly in regions facing water scarcity. Energy provision remains fragmented, with reliance on firewood (3) and biogas (2), but limited integration of innovative sustainable energy solutions such as plant-based sewage treatment (1). Temperature regulation through tree planting (4) and green roofs (1) is observed, but remains underdeveloped in most regions. Additionally, herbal medicine (5) underscores the role of traditional knowledge in urban metabolism. These findings highlight the localized nature of NBS, emphasizing community-driven initiatives in informal settlements, while also pointing to gaps in green infrastructure and energy sustainability (Fig. 6).

Discussion

SENIU–EHWE data framework benefits to UM

Concerning our RQ 1, the study findings demonstrate that NBS contribution to UM are multifaceted benefits as outlined under EHWE. For example under the sub-category E, improved air quality, enhanced water retention, and reduced surface temperatures were identified in settlements with green infrastructure interventions; H, NBS initiatives, such as community tree planting and drainage rehabilitation, reduced exposure to pollutants and improved sanitation conditions; W, the presence of green spaces and improved drainage contributed to better living conditions, psychological well-being, and community cohesion; under E, some residents generated income through urban agriculture and eco-tourism initiatives linked to community-managed green spaces. All the above could be very insightful for planners and decision-makers to scale up community-based initiatives that could lead to the attaining of SDG 11 objectives particularly in Africa where most urban population live in the IS. This is because the analysed NBS initiatives, such as urban

Table 4 Detailed SENIU–EHWE data framework for NBS contribution to UM in the IS

	Categories	Sub-categories	Layers	References
System determinants (SENIU)	Social actors and social provisioning systems (S)	Basic demographic	Population, nationality, education, language, age, gender	Adegun (2023), Das et al. (2023), Diep et al. (2022a, b), Hardoy et al. (2022), Diep et al. (2022c), Thoms and Köster (2022), Sagala et al. (2022), Twinomuhangi et al. (2021), Stålhammar and Brink (2021), Makuwira (2022), Gqomfa et al. (2022), Chhetri (2022), Muñoz Veloza et al. (2022), Koroso et al. (2021), French et al. (2021), Becciu et al. (2020), Arcidiacono et al. (2017), Bunch (2016), Shackleton et al. (2015), Gopal and Nagendra (2014), Roy et al. (2018), Miranda et al. (2016), Jiusto and Kenney (2016), Satterthwaite et al. (2020), Parikh et al. (2020), Adegun (2017a, b), Adegun (2014)
		Basic economic	Household income, type of employment or job	Adegun (2023), Das et al. (2023), Diep et al. (2022c), Twinomuhangi et al. (2021), (2022), Surya et al. (2020), Trundle and Organo (2023), Muñoz Veloza et al. (2022), Bunch (2016), Shackleton et al. (2015), Gopal and Nagendra (2014), Miranda et al. (2016), Jiusto and Kenney (2016), Satterthwaite et al. (2020), Adegun (2017a, b), Adegun (2019), Roy et al. (2018), Chhetri (2022), Muñoz Veloza et al. (2022), Roy et al. (2018), Birtchnell et al. (2019)
		Social provisioning systems	Healthcare, education and training, safe environment, culture and community groups, religious institutions	Stålhammar and Brink (2021), Sagala et al. (2022), Hardoy et al. (2022), Diep et al. (2022c), Diep, Mulligan et al. (2022a, b), Ragheb and Barakat (2022), Surya et al. (2020), Trundle and Organo (2023), Juarez et al. (2008), Roy et al. (2018), Miranda et al. (2016), Birtchnell et al. (2019), Diep et al. (2019)

Table 4 (continued)

Categories	Sub-categories	Layers	References
	Social cohesion and community actors	Government, NGO, religious and traditional cultural institutions, higher learning institutions, youth and women groups	Parikh et al. (2022), Kharisma and Kaswanto (2021), Hamel and Tan (2022), Makuwira (2022), Koroso et al. (2021), Bunch (2016), Arcidiacono and Ronchi (2020), Gopal and Nagendra (2014), Roy et al. (2018), Jiusto and Kenney (2016), Diep et al. (2022a, b, c), Sagala et al. (2022), Hamel and Tan (2022), Chhetri (2022), Trundle (2020), Arcidiacono and Ronchi (2020), Becciu et al. (2020), Roy et al. (2018), Juarez et al. (2008), Gopal and Nagendra (2014), Arcidiacono et al. (2017), Bunch (2016), Jiusto and Kenney (2016), Stålhammar and Brink (2021), Makuwira (2022)
	Beliefs and attitudes	Participation in environmental activities	Thoms and Köster (2022), Adegun (2023), Diep et al. (2022a, b), Hardoy et al. (2022), Thoms and Köster (2022)
Ecological and natural systems (EN)	Water, soil, and ecological systems	Land cover classification, land elevation above the sea level, type of surface water bodies (e.g. coastal zones, rivers	Das et al. (2023), Thoms and Köster (2022), Chhetri (2022), Arcidiacono et al. (2017), Shackleton et al. (2015), Gopal and Nagendra (2014), Cavan et al. (2014), Juarez et al. (2008), Thoms and Köster (2022), Arcidiacono and Ronchi (2020), Becciu et al. (2020), Shackleton et al. (2015), Miranda et al. (2016), Adegun (2017a, b), Adegun (2014), Adegun (2023), Kharisma and Kaswanto (2021), Muñoz Veloza et al. (2022), Koroso et al. (2021), Trundle (2020), Arcidiacono and Ronchi (2020)
	Weather and climate	Temperature, precipitation, wind, climate	Clark et al. (2022)
	Ecosystems	Type of vegetation cover, surface area with green or blue spaces	Adegun (2023), Twinomuhangi et al. (2021), Lizarralde et al. (2021), Arcidiacono and Ronchi (2020), Surya et al. (2020), Hamel and Tan (2022), Adegun (2014), Arcidiacono et al. (2017)

Table 4 (continued)

Categories	Sub-categories	Layers	References
	Characteristics or features of NBS	Implementation for better management	Hardoy et al. (2022), Hamel and Tan (2022), Gqomfa et al. (2022), Chhetri (2022), Muñoz Veloza et al. (2022), Trundle (2020), Arcidiacono and Ronchi (2020), Becciu et al. (2020), Arcidiacono et al. (2017), Shackleton et al. (2015), Gopal and Nagendra (2014), Juarez et al. (2008), Kharisma and Kaswanto (2021), Roy et al. (2018), Birtchnell et al. (2019), Diep et al. (2019), Jiusto and Kenney (2016), Parikh et al. (2020), Adegun (2017a, b), Akinwolemiwa et al. (2018), Adegun (2014)
		Implementation for restoration	Das et al. (2023), Adegun (2023), Diep et al. (2022a, b), Hardoy et al. (2022), Diep et al. (2022c), Thoms and Köster (2022), Ragheb and Barakat (2022), Sagala et al. (2022), Twinomuhangi et al. (2021), Stålhammar and Brink (2021), Lizarralde et al. (2021), Kharisma and Kaswanto (2021), Adegun (2021), Trimmer et al. (2020), Surya et al. (2020), Becciu et al. (2020), Bunch (2016), Shackleton et al. (2015), Sandholz et al. (2018), Diep et al. (2019)
		Level of implementation; household level	Das et al. (2023), Adegun (2023), Sagala et al. (2022), Twinomuhangi et al. (2021), Stålhammar and Brink (2021), Kharisma and Kaswanto (2021), Adegun (2021), Hamel and Tan (2022), Chhetri (2022), Muñoz Veloza et al. (2022), Arcidiacono and Ronchi (2020), Arcidiacono et al. (2017), Shackleton et al. (2015), Gopal and Nagendra (2014), Roy et al. (2018), Sandholz et al. (2018), Birtchnell et al. (2019), Jiusto and Kenney (2016), Adegun (2017a, b), Akinwolemiwa et al. (2018), Bredhauer (2016), Adegun (2014)
		Level of implementation; community level (within the IS)	Diep et al. (2022a, b, c), Thoms and Köster (2022), Ragheb and Barakat (2022)

Table 4 (continued)

Categories	Sub-categories	Layers	References
Physical infrastructure and food systems (I)	Access	Energy (electricity) green and blue infrastructure, water, sanitation, municipal solid waste services, garden	Adegun (2021), Muñoz Veloza et al. (2022), Akinwolemiwa et Adegun (2023), Ragheb and Barakat (2022), Twinomuhangi et al. (2021), Stålhammar and Brink (2021), Trundle and Organo (2023), Gqomfa et al. (2022), Becciu et al. (2020), Miranda et al. (2016), Diep et al. (2022c), Thoms and Köster (2022), Kharisma and Kaswant(2021), Adegun (2021), Hamel and Tan (2022), Chhetri (2022), Muñoz Veloza et al. (2022), Trundle (2020), Arcidiacono and Ronchi (2020), Bunch (2016), Shackleton et al. (2015), Gopal and Nagendra (2014), Sandholz et al. (2018), Diep et al. (2019), Adegun (2017a, b), Adegun (2021), Diep et al. (2022a, b, c), Sagala et al. (2022),
	Consumption	Food, water, public space, energy	Hardoy et al. (2022), Stålhammar and Brink (2021), Chhetri (2022), Thoms and Köster (2022), Surya et al. (2020), Makuwira (2022), Muñoz Veloza et al. (2022), Jiusto and Kenney (2016), Adegun (2017a, b), Chhetri (2022), Trundle (2020), Adegun (2014), Adegun (2021), Hamel and Tan (2022), Makuwira (2022), Satterthwaite et al. (2020
Urban form and design (U)	Density	Housing unit per land area	Lizarralde et al. (2021), Surya et al. (2020), Koroso et al. (2021), French et al. (2021), Arcidiacono and Ronchi (2020), Shackleton et al. (2015), Gopal and Nagendra (2014), Jiusto and Kenney (2016), Thoms and Köster (2022), Sagala et al. (2022)
	The historical formation of the IS (Smit et al. 2017)	Origin, age, size, scale (Smit et al. 2017)	Ragheb and Barakat (2022), Chhetri (2022), Arcidiacono et al. (2017), Thoms and Köster (2022), Stålhammar and Brink (2021), Koroso et al. (2021), French et al. (2021), Shackleton et al. (2015), Adegun (2014), French et al. (2021)
	Land and home ownership	Duration of ownership, rented, self-owned	Diep et al. (2022c), Stålhammar and Brink (2021), Cavan et al. (2014), Adegun (2014)

Table 4 (continued)

Categories	Sub-categories	Layers	References
	Land use	Land use classification, space for land use readjustment (open spaces)	Kharisma and Kaswanto (2021), Gqomfa et al. (2022), Adegun (2014), Hamel and Tan (2022), Miranda et al. (2016)
		Zooning; maps, location and boundaries, distance from central business district, landmark	Diep et al. (2022a, b, c), Surya et al. (2020), Makuwira (2022), Chhetri (2022), Roy et al. (2018), Jiusto and Kenney (2016), Diep et al. (2022a, b, c), Thoms and Köster (2022), Ragheb and Barakat (2022), Thoms and Köster (2022), Jiusto and Kenney (2016)
	Spatial design	Building designs and features	Stålhammar and Brink (2021), Chhetri (2022), French et al. (2021), Arcidiacono et al. (2017), Gopal and Nagendra (2014), Cavan et al. (2014), Satterthwaite et al. (2020), Parikh et al. (2020), Hardoy et al. (2022), Adegun (2014)
	Legality and planning (Smit et al. 2017)	Illegal unplanned	Adegun (2023), Das et al. (2023), Diep et al. (2022c), Ragheb and Barakat (2022), Sagala et al. (2022), Adegun (2023), Adegun (2023), Twinomuhangi et al. (2021), Stålhammar and Brink (2021), Kharisma and Kaswanto (2021), Adegun (2021), Trimmer et al. (2020), Trimmer et al. (2020), Surya et al. (2020), Hamel and Tan (2022), Makuwira (2022), Trundle and Organo (2023), Gqomfa et al. (2022), Chhetri (2022), French et al. (2021), Trundle (2020), Becciu et al. (2020), Arcidiacono et al. (2017), Shackleton et al. (2015), Gopal and Nagendra (2014), Cavan et al. (2014), Juarez et al. (2008), Miranda et al. (2016), Birtchnell et al. (2019), Diep et al. (2019), Jiusto and Kenney (2016), Satterthwaite et al. (2020), Parikh et al. (2020)
		Informal legal planned	Diep et al. (2022a, b, c)
		Legal unplanned	Lizarralde et al. (2021), Muñoz Veloza et al. (2022)

Table 4 (continued)

	Categories	Sub-categories	Layers	References
		Development stages	Internal development, external intervention	Diep et al. (2022c), Surya et al. (2020), Trundle and Organo (2023), Satterthwaite et al. (2020), Parikh et al. (2020), Adegun (2014), Hardoy et al. (2022), Ragheb and Barakat (2022), Hamel and Tan (2022), Chhetri (2022)
Ecosystem benefits outcomes (EHWE)	Environment (E)	Regulation	Temperature and humidity	Adegun (2023), Ragheb and Barakat (2022), Kharisma and Kaswanto (2021), Trundle (2020), Shackleton et al. (2015), Roy et al. (2018), Birtchnell et al. (2019), Adegun (2017a, b), Akinwolemiwa et al. (2018)
			Chemical composition of the atmosphere	Trundle (2020)
			Hydrological cycle and water flows	Das et al. (2023), Diep et al. (2022a, b, c), Thoms and Köster (2022), Lizarralde et al. (2021), Adegun (2021), Surya et al. (2020), Hamel and Tan (2022), Muñoz Veloza et al. (2022), Arcidiacono and Ronchi (2020), Becciu et al. (2020), Shackleton et al. (2015), Roy et al. (2018), Birtchnell et al. (2019), Adegun (2014)
			Filtration, sequestration, storage	Hardoy et al. (2022), Diep et al. (2022c), Thoms and Köster (2022), Ragheb and Barakat (2022), Lizarralde et al. (2021), Hamel and Tan (2022), Birtchnell et al. (2019), Diep et al. (2019)
		Provisioning	Food	Das et al. (2023), Thoms and Köster (2022), Twinomuhangi et al. (2021), Lizarralde et al. (2021), Trundle (2020), Arcidiacono and Ronchi (2020), Becciu et al. (2020), Bunch (2016), Shackleton et al. (2015), Gopal and Nagendra (2014), Birtchnell et al. (2019), Parikh et al. (2020), Adegun (2017a, b), Akinwolemiwa et al. (2018), Adegun (2014)
			Medicinal	Adegun (2021), Gopal and Nagendra (2014), Roy et al. (2018), Birtchnell et al. (2019), Adegun (2017a, b)

Table 4 (continued)

Categories	Sub-categories	Layers	References
		Fresh water	Diep et al. (2022a, b), Thoms and Köster (2022), Ragheb and Barakat (2022), Lizarralde et al. (2021), Kharisma and Kaswanto (2021), Adegun (2021), Surya et al. (2020), Chhetri (2022), Becciu et al. (2020), Juarez et al. (2008), Adegun (2017a, b), Birtchnell et al. (2019)
		Energy	Diep et al. (2022a, b, c), Hardoy et al. (2022), Adegun (2021), Arcidiacono et al. (2017), Bunch (2016), Shackleton et al. (2015), Adegun (2017a, b)
	Social and cultural	Spiritual, cultural, and education	Roy et al. (2018), Diep et al. (2019), Adegun (2017a, b)
		Recreation	Das et al. (2023), Diep et al. (2022a, b), Hardoy et al. (2022), Diep et al. (2022c), Thoms and Köster (2022), Ragheb and Barakat (2022), Stålhammar and Brink (2021), Lizarralde et al. (2021), Kharisma and Kaswanto (2021), Adegun (2021), Surya et al. (2020), Gopal and Nagendra (2014), Roy et al. (2018), Birtchnell et al. (2019), Adegun (2017a, b)
		Aesthetic	Diep et al. (2022a, b, c), Stålhammar and Brink (2021), Das et al. (2023), Adegun (2021), Surya et al. (2020), Becciu et al. (2020), Roy et al. (2018), Diep et al. (2019), Adegun (2014)
Health (H)	Objective health outcomes	Mortality rate, public clean air	Ragheb and Barakat (2022), Gqomfa et al. (2022), Cavan et al. (2014), Juarez et al. (2008)
	Health risks	Public air quality	Diep et al. (2022a, b, c), Hardoy et al. (2022), Thoms and Köster (2022), Kharisma and Kaswanto (2021), Roy et al. (2018), Twinomuhangi et al. (2021)

Table 4 (continued)

Categories	Sub-categories	Layers	References
Subjective well-being outcome (W)	Physical living conditions Cognitive or evaluative well-being		Adegun (2023), Das et al. (2023), Hardoy et al. (2022), Diep et al. (2022c), Ragheb and Barakat (2022), Lizarralde et al. (2021), Surya et al. (2020), Chhetri (2022), Koroso et al. (2021), French et al. (2021), Arcidiacono and Ronchi (2020), Arcidiacono et al. (2017), Bunch (2016), Gopal and Nagendra (2014), Juarez et al. (2008), Birtchnell et al. (2019)
		Happy with life	Das et al. (2023), Diep et al. (2022a, b, c), Arcidiacono and Ronchi (2020), Gopal and Nagendra (2014)
		Purpose in life	Diep et al. (2022a, b, c), Ragheb and Barakat (2022), French et al. (2021)
Economy and security (E)	Economic measure, basic assessment, and resilience	GDP per capita and percentage of population with resources less than basic	–

farming and water management interventions, do enhance the UM by addressing social and ecological challenges.

Energy-related NBS in the IS remain largely reliant on biomass, with firewood serving as a dominant energy source in South Asia and Africa, raising concerns about environmental degradation. However, biogas plants and biomass recovery initiatives, as seen in Tanzania and Brazil, provide promising alternatives. While medicinal NBS, such as herbal gardens, are less frequently reported, their presence in regions like South Africa and India highlights their potential in enhancing community health. The diversity of NBS observed suggests that context-specific approaches, integrating multiple ecosystem benefits, are essential for optimising UM in IS. Future interventions should focus on combining green infrastructure with sustainable water and energy solutions to maximise resilience and long-term ecological benefits.

Overall, the SENIU–EHWE framework provides a structured approach to understanding how NBS interact with social, ecological, infrastructural, and urban form determinants, while also clarifying the diverse benefits they offer to the UM. This framework helps to move beyond theoretical discussions by providing empirical insights into the role of NBS in addressing environmental and socio-economic challenges in IS. While some NBS are implemented at a small scale, broader adoption remains constrained by infrastructural limitations and competing land use demands (Diep et al. 2022a, b, c).

The results in the data framework demonstrate the potential of the framework to show the role of infrastructure and NBS integration to contribute to resource flows. Our findings respond to Birtchnell et al.'s (2019) call for a need to investigate NBS materials and meanings in the IS. The findings have demonstrated that access to essential services, such as water, electricity, and solid waste management, directly influences the effectiveness of NBS in IS. Green infrastructure, such as urban gardens and permeable surfaces, contributes to the UM by improving water retention and reducing waste accumulation. However, disparities in service provision hinder the full integration of NBS into local infrastructure systems. The SENIU framework highlights these infrastructural gaps, providing a lens to assess how NBS can complement or substitute traditional infrastructure in resource-constrained environments. Regarding urban forms and planning implications, the data framework plays a vital role by highlighting the spatial configuration and historical evolution of IS significantly shape the adoption and impact of NBS. Findings indicate that areas with higher population densities and limited open spaces face challenges in implementing large-scale green infrastructure. However, community-driven spatial modifications, such as community gardening and rainwater harvesting initiatives, showcase adaptation strategies suitable for specific urban

Table 5 Case examples of NBS contribution to UM in the IS

Ecosystem benefit	NBS initiative	Name of IS, city	Country	References
Environmental (E)				
Regulation				
Temperature and humidity	Tree planting to improve mangrove cover	Idi-Araba community, Lagos	Nigeria	O. B. Adegun (2023)
	Proposed green rooftops	Ezbiit El-Matabea, Alexandria	Egypt	Ragheb and Barakat (2022)
	Home and community gardens	Sempur, Kedung Badak, and Tajur IS, Boger City	Indonesia	Kharisma and Kaswanto (2021)
	Gardens thinning techniques on backyard 'sup sup' garden crops against tropical cyclones	Port Vila, Vanuatu and Honiara	Solom Island	Trundle (2020)
	Tree planting	Bela bela, Limpopo province	South Africa	Shackleton et al. (2015)
	Public parks, trees, home gardens, potted plants	Dar la salam	Tanzania	Roy et al. (2018)
	Tree planting, bamboo stilts for raised platforms and dwelling support	Korail slum, Dhaka	Bangladesh	Birtchnell et al. (2019)
	Vertical and home gardens	Elias Motsoaledi, Johannesburg	South Africa	Adegun (2017a, b)
	Community-driven vertical gardening	Agege, Lagos	Nigeria	Akinwolemiwa et al. (2018)
Chemical composition of the atmosphere	Gardens, thinning techniques on backyard 'sup sup' garden crops	Port Vila, Vanuatu and Honiara	Solom Island	Trundle (2020)
Hydrological cycle and water flows	Riverbank road	Nimai Sara, English Bazar municipality	India	Das et al. (2023)
Provisioning				
Food	Home gardens	Nimai Sara, English Bazar municipality	India	Das et al. (2023)
	Urban farming,	Bwaise, Kampala	Uganda	Twinomuhangi et al. (2021)

form. Furthermore, the historical formation of settlements influences land tenure security, which in turn affects the willingness of residents to invest in long-term NBS initiatives.

Data collection most suitable for generating knowledge on NBS in the IS

Field surveys and interviews emerged as the most frequently used methods, reflecting a strong emphasis on capturing context-specific insights from local communities. The combination of review and fieldwork approaches was also common, indicating a growing trend towards integrating empirical observations with existing knowledge. This methodological diversity underscores the need for flexible and context-sensitive data frameworks that can accommodate various sources and types of evidence when assessing the role of NBS in supporting UM processes in informal settings.

The findings highlight the pivotal role of the framework to gather data on social actors within the IS who sustain and implement NBS to contribute to metabolic flows. These include community-based organisations, religious institutions, and informal governance structures who actively contribute to the management of green and blue spaces. The presence of local actors who facilitate essential services, such as waste management and communal green spaces, demonstrates how social cohesion influences the success and sustainability of NBS interventions, similar to Adegun's (2021) findings. This shows the SENIU framework's relevance in identifying the social networks that drive UM by supporting ecological functions and infrastructure maintenance. On the other hand, the framework also allows data gathering on environmental hazards, including floods, water scarcity, and extreme heat and reveal how NBS mitigate urban risks and enhance resilience.

It is important to note that data attributes are not presented in this framework because it is developed based on a generic literature review. However, the contextualisation, evaluation, and analysis of NBS data attributes in relation to UM must be guided by case-specific data metrics to ensure effective interpretation and analysis. Currently, no study has explicitly contextualised how to analyse the contribution of NBS to UM in IS. To address this gap, Table 6 presents a

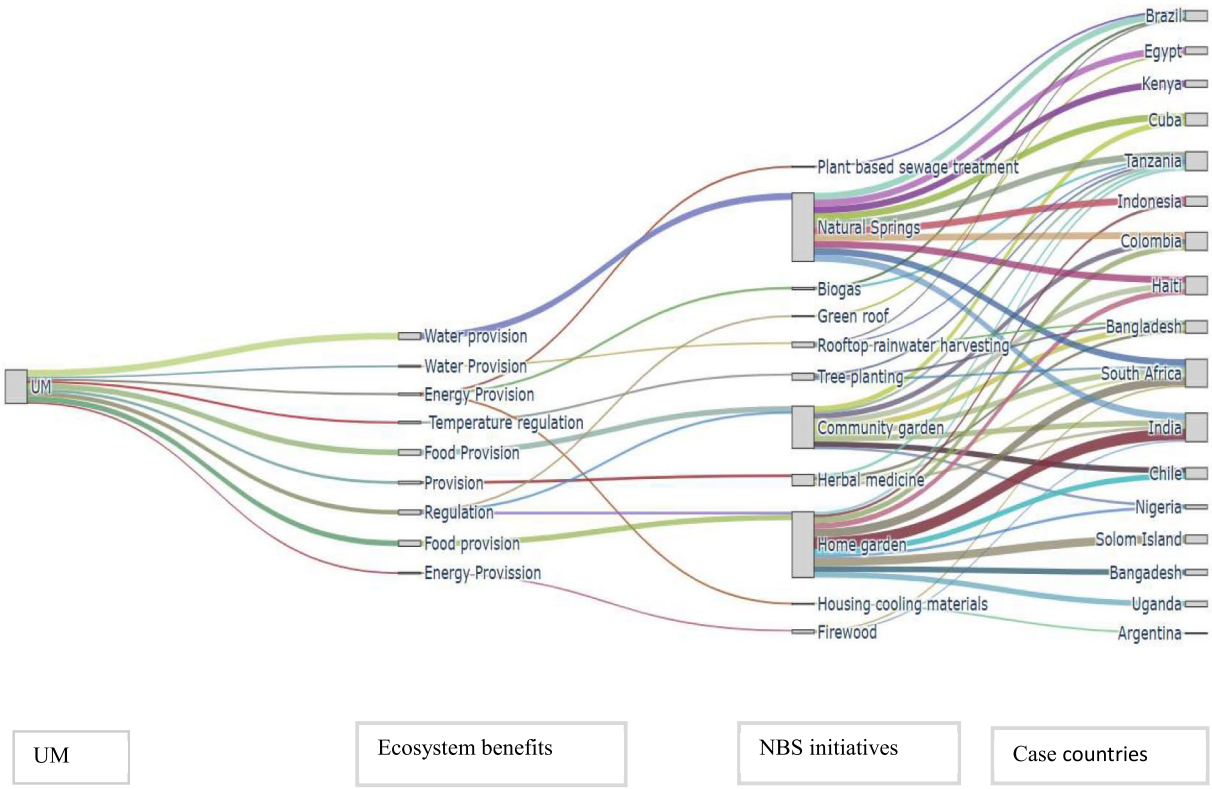


Fig. 6 Cross-cutting themes of NBS contribution to the UM

pathway to contextualise, evaluate, and analyse NBS contributions to metabolic flows in IS. Data can be gathered using the research methods outlined in Table 2. The proposed pathway builds on previous studies that have explored the contextualisation of social and ecological metabolic flows in IS (e.g. Kovacic and Giampietro 2016; Kovacic et al. 2016; Smit et al. 2017; Teferi and Newman 2017; Kaviti Musango et al. 2020).

Furthermore, to enhance the practical application of the proposed framework, it is essential to illustrate how specific data metrics are employed in real-world case studies. For instance, in assessing metabolic flows, primary data on household water consumption can be quantified through household surveys, while spatial data from remote sensing can map variations in water accessibility. Resource flow analysis can be operationalised by tracking energy inputs and outputs in IS, distinguishing between municipal grid reliance and alternative energy sources such as solar installations. Similarly, ecosystem benefits assessment can quantify flood mitigation benefits of urban wetlands by integrating hydrological data with community perceptions of reduced flood frequency. By applying the extended metabolism model (Zafu and Newman 2017; Smit et al. 2018), case studies can analyse the role of urban agriculture in closing nutrient loops, using data on organic waste inputs and agricultural yields. Furthermore, scenario modelling can forecast the long-term impact of improved solid waste management on UM by integrating socio-economic survey data with material flow analysis. These practical examples demonstrate how data-driven insights can inform targeted policy interventions, ensuring that evidence-based recommendations are grounded in measurable outcomes rather than theoretical assumptions.

Policy implications of adopting a UM approach to analyse NBS contribution in the IS

In response to our third RQ, this section presents the implication of adopting the SENIU–EHWE framework for theory, methodology, society, and policy.

The societal impact of this study lies in its ability to illuminate nature's contributions to resource flows in the IS and bring attention to the NBS initiatives that exist in the socialy excluded communities of Global South cities. The study also provides researchers and practitioners with a tool for collecting and analysing NBS data, for broader use and interpretation of the general and specific social and ecological interactions at the household levels to get access to basic

Table 6 Contextualising, evaluating, and SENIU–EHWE data attributes

Contextualisation of metabolic flows	Evaluation of NBS	Integration with UM	Analysis of NBS to UM	Policy implication
SENIU determinants and EHWE ecosystem benefits from Table 2	Primary data on household or community consumption quantity from a specific NBS initiative (Smit et al. 2017)	Resource flow analysis and/or resource consumption profiles of food, water, energy, and population dynamics	For example, the percentage of the population with access to municipal basic services e.g., water (Kaviti Musango et al. 2020)	Evidence-based policy planning and implementation (authors' construction)
Community/stakeholder engagement	Indicator selection (Teferin and Newman 2017)	Material and energy flow analysis (authors' construction)	Impact assessment (authors' construction)	Data-driven actionable strategies (authors' construction)
Site/spatial analysis	**Data collection**: field surveys, remote sensing, and participatory methods (authors' construction based on the results from Table 1)	Ecosystem benefits assessment	Comparative analysis (Kovacic and Giampietro 2017)	Case-specific and tailored strategic proposals, plans, and projects for effective resource use (authors' construction)
Literature review	Scenarios modelling (authors' construction)	Scenario modelling (authors' construction)	Feedback loop (authors' construction)	Synthesised knowledge and insights inform decision-making, programme design, and policy formulation to integrate local knowledge into the international framework (authors' construction)
Literature review and fieldwork surveys	**Qualitative and quantitative analysis**: thematic analysis of interview data, while quantitative methods could involve statistical analysis of environmental and socio-economic indicators (Kovacic et al. 2016)	Characterisation of NBS to societal metabolism in funds and flow elements, to contextualise the observed energy flows (Kovacic and Giampietro 2017)	Application of an extended metabolism model to the analyses of NBS resource consumption (Zafu and Newman 2017) SDG 11 indicators (Zafu and Newman 2017; Smit et al. 2018)	Evidence-based policy recommendations. to policies are grounded in research rather than assumptions (authors' construction)

provisioning services. While the results presented here may not be exhaustive, they present NBS as a possible priority to enhance access to resource in the IS for integrated and inclusive urban development plans.

This study contributes to the international urban policy agenda by highlighting the role of NBS in enhancing UM within IS, aligning with the New Urban Agenda (UN-Habitat 2017) and the UN Sustainable Development Goals (UNDP 2015). To strengthen the integration of NBS into municipal governance, key policy dimensions from the SENIU–EHWE data framework are highlighted in Table 7. The recommendations and their implication include institutionalising community-led NBS initiatives through participatory planning, establishing dedicated municipal NBS units, and implementing incentive schemes such as tax breaks and grants to promote green infrastructure. Adegun (2021) also highlighted that ensuring land tenure security is also critical to fostering long-term NBS investments in IS.

Additionally, successful case studies (Diep et al. 2022a, b) and community-led green infrastructure in Nairobi and Dar-le-Salam provide replicable models for cities seeking to integrate NBS into climate adaptation and disaster risk reduction strategies. Municipalities should prioritise NBS into resilience planning, such as, leveraging urban wetlands and green buffers to mitigate flooding and extreme weather impacts. Strengthening multi-stakeholder collaboration among governments, local communities, NGOs, research institutions, and the private sector will be crucial in scaling up NBS for sustainable urban development. These measures will enable municipal authorities to systematically integrate NBS into urban governance, addressing socio-environmental challenges while enhancing UM and resilience in IS.

Limitations of the study

The generalisability of the framework across different data categories and case studies limits its ability to fully capture the actual contribution of NBS to the UM of IS. This limitation arises because each urban environment possesses unique environmental and socio-economic characteristics, that shape the diverse resource flows entering and exiting its boundaries. This consideration is crucial in the context of NBS and UM, as both concepts aim to be general, yet case specific and context sensitive. While the study provides valuable insights within its specific context, its broad generalisation prevents a comprehensive representation of NBS contributions to UM across different regional and cultural settings.

Another key limitation includes data-related challenges, particularly inconsistencies in data availability and quality across different IS. Data gaps, variations in measurement approaches, and reliance on secondary sources may introduce biases that affect the accuracy and comparability of findings. Future research should also explore how land tenure insecurity and informal governance structures shape the adoption and long-term sustainability of NBS. This would provide a more nuanced understanding of their role in UM across diverse IS contexts.

Furthermore, variations in environmental policies, economic factors, and urban–rural dynamics mean that the findings from various case studies, which were grouped to create a single data framework, may not be directly applicable to all IS in the Global South. To achieve a more comprehensive understanding, future research should incorporate diverse testing, comparative analyses, and multiple case studies to capture the complex and varied contribution of NBS to UM in different contexts. Future research should aim at testing the framework in several IS in fast-growing cities in the Global South.

Enhancing the applicability of the SENIU–EHWE framework requires addressing these limitations through comparative analyses across diverse IS, integrating adaptive methodologies such as participatory research and real-time monitoring to assess the long-term impacts of NBS. Again, incorporating in-depth context-specific data on socio-political dynamics, land tenure, and governance can improve the framework's refinement. Given these challenges, the framework can evolve into a more robust tool for policymakers and urban planners, facilitating the systematic integration of NBS into urban governance to enhance UM in IS.

Table 7 Key policy dimensions and implication of the SENIU–EHWE data framework

Key dimension	Implication
Social actors	Strengthening local networks enhances NBS sustainability and service provision
Ecological and natural systems	NBS mitigate environmental hazards and contribute to urban resilience, but require larger-scale adoption
Infrastructure	Limited access to basic services constrains NBS effectiveness; integration into existing infrastructure is necessary
Urban form	High-density areas face challenges in implementing large-scale NBS, but small-scale adaptive measures are promising
Policy and governance	Municipal governments must institutionalise and incentivise NBS adoption through targeted policies and collaborative planning

Conclusion

The SENIU–EHWE framework provides a comprehensive lens for assessing the contributions of NBS to UM in IS. Systematically analysing social actors, ecological systems, infrastructure, and urban form, the framework highlights both opportunities and challenges in implementing NBS in the specific context of IS in African cities. Its value lies in bridging theoretical insights with empirical data, offering a structured approach to integrating NBS into sustainable urban development strategies. Future research efforts should focus on applying the framework to identify NBS initiatives that successfully contributes to enhancing the metabolism of IS, while pointing to policy priority to foster institutional support, and address governance barriers to enhance the resilience and livability of IS through NBS.

Furthermore, our framework aligns with global sustainability policies, particularly the UN Sustainable Development Goals (SDGs), including SDG 11 (Sustainable Cities and Communities) and SDG 13 (Climate Action). By providing a structured methodology to analyse and scale-up NBS interventions, the framework can support international urban planning efforts, at local levels, influence climate resilience strategies, and contribute to sustainable urban development globally.

Our framework's structured approach holds significant potential for application beyond Africa. IS in Latin America, South Asia, and Southeast Asia exhibit similar socio-ecological dynamics, including environmental vulnerabilities, insecure land tenure, and community-driven adaptation efforts. Adapting the framework to account for regional variations in governance structures, climate conditions, and socio-economic factors, policymakers and urban planners can develop localised strategies for integrating NBS. This adaptability makes the framework a valuable tool for global urban sustainability initiatives, reinforcing its role in shaping inclusive, resilient, and nature-based urban development worldwide.

This study highlights the need for further research on the contextualisation and analysis of data within IS in Africa, particularly in relation to the contribution of NBS to UM. Future research should focus on distinct IS typologies such as peri-urban, inner-city, and coastal settlements to examine how their unique spatial, socio-economic, and environmental characteristics influence NBS implementation and resource flows. A critical area of investigation is the role of NBS in specific resource cycles, such as water reuse in flood-prone settlements or organic waste-to-energy transitions in high-density IS. Additionally, future studies can explore how the SENIU–EHWE framework operationalises these analyses by applying it to case studies with varying access to municipal services. Given data scarcity in IS, integrating innovative data science methods, such as remote sensing for spatial analysis or community mapping, can enhance data availability and quality. Building on methodologies proposed by UN-Habitat (2023), studies by Clark et al. (2022) and Cardenas Mamani and Perrotti (2022), researchers can develop scalable approaches for assessing NBS effectiveness. Furthermore, longitudinal studies can investigate causal relationships between NBS and resource accessibility, considering the historical evolution of IS and projecting future scenarios under different policy interventions. These targeted research directions will contribute to a deeper understanding of how NBS can be leveraged to enhance UM and improve living conditions in IS across different African contexts.

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