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RESEARCH ARTICLE



# Situating the contribution of nature-based solutions in informal settlements within the context of urban metabolism: lessons from selected informal settlements in Ghana

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## ABSTRACT

The assessment of nature-based solutions (NBS) in informal settlements (IS) offers significant potential to enhance urban metabolism (UM). However, there is little recognition of its contribution to UM and addressing socio-ecological challenges. This study selected IS in Accra and Kumasi, Ghana, to address the following research questions: What are the environmental and social challenges in the IS? What are the existing NBSs among the IS typologies, and how can the NBS contribute to UM? 770 household heads were interviewed, supported by 6 focus group discussions and observation. Descriptive statistics, chi-square tests and content analysis revealed common socio-ecological challenges, including waste disposal, water scarcity, and heat, which vary across the IS. For example, water scarcity was more severe in Nima, with 75.9% of residents affected compared to only 21.5% in Ayigya Zongo ( $p < 0.001$ ). Additionally, challenges related to physical infrastructure, such as sanitation systems and access to potable water, were identified. Old Fadama has better sanitation (67.6%) compared to Dagomba Line (51.7%) ( $p < 0.009$ ). Nevertheless, NBS positively contributes to UM through regulation/support, provision, and cultural/spiritual benefits. For example, Nima demonstrates higher provisioning benefits such as water harvesting (59%), thus reducing over-reliance on government water supply. Dakwadwom demonstrates high-temperature control (55%) and water regulation (87%), thus reducing water demands and energy. Policy should therefore focus on supporting NBS interventions such as rainwater harvesting, gardening, tree planting, and soil protection techniques at household levels in the IS, to address socio-ecological challenges and impact on overall UM.

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Informal settlements; nature-based solutions (NBS); socio-ecological challenges; sustainable cities; urban metabolism

## 1. Introduction

Although the contribution of nature-based solutions (NBS) to socioecological systems is increasingly documented in academic literature (Asare, Atun, and Pfeffer 2024; Tzoulas et al. 2021), recent studies highlight the need to more closely examine how NBS

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influence socioecological benefits and urban metabolism (UM) (Cárdenas-Mamani and Perrotti 2022). This is crucial for city planning (Smit et al. 2019) and an in-depth understanding of how NBS can be used to improve UM in informal settlements (IS) (Nalumu and Perrotti 2024). According to Cohen-Shacham et al. (2016, 2), NBS are defined as “actions to protect, sustainably manage, and restore natural or modified ecosystems, which address societal challenges”. In this article, Diep et al. (2022) define NBS as actions that support and are supported by nature to address societal challenges. This definition supports the understanding of NBS and their contribution to the UM of informal settlements (IS) at both the household and community levels, as it emphasises the demand for NBS to provide ecosystem benefits (Nalumu, Perrotti, and Rosa 2025). The UM approach is based on a bottom-up approach to collect and analyse data, and is vital for understanding resource flows in the IS (Smit, Parnell, and Solecki et al. 2018). The UN-Habitat (2012) defined 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 article, IS is referred to 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).

Across the conventional literature, studies (Mulligan et al. 2020; Seddon 2022) have reported that IS in urban areas have NBS initiatives for addressing local environmental challenges. While these are considered important for local environmental sustainability, there is limited research on how NBS contribute to UM, a perspective necessary for a broader understanding of their overall benefits. For example, NBS such as rainwater harvesting, urban gardens, and energy systems contribute to the sustainability of water, energy, and waste flows, which is currently not investigated and how NBS address both environmental and social challenges within distinct IS contexts (Nalumu and Perrotti 2024).

Moreover, urban planners and practitioners are advocating a need to understand the social-ecological interactions that exist in the IS (Azunre et al. 2021; Cobbinah, Erdiaw-Kwasie, and Amoateng 2015). Presently, there is an urgent need for data on how NBS are supporting the social and ecological needs of the inhabitants of the IS (UN-Habitat 2022). UM studies (Currie and Musango 2017) provide studies that guide sustainable urban planning and design. However, they have not effectively captured the social and ecological processes that exist in the IS. IS are either excluded or overlooked in the metabolic analysis (de Souza and Torres 2021). In response to this gap, it is critical to explore NBS’s contribution to UM, offering a better understanding of how to protect the natural environment in IS while creating context-specific environmental strategies that align with local needs. About 199.5 million people live in the IS in sub-Saharan Africa (UN-Habitat 2003), and by 2030, the urban population of developing countries is predicted to double, (UN-Habitat 2016). Therefore the focus of IS are important component of city interactions because they provide housing for a significant part of the urban labour force (Becciu et al. 2020) and also contribute to socio ecological system and UM as they are consumers of energy and material goods and generators of waste.

While global studies on NBS and UM have largely focused on formal urban contexts in the Global North and parts of Asia, there remains a limited empirical understanding of how these concepts operate in rapidly urbanising sub-Saharan African cities. Ghana presents a critical entry point for bridging this gap, as its IS reveal how locally driven ecological practices can illuminate the broader theoretical relationships between NBS and UM in

the Global South. One of the primary environmental challenges facing cities in SSA, particularly Ghana, is the degradation of natural resources (Cobbinah, Poku-Boansi, and Peprah 2017). Rapid urbanisation has resulted in significant land consumption, deforestation, and habitat destruction. This is particularly critical in Accra and Kumasi, where urban sprawl has encroached on green spaces and led to a loss of biodiversity (Schiavina et al. 2019). For example, flash floods are more frequent in Accra than in Kumasi. Furthermore, there is a large proportion of the urban poor, who lack access to basic services such as clean water, sanitation, and affordable housing (Doe and Aboagye 2022). In this context, NBS in IS has demonstrated significant potential to address environmental and social challenges by enhancing the UM process in Kumasi and Accra at the household and community level within the IS (Nalumu, Perrotti, and Rosa 2025). Accordingly, NBS can contribute to the efficient management of water, energy, and waste, thereby addressing some of the critical challenges facing these cities (Cárdenas-Mamani and Perrotti 2022). Although NBS are central to enhancing socioecological resilience, their integration with emerging sustainability paradigms such as artificial intelligence-driven urban management, green energy technologies, and circular economy models is increasingly emphasised for improving city liveability (Li et al. 2024). These complementary approaches, when compared with NBS, highlight the potential for synergistic and technology-informed pathways toward sustainable UM. For example, rainwater harvesting, wetland restoration, and the use of green infrastructure in the IS can reduce their reliance on centralised water supply systems and improve water security (Diep et al. 2022). Additionally, the restoration of natural drainage systems can mitigate flooding and prevent the contamination of water sources, which is a major issue in Accra's IS (Okyere et al. 2021). Solar energy and other sustainable energy practices can reduce the pressure on the national grid and promote energy self-sufficiency in IS (Adusei et al. 2018).

NBS can contribute to waste management by promoting composting and recycling practices, which convert organic waste into useful products such as fertiliser for urban gardens (Wolff, Rauf, and Hamel 2023). This not only reduces the amount of waste generated but also creates a circular economy where waste is repurposed to support urban agriculture and enhance food security (Makuwira 2022). There is limited evidence and contextualisation of NBS contribution to specific cases (Kabisch, Frantzeskaki, and Hansen 2022; Nalumu and Perrotti 2024). Along the same line, most studies on UM focus on formal urban areas with well-established infrastructure, leaving a gap in understanding how IS contribute to and benefit from sustainable resource flows (Broto, Allen, and Rapoport 2012; Smit et al. 2017). In Kumasi and Accra, IS play a crucial role in cities' sustainable development (Azunre et al. 2021), but NBS's contribution to UM remains unexplored. While many studies have identified how people perceive the NBS (Asare 2021; Boateng and Adams 2023), the diversity in people's perceptions represents a challenge for practitioners who may desire to derive practical implications from such studies. In Ghana, IS are outside formal urban planning and regulatory frameworks, with no or limited access to municipal services, as informal dwellers rely on NBS to address some of their social-ecological challenges, and desire for support to implement and enhance the existing NBS initiatives (Asare 2021; Boateng and Adams 2023). Therefore, assessing people's perceptions or understanding of the benefits and contribution of NBS to UM can aid planners and urban managers to better identify and incorporate diverse community needs, such as awareness creation in urban management.

Against this backdrop, the goal of this study is to assess the contribution of NBSs and how they enhance UM in the various types of IS in Ghana. This allows cross-examination of the problems, lessons learned and suitable solutions (Smit et al. 2019). Three key research questions were formulated, including what the environmental and social challenges are in the IS? What are the existing NBSs among the IS typologies, and how can the NBS contribute to UM? The key questions informed the design of the household survey questionnaire, with each question further supported by guiding sub-questions (see *Supplementary Materials*)

This study contributes to the literature in four different ways: firstly, it examines the typologies of IS in Kumasi and Accra and analyses the NBS approaches currently in place; secondly, this study provides a typology-specific understanding of NBS implementation. Thirdly, the study offers insights into how different forms of NBS address both environmental and social challenges within distinct IS. This adds value to the literature by categorising NBS approaches based on settlement typologies, which could be applied to similar urban areas in West Africa and beyond. Fourthly, the study provides empirical evidence on how NBS could contribute to sustainable UM of water, energy, and waste flows in IS.

### **1.1. Conceptualisation of UM**

Understanding the UM concept in the IS is an emerging area of interest (Nalumu, Perrotti, and Rosa 2025). Smit et al. (2017) report that to make robust and appropriate infrastructure choices, urban planners need better information on the material reality of IS and their contribution to the city's metabolism. The concept of UM provides a valuable framework for examining the contribution of NBS to improving the flow of energy, materials, and resources within IS. Rooted in a bottom-up approach (Currie and Musango 2017; Smit, Parnell, and Solecki 2018), UM is particularly suited to studying resource dynamics at the household level. Smit et al. (2017) emphasised the importance of integrating the historical UM concept, originally formulated in 1894, with contemporary sustainable development paradigms. This integration facilitates the analysis of sustainable urban development issues, such as quality of life and urban planning for sustainable cities. Adopting the 2030 Agenda for SDGs has further strengthened the connection between UM and sustainable development, highlighting their collaborative potential. As such, this study focuses on land resource input elements of UM, which include water, energy, food, buildings and materials, as these are directly delivered by NBS initiatives. They also have a direct societal impact at both the household and community levels within IS. Given the NBS as contributors to the metabolic inputs of key resources, this study aims to explore their role in supporting social-ecological livability and sustaining ecosystem benefits at the household level.

### **1.2. Conceptualisation of NBS**

NBS is an umbrella concept for ecosystem-based adaptation and urban green infrastructure rooted in climate change mitigation and adaptation strategies (Pauleit et al. 2017). Some authors argue that, unlike other approaches, NBS is based on a participatory bottom-up approach and is conscientious in first addressing the most vulnerable

(Wolff, Rauf, and Hamel 2023). These principles are reported to be valuable when planning for natural resource use in cities with high rates of IS because inhabitants have demonstrated unique and complex interactions with social-ecological systems for ecological benefits contributing to sustainable development (McEvoy et al. 2024; United Nations 2023). Studies on IS highlight NBS as common sources of essential provisioning benefits, such as access to water, energy, and solid waste management. Furthermore, these studies provide insights into how nature contributes to resource flows at the household level, aligning with the concept of UM. In IS, various NBS initiatives are implemented to address specific issues such as water scarcity, food security, human health, disaster risk reduction, and climate change. The contribution of NBS to resource flows such as water, energy, and housing materials is classified using the Common International Classification of Ecosystem Services (CICES) v5.1. The classification organises the services into provisioning, regulating, and socio-cultural benefits (Haines-Young and Potschin 2010). Additionally, this classification aids in understanding how NBS supports resource flows and UM processes in IS (Cárdenas-Mamani and Perrotti 2022).

### **1.3. Nexus between NBS and UM**

This section examines the commonalities and interconnections between the social and ecological concepts of NBS and UM. It underscores the critical role of nature in facilitating resource flows at the household level. NBS and UM are characterised by bottom-up approaches, which are essential for data collection, contextualisation, and the analysis of material flows in UM studies (Currie and Musango 2017; Smit, Parnell, and Solecki 2018). Similarly, bottom-up methodologies are highly recommended for knowledge generation and data gathering in NBS studies, as they enhance the relevance and applicability of findings within the IS context (McEvoy et al. 2024). Teferi and Newman (2017) used the extended metabolism model and the SDG to highlight the importance of key resource inputs such as land, water, energy, buildings, and materials in IS redevelopment. These inputs align closely with the resources required for NBS initiatives to improve UM through ecosystem benefits (Cárdenas-Mamani and Perrotti 2022). Ecosystem benefits include: provisioning (e.g. water, food, and energy), regulating (e.g. temperature and humidity control, hydrological cycle management, filtration, sequestration, and storage), and socio-cultural (e.g. recreation, aesthetics, spirituality, culture, and education) (Cárdenas-Mamani and Perrotti 2022; Nalumu and Perrotti 2024). Importantly, the alignment of ecosystem benefits with resource inputs provides the integrative potential of NBS and UM in addressing resource flow challenges in IS. Finally, both NBS and UM emphasise co-design processes that involve community participation (Diep et al. 2022; Smit et al. 2019). This shared focus extends to the incorporation of local knowledge and practices at the household level during data collection, reinforcing the relevance of these frameworks in addressing the complex challenges faced by IS. In the context of Kumasi and Accra, UM theory helps to analyse NBS contribution to resource flows in the IS in the face of rapid urbanisation. IS are often under-studied in terms of how they get access to basic provisioning utility services and their contributions to the city's metabolism. Therefore, exploring NBS's contribution to UM will provide insight into how NBS can address local environmental challenges and enhance resource flows within the IS.

## 2. Method

### 2.1. Study settings

The study was conducted in Kumasi and Accra IS. Geographically, Accra is the largest city and the biggest economic and administrative hub of Ghana. According to the Ghana Statistical Services (GSS 2021), it has a population of 5,455,692. Over the past two decades, it has experienced rapid urbanisation (de-Graft Aikins and Koram 2017). This is due to the diverse economic, administrative and industrial opportunities, and various migrants from different backgrounds are attracted to the city. This has resulted in the development and expansion of IS. The city is situated at an elevation of approximately 61 meters (200 feet) above sea level and is located between Latitude 5.55°N and Longitude 0.20°W. The Greater Accra Region covers an area of 3,245 km<sup>2</sup>, with the Greater Accra metropolitan area covering a total land area of 139.674 Km<sup>2</sup> (GSS 2012).

Kumasi is the second-largest city in Ghana. The land area of Greater Kumasi is approximately 2,589 km<sup>2</sup>, with the Kumasi metropolitan area with 214.3 square km of land area. Kumasi has an elevation of between 250 and 300 m above sea level and is situated between Latitude 6.35°N and 6.40°S and Longitude 1.30°W and 1.35°E (GSS 2014). Kumasi metropolitan area is one of the fastest urbanising cities in Ghana, with a population of 3,490,000 and an annual growth rate of over 5% (GSS 2021). Kumasi is the business hub of the Ashanti Region, and its population is projected to grow due to high in-migration and natural demographic increase (Cobbinah et al. 2020). Kumasi was previously called the “garden city of West Africa” because of its widespread green infrastructure; however, the city has lost most of its green spaces to socio-economic developments and faces several environmental challenges (Takyi et al. 2022).

The two cities have contrasting socioeconomic and climatic profiles, allowing the exploration of NBS contribution to UM under different contextual conditions and metropolitan areas. IS in each city represent three types of Ghanaian slums in Paller (2015) as indicated in Table 1, in the brackets are names of IS that fall in the same category; the italic ones from Accra and the non-highlighted ones from Kumasi. Namely: Extra-legal (not officially recognised by local/national authorities) (*Agbogbloshie* and *Dagomba Line*); Indigenous (traditional settlements) have descended into slums due to urban planning failures (*Ga Mashie* and *Dakodwom*); and purchased (legitimised through legal processes followed by settlers) (*Nima* and *Ayigya Zongo*). The suburbs were selected for this study because they remain among the largest slums in Ghana and are characterised by

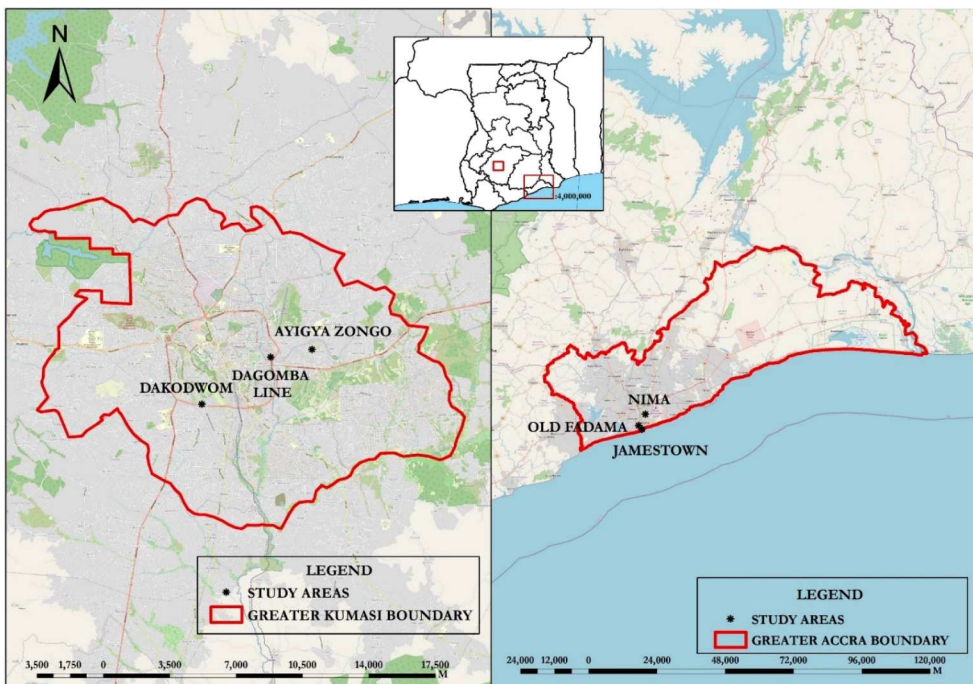
**Table 1.** The number of households sampled in locations and sublocations.

Typology of IS	Location	Sub location	Projected Population (2024)	Total household	Sample household
	Kumasi				
Purchased		Ayigya Zongo	11515	2094	144
Indigenous		Dakodwom	4775	1592	110
Extra-legal		Dagomba Line	3599	1714	118
	Accra				
Purchased		<i>Nima</i>	145269	26412	145
Indigenous		<i>Jamestown</i>	31218	20812	114
Extra-legal		<i>Old Fadama</i>	126857	25371	139
	Total				770

poor sanitary conditions, limited provision of utility services, sub-standard buildings, and rapid diminishing of green spaces (Adusei et al. 2018; Tutu et al. 2017) (Figure 1).

## 2.2. Research design

This study employed a multiple case study within a mixed-method approach (Malina, Nørreklit, and Selto 2011) to examine the contribution of NBS to UM in IS. Using a case study within a mixed-method approach allows the study to investigate a particular real-life situation (the case study) while simultaneously gathering both qualitative and quantitative data to provide a comprehensive understanding (Plano Clark 2017). Consequently, there is a need for a study that prioritises quantitative data while still incorporating qualitative data to gain a deeper understanding of the contribution of NBS to UM of the IS phenomenon in Ghana. Additionally, the case study method is a suitable and effective approach because it aligns well to explore the context-specific environmental and social challenges in the different IS typologies, as well as their contribution to UM (Nalumu et al. 2025). The qualitative approach was used to collect qualitative data on respondents' opinions on the environmental and social challenges, types and sources of basic provisioning services, and existing NBS in IS. The interview guide was used to interview key informants (basic utility service vendors in the IS) due to their experience and influence. The secondary data primarily use journal articles that focus on the environmental and social challenges, existing NBS in IS and their contribution to UM. Field surveys were used to obtain data from the household heads.



**Figure 1.** Location of the study areas.

### 2.3. Sampling

The study used a cross-sectional survey design on house questionnaire surveys and interviews for data collection. Stratified proportionate sampling and simple random sampling techniques were used to sample the respondents from the population. The sub-locations in Accra were Nima, Old Fadama, Jamestown and Kumasi; Ayigya Zongo, Dakodwom, and Dagomba Line. Through a random sampling technique, a total of 770 household heads were selected and proportionally distributed among the six settlements in Table 1. Given the challenges in obtaining up-to-date population data in the IS of Ghana, the current population estimates were derived through projection methods shown in Table 1. The types of IS presented in Table 1 represent three IS in Accra and three in Kumasi. In each city, three types of Ghanaian IS are presented (Paller 2015). Each IS, although they may fall in the same typology, has different social-ecological characteristics and an independent presentation. In addition, they are located in different municipal areas, each with a different average household size as reported by the Municipal Planning Office, which was used to calculate the sample size (See Table 1). This approach is often necessary when reliable or current census data is unavailable, allowing for informed estimations based on historical trends or other demographic indicators (Smith, Tayman, and Swanson 2013; United Nations 2019). Purposive sampling was used to select key participants for the focus group discussion (FGD) because of their rich experience and leadership in the selected communities.

The study offers a short overview of respondent socio-demographics. A complete variables is listed in the Appendix. 1 (*Supplementary material*). It shows the comparison of the three types of IS – Purchased, Indigenous, and Extra-legal, as well as the socio-demographic differences across different communities in Accra and Kumasi.

### 2.4. Data collection

#### 2.4.1. A questionnaire survey

Semi-structured interviews were conducted with 770 respondents, and the unit of inquiry was the household heads to capture their socio-economic information, knowledge about the environmental and social challenges, type and source of basic provisioning services, NBS ecosystem benefits, the existing NBSs to the environmental and social challenges as well as their contribution to UM. The questionnaire was based on previous studies that aimed to investigate household environmental and social challenges in the IS, and how NBS contribute to ecosystem benefits (e.g. Diep et al. 2022; Roy et al. 2018). Data were collected through face-to-face interviews. Respondents were requested to rate the environmental and social challenges using 0 = No, Yes = 1, the existing NBSs coping strategies among the IS using 0 = No, Yes = 1, as well as the contribution of NBS to ecosystem benefits using 0 = No, Yes = 1, To what extent do you agree with the statement: Land should be reserved for gardening in your neighbourhood? Using a Likert scale, 1 = Strongly disagree, 5 = Strongly agree. The contribution of NBS to UM is classified into provisioning, regulating and social-cultural. The NBS coping strategies were divided into flood management and water conservation: rain garden, water harvesting, planting trees, community and domestic gardens, improving air quality and reducing heat: green roof and walls, waste management and sanitation: soil protection/composting, soil erosion and land stabilisation:

permeable paving, sandbags, hedges. Besides the closed questions, free space for comments or alternative answers was also included.

The questionnaires were designed and collected with Kobo Collect software because of its capacity to synchronise data offline and enable data collection with limited internet access (Nampa et al. 2020). Fieldwork assistants from Kwame Nkrumah University of Science and Technology (KNUST) were trained to assist in the data collection. Fieldwork assistant recruitment primarily utilised two local languages: Twi and Hausa. Though the survey was initially developed in English, the fieldwork assistants translated questions into these local languages when necessary, ensuring clarity and engagement. Data collection spanned six months, from November 28, 2023, to April 14, 2024. Surveys were conducted predominantly during weekends, public holidays, and weekday evenings from 4:00 to 6:00 pm, as these times aligned with the availability of household heads. Before the survey, the questionnaire was initially tested for content and face validity and modified accordingly based on certain comments of experts from KNUST and respondents from a neighbouring and comparable area.

#### **2.4.2. Focused group discussion**

In April 2024, six FGDs were conducted in the selected IS to capture detailed knowledge about environmental and social challenges, existing NBSs, as well as the contribution of NBS to UM. The FGD was conducted to validate the interpretation of responses and provide a basis to formulate suitable recommendations. The group comprised: traditional authority, assemblyman, unity committee, religious, opinion leaders, women and youth and women representatives. Each group comprised 8 members, and the interview lasted for 50 min. The participants were asked a set of questions, initially derived from the literature and based on observation, which discovered key environmental and social challenges, the existing relevance of NBS and its association with UM. After permission from the participant, the session was audio-recorded to avoid missing any important points. Notes were taken during the FGD as a backup.

#### **2.4.3. Observation**

Field observation was used to improve the validity of the information obtained from the household through triangulation. Photographs were taken from the field to further provide clarity on the presence of NBS initiatives, environmental and social challenges, housing infrastructures and designs. This strategy was useful when respondents were unable to convey their feelings verbally for a variety of reasons. This visual documentation enabled the comparison between reported and observed conditions, thereby improving the reliability of the data.

### **2.5. Data analysis**

Data were subjected to analyses using SPSS 27.0 software (BM Corp 2020). Descriptive (frequency, percentage) and nonparametric (chi-square,  $X^2$ ) tests were used. First, descriptive statistics were reported, such as the percentages of study participants' coping strategies, and the existing NBSs among the IS typologies meant to solve the social and environmental challenges. The divergent bar graph was also applied to describe the extent to which respondents agree with the statement: Land should be reserved for gardening

(including ornamental and edible) in our private house or around the neighbourhood. The chi-square goodness-of-fit test was carried out for the binary questions. This allowed the relative proportions of the observed and expected frequencies to be compared, response by response, between the two groups; and the usual statistical procedure recommended would be a chi-square test. When the response frequency is lower than five in any category, the chi-square test is not appropriate, so Fisher's exact test was used. We report 95% confidence intervals (CIs) to convey the precision and practical significance of all estimates. The chi-square test is a widely used method for measuring if a significant association or similarity exists between two nominal or categorical variables (Agresti 2007; Anderson 1996). Chi-square was used to compare responses related to the environmental and social challenges in Kumasi and Accra. The chi-square was also applied to test whether differences exist in the contribution of NBS to UM in IS under the null hypothesis of no significant differences between the observed and the expected value.

The qualitative responses to questions: "What are the environmental challenges in the community and how can they be addressed through NBS?", "What NBS exist and how can you promote it?", and How do you benefit from the ecosystem in the community? responses were coded to fit into the following categories: environmental challenges, social challenges, NBS initiative, ecosystem benefits and preferred NBS. In this approach, the material is read several times until the main headings are obtained. The whole coding process was analysed in Excel software. Based on the convergent mixed-methods approach, the quantitative and qualitative data were collected at the same time and analysed separately. Then integrated by laying out the quantitative results beside the qualitative insights. We looked for where the results agreed, where they added different pieces of the story, and where they conflicted. Qualitative insights helped explain any unexpected quantitative patterns. Finally, we assessed agreement, complementarity, and discrepancies, using qualitative findings to clarify unexpected quantitative results and to form a single, combined conclusion for each research question drew overall conclusions for each research question by considering both strands together.

To ensure the reliability and validity of the instruments, three experts in the field from the Kwame Nkrumah University of Science and Technology (KNUST) confirm content validity and ensure alignment with the study objectives. A pilot test was then conducted in a comparable informal settlement to evaluate the clarity, relevance, and internal consistency of the items. The Cronbach's alpha coefficient for the Likert-scale items was 0.81, indicating good internal reliability (George and Mallery 2018). Finally, this study was approved by the Humanities and Social Sciences Research Ethics Committee, Kwame Nkrumah University of Science and Technology.

### **3. Results and discussion**

#### ***3.1. Socio-ecological challenges in the selected IS***

It is important to understand the social and ecological challenges facing the IS, and this will allow the identification of suitable solutions to address them. In the conventional literature (Amoako and Inkoom 2018; Boateng and Adams 2023), several challenges are reported, including limited access to essential services such as water,

sanitation, and electricity, which are compounded by tenure insecurity and poor solid waste disposal. On the ecological side, IS is located in ecologically fragile zones that are exposed to floods, landslides, and heat stress (Hamel and Tan 2022). From the UM perspective, these challenges reflect imbalances in the flows of energy, materials, and ecosystem services that sustain urban life. Drawing on the Common International Classification of Ecosystem Services (CICES, v5.1) these disturbances constrain both provisioning (e.g. access to clean water), regulating (e.g. flood control and air quality regulation), and cultural services (e.g. social cohesion and place attachment), revealing a disruption in the socio-ecological exchange processes that underpin urban functioning.

The SENIEU–EHWE framework (Nalumu, Perrotti, and Rosa 2025) further advances this understanding by linking social–ecological network interactions (SENIEU) with ecosystem health and human well-being (EHWE) outcomes. This framework emphasises that the vulnerabilities observed in IS such as water scarcity, flooding, and waste mismanagement represent both ecological stressors and social inequities that weaken the UM of these communities. According to the findings (Table 2), of the comparison of various environmental challenges between Accra and Kumasi, the chi-square test result shows significant differences in environmental challenges such as water scarcity, flooding, heat stress, improper waste dumping, air pollution, and erosion. In Purchase settlements, for example, it was revealed that water scarcity is significantly more severe in Nima, with 75.9% of residents affected compared to only 21.5% in Ayigya Zongo ( $p < 0.001$ ). Conversely, flooding is more prevalent in Nima, where 86.1% report flooding, compared to 51% in Ayigya Zongo ( $p < 0.001$ ). Heat stress is more common in Nima (22.1%) than in Ayigya Zongo (11.1%) with ( $p = 0.012$ ). Erosion is a major concern in Nima (64.1%), much more so than in Ayigya Zongo (4.9%;  $p < 0.001$ ). Waste management challenges are also significantly greater in Nima, where 57.9% struggle compared to 19.4% in Ayigya Zongo ( $p < 0.001$ ). Viewed through the combined CICES and SENIEU–EHWE lenses, these differentiated patterns illustrate how ecological pressures and social structures interact to produce uneven urban metabolic outcomes where the degradation of regulating and provisioning benefits corresponds to heightened social vulnerabilities and declining well-being. The narratives of residents provide a grounded reflection of these intertwined processes, capturing how the lived realities of scarcity, exposure, and adaptation express the metabolic and socio-ecological dynamics of their environments. For example, a respondent from Nima narrated that:

We are contributing to environmental problems. People generate garbage, and instead of sending it to where it is supposed to go, they dump it in someone's backyard or the gutters. When it rains, the smell is unbearable.

Additionally, in Nima, respondents identified flooding as a significant issue due to improper waste management. A respondent stated that: “People dump garbage in the gutters, which later causes flooding”. Meanwhile, respondents in Ayigya Zongo emphasised the waste disposal problem and its contribution to erosion, as one participant remarked, “No matter how many times you clear the gutters, they get choked when it rains”.

**Table 2.** Comparisons of the state of socio-ecological challenges between selected IS.

	Purchased						Indigenous						Extra-legal					
	Accra		Kumasi		Statistic		Accra		Kumasi		Statistic		Accra		Kumasi		Statistic	
	No	Yes	No	Yes			No	Yes	No	Yes			No	Yes	No	Yes		
N (%)	N (%)	N (%)	N (%)	N (%)	N (%)	N (%)	N (%)	N (%)	N (%)	N (%)	N (%)	N (%)	N (%)	N (%)	N (%)	N (%)	N (%)	N (%)
Water scarcity	35 (24.1)	110 (75.9)	113 (78.5)	31 (21.5)	<0.001		30 (26.3)	84 (73.7)	70 (63.6)	40 (36.4)	<0.001		33 (23.7)	106 (76.25)	73 (61.9)	45 (38.1)	<0.001	
Flooding	71 (49.0)	74 (51.0)	124 (86.1)	20 (13.9)	<0.001		61 (53.5)	53 (46.5)	70 (63.6)	40 (36.4)	0.124		46 (33.1)	93 (66.9)	46 (39.0)	72 (61.0)	0.326	
Heat stress	32 (22.1)	113 (77.9)	16 (11.1)	128 (88.9)	0.012		38 (33.3)	76 (66.7)	20 (18.2)	90 (81.8)	0.010		26 (18.7)	113 (81.3)	13 (11.0)	105 (89.0)	0.087	
Improper Waste dumping	84 (57.9)	61 (42.1)	116 (80.6)	28 (19.4)	<0.001		46 (40.4)	68 (59.6)	81 (73.6)	29 (26.4)	<0.001		78 (56.1)	61 (43.9)	76 (64.4)	42 (35.6)	0.176	
Air pollution	22 (15.2)	123 (84.8)	21 (14.6)	123 (85.4)	0.888		15 (13.2)	99 (86.8)	20 (18.2)	90 (81.8)	0.301		23 (16.5)	116 (83.5)	23 (19.5)	95 (80.5)	0.540	
Erosion	52 (35.9)	93 (64.1)	137 (95.1)	7 (4.9)	<0.001		45 (39.5)	69 (60.5)	98 (89.1)	12 (10.9)	<0.001		67 (48.2)	72 (51.8)	103 (82.3)	15 (12.7)	<0.001	

Notes: \* significant at  $p < 0.05$ .

In Indigenous communities, Jamestown and Dakwadwom face different environmental problems. Water scarcity is more prominent in Jamestown, affecting (73.7%) of residents, compared to (36.4%) in Dakwadwom ( $p < 0.001$ ). Flooding did not show a significant difference between the two ( $p < 0.124$ ), but Jamestown experiences significantly higher heat stress (33.3%) than Dakwadwom (18.2%) ( $p < 0.010$ ). Waste management challenges are more severe in Jamestown, with 40.4% facing problems, compared to 26.4% in Dakwadwom ( $p < 0.001$ ). Erosion is also a greater issue in Jamestown (60.5%) ( $p < 0.001$ ), indicating a significant environmental challenge. A respondent from Jamestown mentioned that:

During the rainy season, we who are located beside the slope face a lot of problems. The rain washes away the sand, leaving holes in the streets. Even when we fill in the holes, the heavy rain comes again to remove the sand." We need more trees and grass to protect our local environment

In James Town, respondents pointed out waste as a primary challenge, highlighting communal difficulties with organising labour for clean-up and the lack of proper waste disposal practices, as narrated by a respondent: "Communal labour has become difficult; people don't want to pay for waste collection, and garbage piles up". On the other hand, Dakwadwom respondents mentioned better management of drainage systems and less severe waste problems.

Old Fadama and Dagomba Line, both classified as extra-legal settlements, experience major environmental challenges. Water scarcity is far more prevalent in Old Fadama, with 76.25% of residents affected compared to 38.1% in the Dagomba Line ( $p < 0.001$ ). Flooding presents no significant difference ( $p < 0.326$ ), but Old Fadama experiences higher heat stress (81.3%) compared to Dagomba Line (11%;  $p < 0.087$ , not significant). Waste management problems are slightly more common in the Dagomba Line (35.6%) than in Old Fadama (43.9%), though this difference is not statistically significant ( $p < 0.176$ ). Erosion is a major concern in Old Fadama (82.3%) compared to the Dagomba Line (12.7%) ( $p < 0.001$ ). One respondent from Old Fadama noted: "When it's sunny, you don't get anywhere to sit. We need trees that provide shade, like mango, which can also give us fruit". Additionally, respondents noted, "the sawdust used to fill lands worsens soil conditions". Additionally, waste is transported to distant sites like Malam and Ashaiman, with complaints that "waste isn't well-managed, causing environmental problems". Dagomba line respondents also face challenges with heat stress, erosion and poor drainage.

In Nima (Accra) and Ayigya Zongo (Kumasi), significant differences were found in environmental challenges such as water scarcity and flooding. Ayigya Zongo, for example, experiences severe water scarcity, while Nima is more prone to flooding. These results add to previous studies that emphasise NBS are a general solution, context-specific and case-sensitive (Andersson et al. 2021; Sarabi et al. 2022). These findings highlight the interplay between expected or desired ecosystem benefits and their influence on metabolic flows. This could be an opportunity to enhance the social-ecological systems of the IS. For instance, in Nima, rainwater harvesting and flood retention measures are already common practices, and further enhancement of these will address water needs (Birchnell, Gill, and Sultana 2019; Bunch 2016). The findings

contribute to the literature on specific NBS initiatives for context-specific social and ecological challenges (Babí Almenar et al. 2021).

It is important to note that the survey results on water scarcity and other socio-ecological challenges reflect residents' lived experiences and perceptions, rather than official supply statistics. This distinction is crucial in the context of IS in Ghana, where no disaggregated or reliable data exist from the Ghana Water Company Limited or other municipal agencies regarding service provision in unregulated areas. As a result, perception-based data provide the most direct insight into local realities of access, reliability, and quality of services. Consistent with previous studies in Accra and Kumasi (e.g. Adusei et al. 2018; Cobbinah et al. 2020), residents' reports of scarcity often align closely with field observations such as long water-fetching distances, irregular tanker supply, and dry standpipes, demonstrating a high level of construct validity. The use of a mixed-methods design, combining quantitative surveys with qualitative focus group discussions and direct field observation, further enhanced data reliability and triangulation. The convergence between statistical patterns (e.g. 79% of Nima residents reporting scarcity) and qualitative narratives provides confidence that these perceptions are not isolated but reflect the broader empirical reality of infrastructural exclusion in the study areas.

### ***3.2. Situational analysis of physical infrastructure and its potential for NBS interventions in selected IS***

Physical infrastructure plays a critical role in shaping UM in IS, in a complex way where basic provisioning infrastructures are inspired by environmental and social systems but are often poorly integrated and vulnerable to weather extremes. From a UM theoretical standpoint, cities function as living systems that consume, transform, and excrete energy and material flows (Kennedy, Cuddihy, and Engel-Yan 2007; Pincetl, Bunje, and Holmes 2012; Wolman 1965). Within IS, this metabolic process is constrained by infrastructural deficits that interrupt essential material and ecological cycles. Well-designed NBS interventions, such as green roofs, urban gardens, and constructed wetlands, not only improve the functionality of physical infrastructure but also sustain ecological systems, such as reduced heat stress, improved biodiversity, and improved water management (Kabisch et al. 2017). Moreover, integrating NBS into existing physical infrastructure, such as improving stormwater drainage systems with vegetated bioswales, could significantly reduce vulnerabilities to environmental hazards like floods and heatwaves (Kamer et al. 2023). Table 3 shows the state of physical infrastructure and the potential for NBS interventions, which are key to improving UM in the IS. The chi-square test results indicate that key variables such as sanitation, drainage, and potable water show differences across the IS in Accra and Kumasi. For example, Nima has better sanitation, with only (5.5%) of households reporting a lack of adequate sanitation compared to 34.7% in Ayigya Zongo ( $p < 0.001$ ). However, potable water access is similar between Nima (15.9%) and Ayigya Zongo (18.75%), with ( $p < 0.516$ ), and both areas have a high prevalence of gardening. James Town shows better waste disposal with 14% compared to 13.6% in Dakwadwom ( $p < 0.931$ ). However, Dakwadwom has significantly better drainage channel access (Dakwadwom 46.4%, James Town 17.5%,  $p < 0.001$ ). Old Fadama has better sanitation (67.6%) compared to the Dagomba Line (51.7%,  $p < 0.009$ ). Potable water access is much lower in

**Table 3.** Comparisons of access to physical infrastructure in the selected IS.

	Purchased slums						Indigenous						Extra-legal									
	Accra		Kumasi		Ayigya Zongo (144)		Accra		Kumasi		Dakodwom (110)		Jamestown (114)		Old Fadama (139)		Accra		Dagomba line (118)		Kumasi	
	No N (%)	Yes N (%)	No N (%)	Yes N (%)	No N (%)	Yes N (%)	Statistic	No N (%)	Yes N (%)	No N (%)	Yes N (%)	Statistic	No N (%)	Yes N (%)	No N (%)	Yes N (%)	Statistic	No N (%)	Yes N (%)	No N (%)	Yes N (%)	Statistic
Sanitation system	8 (5.5)	137 (94.5)	50 (34.7)	94 (65.3)	19 (16.7)	95 (83.3)	<0.001	33 (30)	77 (70)	45 (32.4)	94 (67.6)	0.018	45 (32.4)	94 (67.6)	57 (48.3)	61 (51.7)	0.009	57 (48.3)	61 (51.7)	4 (3.4)	114 (96.6)	0.083
Gardening	121 (83.4)	24 (16.6)	121 (84.0)	23 (16.0)	105 (92.1)	9 (7.9)	0.894	93 (84.5)	17 (15.5)	127 (91.4)	12 (8.6)	0.077	127 (91.4)	12 (8.6)	4 (3.4)	114 (96.6)	0.695	127 (91.4)	12 (8.6)	25 (21.2)	93 (78.8)	<0.001
Potable water	23 (15.9)	122 (84.1)	27 (18.75)	117 (81.3)	20 (17.5)	94 (82.5)	<0.001	19 (17.2)	91 (82.7)	20 (17.5)	94 (82.5)	0.434	51 (46.4)	59 (53.6)	87 (62.6)	51 (43.2)	0.001	87 (62.6)	51 (43.2)	2 (1.4)	137 (110)	0.001
Drainage channel	9 (18.6)	136 (81.4)	6 (38.9)	138 (61.1)	1 (0.9)	113 (99.1)	0.003	0 (0)	110 (100)	6 (5.3)	108 (94.7)	0.004	7 (6.4)	103 (93.6)	25 (18.0)	114 (82.0)	0.931	25 (18.0)	114 (82.0)	66 (47.5)	73 (52.5)	<0.001
Energy	6 (6.2)	93 (93.8)	25 (42)	119 (95.8)	16 (14.0)	98 (86.0)	0.004	15 (13.6)	95 (86.4)	16 (14.0)	98 (86.0)	0.004	15 (13.6)	95 (86.4)	23 (19.5)	95 (80.5)	0.892	23 (18.6)	96 (81.4)	23 (19.5)	95 (80.5)	<0.001
Water services	9 (6.2)	136 (93.8)	25 (42)	119 (95.8)	16 (14.0)	98 (86.0)	0.004	15 (13.6)	95 (86.4)	16 (14.0)	98 (86.0)	0.004	15 (13.6)	95 (86.4)	23 (19.5)	95 (80.5)	0.892	23 (18.6)	96 (81.4)	23 (19.5)	95 (80.5)	<0.001
Waste disposal system.	8 (5.5)	137 (94.5)	23 (16.0)	121 (84.0)	16 (14.0)	98 (86.0)	0.004	15 (13.6)	95 (86.4)	16 (14.0)	98 (86.0)	0.004	15 (13.6)	95 (86.4)	23 (19.5)	95 (80.5)	0.892	23 (18.6)	96 (81.4)	23 (19.5)	95 (80.5)	<0.001

Notes: \* significant at  $p < 0.05$ .

Old Fadama (54%) compared to the Dagomba line (78%,  $p < 0.001$ ). Drainage and waste disposal systems were better in Old Fadama.

Interpreted through the UM and CICES frameworks, these results extend the understanding of NBS beyond their immediate environmental benefits to their role as metabolic infrastructure. They also align with the SENIEU–EHWE framework (Nalumu, Perrotti, and Rosa 2025), which links improved infrastructure to strengthened ecosystem health and human well-being. The findings suggest that IS are not passive consumers in the urban system but active metabolic agents whose practices correspond to both biophysical flows (Kennedy, Pincetl, and Bunje 2011) and ecosystem functions (Potschin-Young et al. 2018). This dual framing provides the theoretical relevance of integrating UM theory and ecosystem benefits classification (Nalumu, Perrotti, and Rosa 2025) in assessing sustainability in informal urban contexts.

James Town and Dakwadwom show distinct environmental profiles as well, with James Town having a higher occurrence of heat stress and waste management issues while Dakwadwom has better drainage channels and less severe erosion. The potential for NBS interventions could focus on enhancing green infrastructure, such as flood retention measures as indicated by Hamel and Tan (2022) and soil protection in James Town, to manage heat stress and improve waste treatment. For Dakwadwom, tree planting and rainwater harvesting could enhance ecosystem benefits such as air quality regulation and water management. Generally, the household head strongly agrees that land should be reserved for gardening, which opens opportunities for urban agriculture or green roof initiatives, contributing to both social cohesion and ecological balance. This is in line with the study of those who reported a need to understand actors who demand more land for urban gardening to regulate land-use activities.

### **3.3. The existing NBS initiatives in IS**

NBS has multiple functions, and these are utilised by IS in addressing their local environmental problems (Kharisma and Kaswanto 2021). While this is also critical in terms of UM, it is important to encourage its implementation. Moreover, existing and preferred coping strategies for context-specific challenges are critical for UM studies (Kovacic and Giampietro 2017). NBS initiatives in the IS, such as rainwater harvesting, community gardens, and flood retention, not only address immediate social-ecological challenges but also contribute to the systemic flows of resources, energy, and waste (Cárdenas-Mamani and Perrotti 2022). In this study, the results show that the three most frequent practices across all settlements are rainwater harvesting, flood retention, and soil protection/composting. These practices relate to those of Diep, Mulligan et al. (2020) and Roy et al. (2018). People implement NBS for direct ecosystem benefits at the household level within the IS, which could be an opportunity for practitioners to improve the UM within the IS. From the multiple response question analysis, it was revealed that Nima had more flood retention measures Nima (33) than Ayigya Zongo (15) and greater use of composting Nima (35) than Ayigya Zongo (12). However, Ayigya Zongo showed higher implementation of tree planting (20) than Nima (17). In James Town, it was found that respondents engage less in rainwater harvesting (89) as compared to Dakwadwom (91), but have stronger flood retention (33) than Dakwadwom (16). Comparison between Old Fadama and Dagomba Line revealed that Old Fadama had more flood retention (33) than

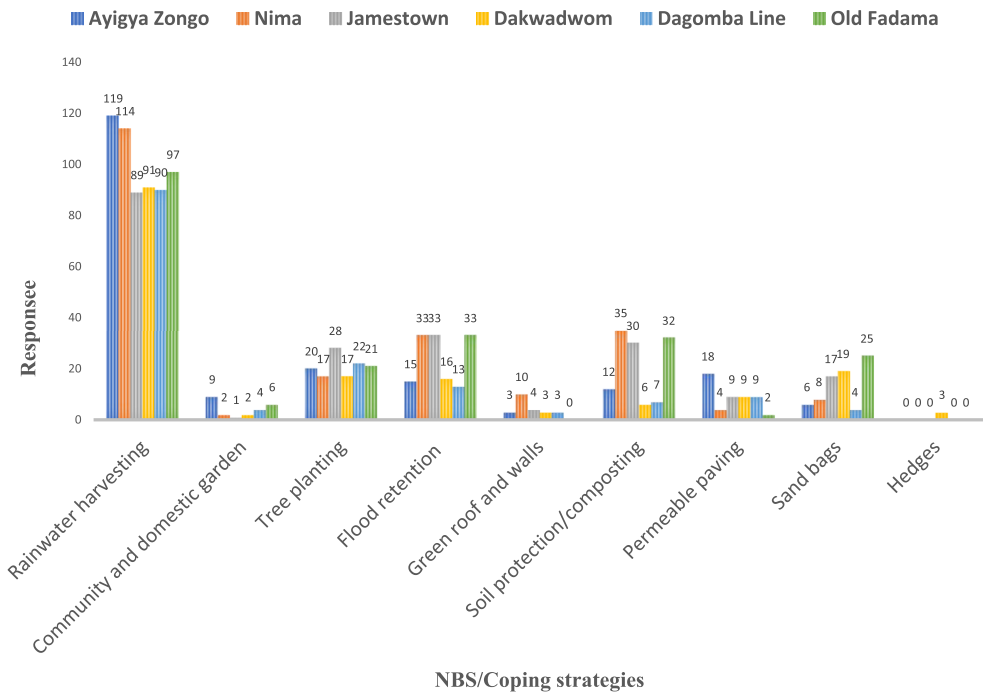
Dagomba Line (13) and composting (32) than Dagomba Line (7), whereas Dagomba Line and Old Fadama showed similar tree planting practices. [Figure 2](#) shows examples of NBSs implemented within the IS.

Nima respondents pointed out the absence of green infrastructure in the area, stressing the importance of community engagement in maintaining any new environmental initiatives. The respondent mentioned that: “When the government plants trees, no one takes care of them”. This finding is similar to that of Diep, Parikh et al. (2022) recommended the need for a participatory bottom-up approach in implementing NBS projects to enhance UM in Kenya and Tanzania IS. In our current study in Ayigya Zongo, there was a more organised approach, with residents ready to embrace green projects if led by trusted local leaders. “If the king supports it, people will follow his example”, suggested a respondent at Ayigya Zongo. In James Town, respondents mentioned the loss of trees was due to urban expansion, with someone indicating that “Every household used to have a tree, but now they are cutting them down for buildings”. In Dakwadwom, however, better drainage management has supported tree planting efforts, with more openness to adopting green infrastructure solutions in areas like Dakwadwom, where infrastructure supports the integration of NBS ([Figure 3](#)).

It is critical that, for NBS to be implemented and have the advantage of contributing to UM, land is key (Teferi and Newman 2017). Land in this context connotes the available space designated for the implementation of NBS initiatives to facilitate metabolic flows. In this study, it was important to assess the public readiness to promote NBS (Wolff, Rauf, and Hamel 2023). An assessment was conducted to test household head agreement

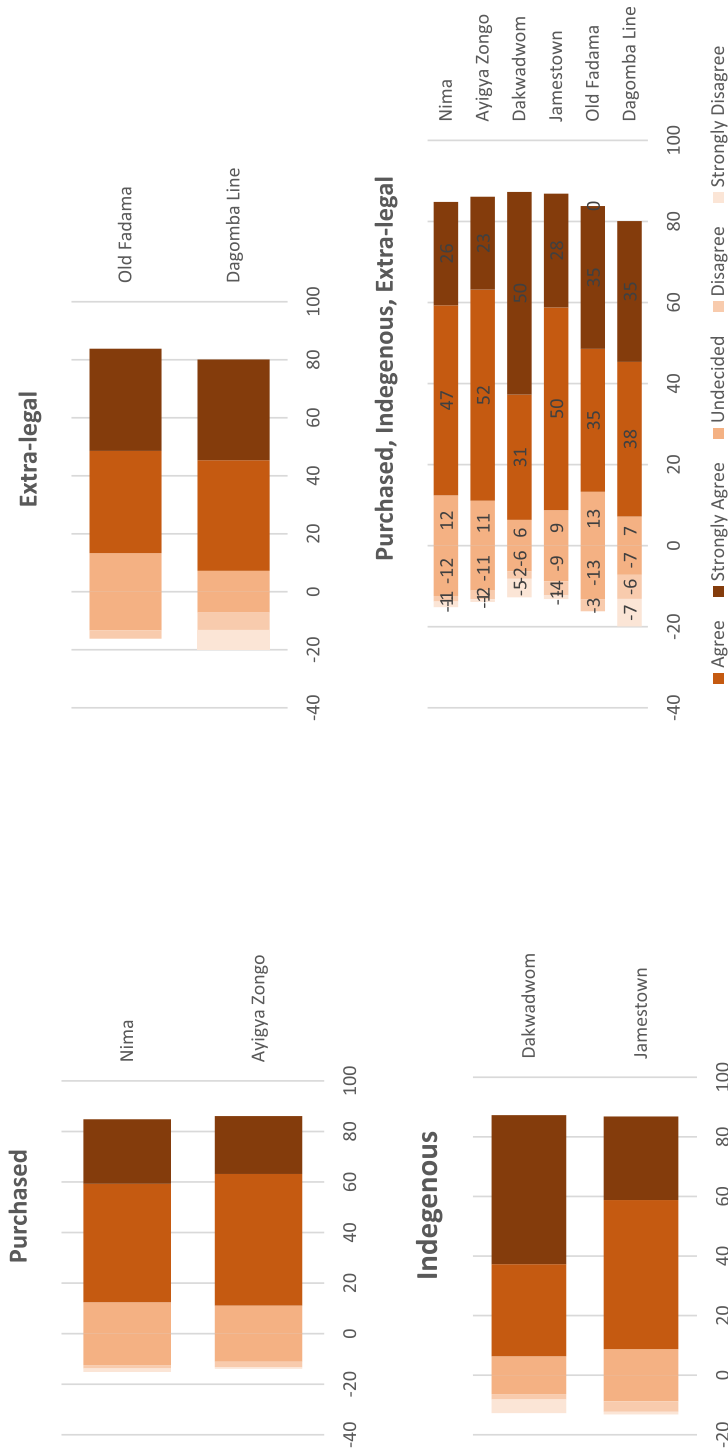


**Figure 2.** Examples of NBSs implemented within the IS. (A) Potted garden featuring plants for medicinal use and tea spices. (B) The avocado tree provides shade and the bark, leaves and roots provide herbal medicine. Blue containers capture rainwater from the rooftop. All have implications for improving the flow of energy, materials, and resources.



**Figure 3.** The existing NBSs in the IS.

or disagreement on whether land should be reserved for gardening in selected IS. **Figure 4** shows the public opinion results on whether land should be reserved for gardening (ornamental/edible) in the house or neighbourhood. It was revealed that Nima and Ayigya showed strong support, for example, Nima (46.89%) agreed, and (25.51%) strongly agreed whereas Ayigya Zongo(52.08%) agreed, and (22.91%) strongly agreed. A participant Nima suggested: “If you give them edible trees, they will see the benefit and won’t cut them down”. One participant from Ayigya stated: “If the chief stands on one platform to say it, the people will accept it”. These findings indicate the need for collaborative and citizen-driven NBS proposals, plans and projects (Kiss et al. 2022), and this could enhance the UM at the household level. In James Town, 50% agreed, and 28.07% strongly agreed, whereas in Dakwadwom, (30.90%) agreed, and (50%) strongly agreed. Old Fadama had (35.25%) agree and (35.25%) strongly agree, while Dagomba Line had (38.13%) agree and (34.74%) strongly agree. In Old Fadama, a respondent expressed interest in shade-providing trees, but noted the challenge of limited space for planting. A participant said: “We don’t have enough space unless by the roads for trees”. This finding relates to that of Tozer et al. (2020), who pin insecure and equitable access to land limits NBS co-creation and co-protection of diverse uses. This could be a possible threat to strengthening NBS implementation to improve metabolism. In contrast, Dagomba Line respondents were more concerned about erosion and emphasised that tree planting in communal spaces could help mitigate environmental challenges. Another household head narrated that “Trees like mango would give us both shade and food, encouraging community care”. Diep, Parikh et al. (2022) and Adegun (2018) reported a lack of attention to society-ecological relationships, to hinder people from



**Figure 4.** The extent to which respondents agree with the statement land should be reserved for gardening (ornamental/edible) in selected IS.

agreeing to the promotion of NBS. Therefore, actors should seek to minimise the negative experiences while simultaneously improving the NBS initiative to boost the UM in IS.

### **3.4. The contribution of NBS classifications to UM in Kumasi and Accra IS**

The analysis of NBS contributions to UM in this study draws directly on the UM framework proposed by Kennedy, Cuddihy, and Engel-Yan (2007), Kennedy, Pincetl, and Bunje (2011) and expanded by Currie and Musango (2017), which conceptualises cities as living systems where material and energy flows are mediated through socio-technical and ecological processes. Within this framework, the NBS identified in IS are interpreted as metabolic regulators that facilitate the exchange and circulation of water, energy, and organic matter at the household and community levels. The application of this theory enables the identification of informal metabolic pathways, such as composting, water harvesting, and greening, that contribute to closing resource loops within the settlements.

The contribution of NBS to UM is classified into Provisioning (P), Regulation/Supports (RS) and social-cultural (SC) benefits, which are considered for understanding NBS's contribution to UM. These categories are rooted in NBS and UM literature (Cárdenas-Mamani and Perrotti 2022), and the data framework for organising NBS contribution to UM in the IS of the Global South (Nalumu, Perrotti, and Rosa 2025). In this study, significant differences in the ecosystem benefits provided to these settlements are categorised into regulation/support, provision, and cultural/spiritual aspects. These benefits show how NBS can support UM, thus reducing resource consumption and improving sustainability in IS (Nalumu and Perrotti 2024). In this study, it was found that Nima demonstrates higher provisioning benefits, such as food production (50%) and water resources (59%). In comparison, Ayigya Zongo contributes more significantly to erosion regulation (49%) and temperature control (49%). However, Nima exhibits higher air quality regulation (48%) than Ayigya Zongo (47%). Ayigya Zongo also has more contributions in water provisioning (76%) than Nima (59%), indicating a focus on regulating support services in Ayigya Zongo, while Nima has more provisioning services. These results imply that ecosystem benefits reduce the communities' reliance on external resources, such as water and energy, and decrease their ecological footprint (Ghaffarian-Hoseini et al. 2016). The rainwater harvesting and urban agriculture practices in Nima could reduce water demand, while expanding tree planting in Ayigya Zongo would improve air quality and thermal comfort, leading to more self-sustaining communities as indicated in previous studies (Satterthwaite et al. 2020). These findings indicate a need to support improved rainwater harvesting techniques (Campisano et al. 2017) to overcome water challenges.

James Town exhibits higher ecosystem benefits across multiple categories, particularly in erosion regulation (54%) and waste treatment (43%), alongside cultural values like aesthetics and inspiration (91%) and spiritual/religious contributions (85). Dakwadwom has a contribution, with notable strengths in temperature control (55%) and water regulation (87%). James Town's ecosystem offers significant UM contributions, particularly in cultural benefits and regulation support. Dakwadwom's strengths in temperature control and water regulation suggest that it could serve as a model for other areas in using NBS to enhance UM. The benefits of tree planting for thermal comfort are reported by previous studies (de Abreu-Harbich, Labaki, and Matzarakis 2015; Wang and Akbari 2016). By improving water flow through rainwater harvesting, Dakwadwom can maintain a more

stable and efficient use of natural resources. Moreover, these communities could achieve a closed-loop system (Van Broekhoven and Vernay 2018), where waste is reduced, water is recycled, and energy use is minimised. For example, waste composting initiatives in James Town could transform organic waste into valuable resources for urban gardening, closing the nutrient loop and enhancing food production locally, which is in line with previous studies (Nassar and Elsayed 2018).

Old Fadama shows higher contributions across both regulation and provisioning categories, particularly in air quality (63%) and flood regulation (35%). It also performs better in cultural services such as outdoor recreation (49%) and livelihood support (81%). Dagomba Line, though lower in many areas, excels in freshwater provision (48%) and psychological comfort (37%). Old Fadama's ecosystems have more contribution to UM, especially in provisioning and cultural benefits. Old Fadama and Dagomba Line show high levels of contribution to both regulatory and cultural benefits, especially in areas like air quality regulation, flood control, and outdoor recreation. The metabolism approach can help assess the effectiveness of these NBS interventions in reducing the flow of pollutants and improving the quality of life in the IS. For instance, green roofs and permeable pavements could help regulate urban heat and reduce stormwater runoff, while community gardening and composting could lessen waste and provide food security (Acevedo-De-los-Ríos and Perrotti 2024). Figure 5 shows urban ecosystem benefits within the context of UM based on the selected IS.

## 4. Conclusions, limitations and recommendations

### 4.1. Conclusions

This study examined how NBS contribute to the UM of IS in Accra and Kumasi through ecosystem benefits. Empirically, the study demonstrated that household and community-level NBS, initiatives such as rainwater harvesting, flood retention, composting, and tree planting, aid in addressing local socio-ecological challenges and improve the flow of water, waste, and energy resources within the IS. The study offers theoretical implications for understanding the NBS–UM nexus in contexts of informality. The results has shown that strengthening the linkage between NBS and UM is essential for enhancing the sustainability of IS, as it promotes resource flows at the household and community level, through ecosystem benefits (regulation, provisioning and social-cultural), all of which contribute to ecological resilience, and inclusive socio-environmental transformation within rapidly urbanising contexts. NBS within IS is not only a matter of environmental improvement but also of re-conceptualising UM as a socially inclusive process. Recognising IS as active metabolic agents advances theoretical debates on how cities sustain material and energy flows under uneven urbanisation.

The analysis has demonstrated that NBS act as an entry point for closing metabolic loops in resource-constrained environments. This empirical insight strengthens theoretical claims (Cárdenas-Mamani and Perrotti 2022; Currie and Musango 2017) about the co-dependence of ecological and social metabolism and extends them to contexts where formality and informality coexist. The study highlights that the spatial and institutional constraints of informality shape the ways NBS can operate metabolically. Limited land

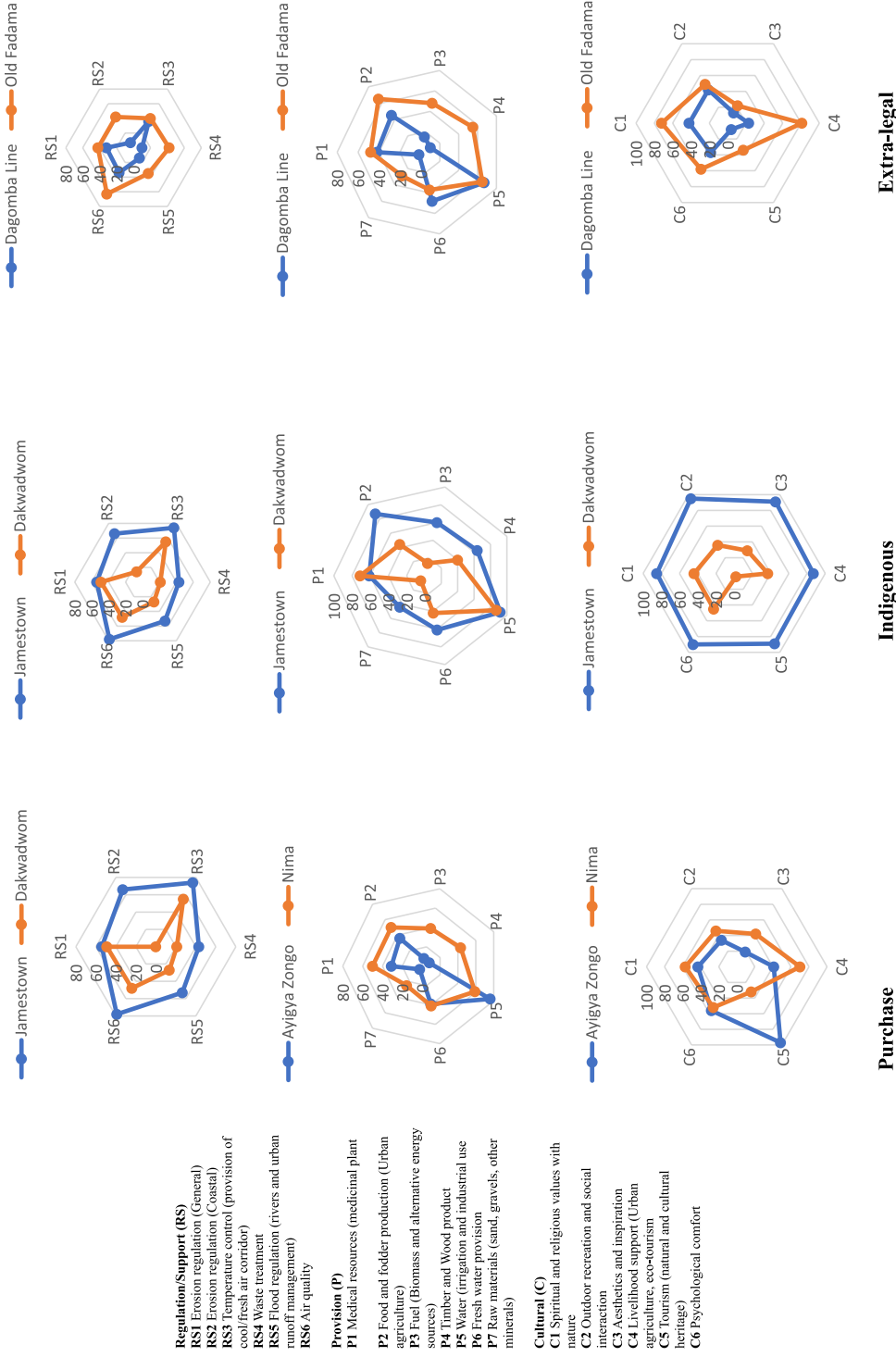


Figure 5. The available ecosystem benefits within the context of UM in the selected IS.

tenure, irregular governance, and infrastructural fragmentation redefine how NBS circulate resources and knowledge.

#### **4.2. Limitations of the study and implications for future research**

This study's main limitation lies in its cross-sectional design, which captures socio-ecological interactions at a single point in time and therefore cannot account for how NBS and UM evolve under changing social, ecological, and infrastructural conditions. Future research will address this limitation in two ways. First, it will adopt a longitudinal and multi-scalar approach to monitor temporal changes in NBS-driven resource flows and community resilience, providing stronger evidence of causal relationships. Second, it will integrate UM modelling and material flow analysis (MFA) to quantitatively simulate how different NBS scenarios influence water, energy, and waste cycles in IS. These studies will enhance the analytical precision and policy relevance of NBS–UM assessments in rapidly urbanising contexts.

#### **4.3. Recommendations**

Based on the results, efforts to strengthen the linkages between NBS and UM in IS should focus on addressing key and actionable challenges.

- (1) First, households, with support from local NGOs and Environmental Health and Management Department, should promote small-scale recycling initiatives such as rain-water harvesting, composting, and community gardening. Providing affordable equipment and neighbourhood training can enhance local resource loops while reducing dependence on centralised systems.
- (2) Second, community associations and youth groups can take a lead role by developing collective green space maintenance schedules and adopting community-led stewardship models that assign rotating responsibilities. Linking participation to local incentives, such as reduced waste levies, can further strengthen social cohesion and environmental ownership.
- (3) Third, weak integration of NBS in policy and planning limits systemic inclusion. The Municipal Assembly, Physical Planning Department and, Parks and Gardens Department, Environmental Health and Management Department should incorporate NBS components into urban infrastructure and IS upgrading plans. Allocating land for small-scale NBS projects, such as vegetated drains or community gardens, within local development schemes can enhance adaptive capacity and improve resource flows.
- (4) Fourth, insufficient technical and governance capacity has constrained the sustained implementation of co-designed NBS initiatives aimed at enhancing ecosystem benefits within IS and improving UM. Therefore, it is important for academic institutions, NGOs, municipal assemblies, and the Parks and Gardens Department to train community members in technical and managerial skills. Establishing participatory platforms for planning and monitoring will enhance shared governance and foster innovation in NBS management.
- (5) Finally, limited coordination among stakeholders weakens the scaling up of successful NBS and socio-ecological practices that can improve UM of IS. Local authorities, NGOs,

and research institutions should strengthen collaboration through partnership frameworks and data-sharing mechanisms that align community-led NBS initiatives with broader municipal sustainability objectives. Such coordination can attract external funding and enhance the overall resilience of IS towards achieving inclusive and sustainable cities.

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## Data availability statement

Data will be made available on request.

## References

- Abreu-Harbich, Loyde Vieira de, Lucila Chebel Labaki, and Andreas Matzarakis. 2015. "Effect of Tree Planting Design and Tree Species on Human Thermal Comfort in the Tropics." *Landscape and Urban Planning* 138 (June): 99–109. <https://doi.org/10.1016/j.landurbplan.2015.02.008>.
- Acevedo-De-los-Ríos, A., and D. Perrotti. 2024. "Role of Urban Metabolism Assessments in Addressing Food Security through Urban Agriculture in Informal Settlements: A Critical Review." *IOP Conference Series: Earth and Environmental Science* 1363 (1): 012080.
- Adegun, O. B. 2018. "When Green Is Grievous: Downsides in Human-Nature Interactions in Informal Urban Settlements." *Journal of Urbanism* 11 (3): 347–361. <https://doi.org/10.1080/17549175.2018.1470102>.
- Adusei, Peter Kwadwo, Eric Oduro-Ofori, Owusu Amponsah, and Kwasi Osei Agyeman. 2018. "Participatory Incremental Slum Upgrading towards Sustainability: An Assessment of Slum Dwellers' Willingness and Ability to Pay for Utility Services". Environment." *Development and Sustainability* 20 (6): 2501–2520. <https://doi.org/10.1007/s10668-017-0002-1>.
- Agresti, Alan. 2007. *An Introduction to Categorical Data Analysis. An Introduction to Categorical Data Analysis: Second Edition. Wiley Series in Probability and Statistics*. Hoboken, NJ: Wiley. <https://doi.org/10.1002/0470114754>.
- Amoako, Clifford, and Daniel Kweku Baah Inkoom. 2018. "The Production of Flood Vulnerability in Accra, Ghana: Re-Thinking Flooding and Informal Urbanisation." *Urban Studies* 55 (13): 2903–2922. <https://doi.org/10.1177/0042098016686526>.

- Anderson, Jeffrey L. 1996. "A Method for Producing and Evaluating Probabilistic Forecasts from Ensemble Model Integrations." *Journal of Climate* 9 (7): 1518–1530. [https://doi.org/10.1175/1520-0442\(1996\)009<1518:AMFPAE>2.0.CO;2](https://doi.org/10.1175/1520-0442(1996)009<1518:AMFPAE>2.0.CO;2).
- Andersson, Erik, Sara Borgström, Dagmar Haase, Johannes Langemeyer, André Mascarenhas, Timon McPhearson, Manuel Wolff, et al. 2021. "A Context-Sensitive Systems Approach for Understanding and Enabling Ecosystem Service Realization in Cities." *Ecology and Society* 26 (2): art35. <https://doi.org/10.5751/ES-12411-260235>.
- Asare, Prince. 2021. *Nature-Based Solutions (Nbs) As an Urban Flood Mitigation Measure: The Case of Ga East Municipality, Accra, Ghana*. Enschede, Netherlands: Faculty of Geo-Information Science and Earth Observation, University of Twente.
- Asare, Prince, Funda Atun, and Karin Pfeffer. 2024. "Spatial Multi-Criteria Analysis for Discovering Nature-Based Solutions Location for Urban Flood Mitigation in Accra." *Applied Spatial Analysis and Policy* 17 (12): 207–239. <https://doi.org/10.1007/s12061-023-09541-y>.
- Azunre, Gideon Abagna, Owusu Amponsah, Stephen Appiah Takyi, and Henry Mensah. 2021. "Informality-Sustainable City Nexus: The Place of Informality in Advancing Sustainable Ghanaian Cities." *Sustainable Cities and Society* 67 (April): 102707. <https://doi.org/10.1016/j.scs.2021.102707>.
- Babí Almenar, Javier, Thomas Elliot, Benedetto Rugani, Bodénan Philippe, Tomas Navarrete Gutierrez, Guido Sonnemann, and Davide Geneletti. 2021. "Nexus between Nature-Based Solutions, Ecosystem Services and Urban Challenges." *Land Use Policy* 100 (January): 104898. <https://doi.org/10.1016/j.landusepol.2020.104898>.
- Becciu, Gianfranco, Stefano Mambretti, Gabriele Masera, Umberto Sanfilippo, and Massimo Tadi. 2020. "Management of Water and Wastewater under the Framework of the IMM: The Case of the Favela Ro Cinha." *International Journal of Sustainable Development and Planning* 15 (01): 81–94. <https://doi.org/10.2495/SDP-V15-N1-81-94>.
- Birtchnell, Thomas, Nicholas Gill, and Razia Sultana. 2019. "'Sleepers Cells for Urban Green Infrastructure: Harnessing Latent Competence in Greening Dhaka's Slums.'" *Urban Forestry & Urban Greening* 40 (April): 93–104. <https://doi.org/10.1016/j.ufug.2018.05.014>.
- BM Corp. 2020. *IBM SPSS Statistics for Windows, Version 27.0*. Armonk, NY: IBM Corp.
- Boateng, Godfred O., and Ellis Adjei Adams. 2023. "A Multilevel, Multidimensional Scale for Measuring Housing Insecurity in Slums and Informal Settlements." *Cities* 132 (January): 104059. <https://doi.org/10.1016/j.cities.2022.104059>.
- Broekhoven, Saskia Van, and Anne Lorène Vernay. 2018. "Integrating Functions for a Sustainable Urban System: A Review of Multifunctional Land Use and Circular Urban Metabolism." *Sustainability* 10 (6): 1875. <https://doi.org/10.3390/su10061875>.
- Broto, Vanesa Castán, Adriana Allen, and Elizabeth Rapoport. 2012. "Interdisciplinary Perspectives on Urban Metabolism." *Journal of Industrial Ecology* 16 (6): 851–861. <https://doi.org/10.1111/j.1530-9290.2012.00556.x>.
- Bunch, Martin J. 2016. "Ecosystem Approaches to Health and Well-Being: Navigating Complexity, Promoting Health in Social–Ecological Systems." *Systems Research and Behavioral Science* 33 (5): 614–632. <https://doi.org/10.1002/sres.2429>.
- Campisano, Alberto, David Butler, Sarah Ward, Matthew J. Burns, Eran Friedler, Kathy DeBusk, Lloyd N. Fisher-Jeffes, et al. 2017. "Urban Rainwater Harvesting Systems: Research, Implementation and Future Perspectives." *Water Research* 115 (May): 195–209. <https://doi.org/10.1016/j.watres.2017.02.056>.
- Cárdenas-Mamani, Úrsula, and Daniela Perrotti. 2022. "Understanding the Contribution of Ecosystem Services to Urban Metabolism Assessments: An Integrated Framework." *Ecological Indicators* 136: 108593. <https://doi.org/10.1016/j.ecolind.2022.108593>.
- Charmes, Jacques. 2012. "The Informal Economy Worldwide: Trends and Characteristics." *Margin: The Journal of Applied Economic Research* 6 (2): 103–132. <https://doi.org/10.1177/097380101200600202>.
- Cobbinah, Patrick Brandful, Michael Odei Erdiaw-Kwasie, and Paul Amoateng. 2015. "'Africa's Urbanisation: Implications for Sustainable Development.'" *Cities* 47: 62–72. <https://doi.org/10.1016/j.cities.2015.03.013>.

- Cobbinah, Patrick Brandful, Eric Gaisie, Nana Yaw Oppong-Yeboah, and Desmond Ofosu Anim. 2020. "Kumasi: Towards a Sustainable and Resilient Cityscape." *Cities* 97 (February): 102567. <https://doi.org/10.1016/j.cities.2019.102567>.
- Cobbinah, Patrick Brandful, Michael Poku-Boansi, and Charles Pephrah. 2017. "Urban Environmental Problems in Ghana." *Environmental Development* 23 (September): 33–46. <https://doi.org/10.1016/j.envdev.2017.05.001>.
- Cohen-Shacham, E, G. Walters, C Janzen, and S. Maginnis. 2016. *Nature-based Solutions to Address Global Societal Challenges*. Gland, Switzerland: IUCN (International Union for Conservation of Nature).
- Currie, Paul Klugman, and Josephine Kaviti Musango. 2017. "African Urbanization: Assimilating Urban Metabolism into Sustainability Discourse and Practice." *Journal of Industrial Ecology* 21 (5): 1262–1276. <https://doi.org/10.1111/jiec.2017.21.issue-5>.
- de-Graft Aikins, A., and K. Koram. 2017. "The Economy of Ghana Sixty Years after Independence – Ernest Aryeetey, Ravi Kanbur – Oxford University Press.Pdf." In *The Economy of Ghana Sixty Years after Independence*.
- de Souza, M. L., and H. G. Torres. 2021. "Urban Planning and Social Justice in Latin America: A Critical Perspective." *Cities* 114: 103215.
- Diep, Loan, Joe Mulligan, Martha Akinyi Oloo, Loè Guthmann, Mussa Raido, and Tim Ndezi. 2022. "Co-Building Trust in Urban Nature: Learning from Participatory Design and Construction of Nature-Based Solutions in Informal Settlements in East Africa." *Frontiers in Sustainable Cities* 4: 927723. <https://doi.org/10.3389/frsc.2022.927723>.
- Diep, Loan, Priti Parikh, Barbara Pozzan dos Santos Duarte, Anaïs Figueiredo Bourget, David Dodman, and José Rodolfo Scarati Martins. 2022. "It Won't Work Here: Lessons for Just Nature-Based Stream Restoration in the Context of Urban Informality." *Environmental Science & Policy* 136 (October): 542–554. <https://doi.org/10.1016/j.envsci.2022.06.020>.
- Doe, Benjamin, and Prince Dacosta Aboagye. 2022. "The Place of Subsidy: Affordable Sanitation Service Delivery in Slums of Kumasi, Ghana." *GeoJournal* 87 (1): 295–317. <https://doi.org/10.1007/s10708-020-10256-7>.
- Dovey, Kim, and Ross King. 2011. "Forms of Informality: Morphology and Visibility of Informal Settlements." *Built Environment* 37 (1): 11–29. <https://doi.org/10.2148/benv.37.1.11>.
- George, Darren, and Paul Mallery. 2018. "Reliability Analysis." In *IBM SPSS Statistics 25 Step by Step: A Simple Guide and Reference*, 249–260. Routledge.
- Ghaffarian-Hoseini, Ali, John Tookey, Amirhosein GhaffarianHoseini, Safiah Muhammad Yusoff, and Norhaslina Binti Hassan. 2016. "State of the Art of Rainwater Harvesting Systems towards Promoting Green Built Environments: A Review." *Desalination and Water Treatment* 57 (1): 95–104. <https://doi.org/10.1080/19443994.2015.1021097>.
- Ghana Statistical Service. 2012. *2010 Population and Housing Census: Summary Report of Final Results*. Accra: Ghana Statistical Service.
- Ghana Statistical Service. 2014. *2010 Population and Housing Census: District Analytical Report - Kumasi Metropolis*. Accra: Ghana Statistical Service.
- Ghana Statistical Service. 2021. *2021 Population and Housing Census: General Report*. Accra: Ghana Statistical Service.
- Haines-Young, Roy, and Marion Potschin. 2010. *Common International Classification of Ecosystem Goods and Services (CICES): Nottingham, Consultation on Version 4, August–December 2012*. European Environment Agency. EEA Framework Contract No. EEA/IEA/09/003.
- Hamel, Perrine, and Leanne Tan. 2022. "Blue–Green Infrastructure for Flood and Water Quality Management in Southeast Asia: Evidence and Knowledge Gaps." *Environmental Management* 69 (4): 699–718. <https://doi.org/10.1007/s00267-021-01467-w>.
- Kabisch, N., J. Stadler, H. Korn, and A. Bonn. 2017. "Nature-Based Solutions for Societal Goals under Climate Change in Urban Areas–Synthesis and Ways Forward." In *Nature-Based Solutions to Adaptation to Climate change in Urban Areas: Linkages Between Science, Policy and Practice*, 323–336. Cham: Springer International Publishing.
- Kabisch, Nadja, Niki Frantzeskaki, and Rieke Hansen. 2022. "Principles for Urban Nature-Based Solutions." *Ambio* 51 (6): 1388–1401. <https://doi.org/10.1007/s13280-021-01685-w>.

- Kamer, Omer, Ehud Rinott, Gal Tsaban, Alon Kaplan, Anat Yaskolka Meir, Hila Zelicha, Dan Knights, et al. 2023. "Successful Weight Regaining Attenuation by Autologous Fecal Microbiota Transplantation Is Associated with Non-Core Gut Microbiota Changes during Weight Loss: Randomized Controlled Trial." *Gut Microbes* 15 (2): 2264457. <https://doi.org/10.1080/19490976.2023.2264457>.
- Kennedy, C., S. Pincetl, and P. Bunje. 2011. "The Study of Urban Metabolism and its Applications to Urban Planning and Design." *Environmental Pollution* 159 (8-9): 1965–1973.
- Kennedy, Christopher, John Cuddihy, and Joshua Engel-Yan. 2007. "The Changing Metabolism of Cities." *Journal of Industrial Ecology* 11 (2): 43–59. <https://doi.org/10.1162/jie.2007.1107>.
- Kharisma, D., and Kaswanto. 2021. "Management of Home Garden in Formal and Informal Settlement along Riparian Ciliwung River in Bogor." *IOP Conference Series: Earth and Environmental Science* 694 (1): 012021. <https://doi.org/10.1088/1755-1315/694/1/012021>.
- Kiss, Bernadett, Filka Sekulova, Kathrin Hörschelmann, Carl F. Salk, Wakana Takahashi, and Christine Wamsler. 2022. "Citizen Participation in the Governance of Nature-Based Solutions." *Environmental Policy and Governance* 32 (3): 247–272. <https://doi.org/10.1002/eet.1987>.
- Kovacic, Zora, and Mario Giampietro. 2017. "Between Theory and Quantification: An Integrated Analysis of Metabolic Patterns of Informal Urban Settlements." *Energy Policy* 100 (January): 377–386. <https://doi.org/10.1016/j.enpol.2016.06.047>.
- Li, D., J. Q. Gao, G. H. Qiao, Q. R. Jia, S. R. Li, and H. L. Gao. 2024. "Circular Economy Strategies in Supply Chains: Enhancing Resource Efficiency and Sustainable Development Goals." *Environmental Science and Pollution Research* 31 (6): 8751–8767.
- Makuwira, Jonathan. 2022. "Marginal Voices, Resilient Acts: Urban Marginality and Responses to Climate-Related Events in Lilongwe City Informal Settlements." *Urban Forum* 33 (1): 51–64. <https://doi.org/10.1007/s12132-022-09460-0>.
- Malina, Mary A., Hanne S.O. Nørreklit, and Frank H. Selto. 2011. "Lessons Learned: Advantages and Disadvantages of Mixed Method Research." *Qualitative Research in Accounting & Management* 8 (1): 59–71. <https://doi.org/10.1108/11766091111124702>.
- McEvoy, Darryn, Ata Tara, Mittul Vahanvati, Serene Ho, Kim Gordon, Alexei Trundle, Cyril Rachman, and Yuyun Qomariyah. 2024. "Localized Nature-Based Solutions for Enhanced Climate Resilience and Community Wellbeing in Urban Informal Settlements." *Climate and Development* 16 (7): 600–612. <https://doi.org/10.1080/17565529.2023.2277248>.
- Mulligan, Joe, Vera Bukachi, Jack Campbell Clause, Rosie Jewell, Franklin Kirimi, and Chelina Odbert. 2020. "Hybrid Infrastructures, Hybrid Governance: New Evidence from Nairobi (Kenya) on Green-Blue-Grey Infrastructure in Informal Settlements." *Anthropocene* 29 (March): 100227. <https://doi.org/10.1016/j.ancene.2019.100227>.
- Nalumu, D. J., D. Perrotti, and E. Rosa. 2025. "A Data Framework for Assessing Nature-Based Solutions' Contribution to the Urban Metabolism of Informal Settlements." *Sustainability Science* 20 (5): 1935–1963. <https://doi.org/10.1007/s11625-025-01700-z>.
- Nalumu, D. J., D. Perrotti, E. Rosa, O. Amponsah, and S. A. Takyi. 2025. "The Application of a Data Framework to Assess the Contribution of Nature-based Solutions to Urban Metabolism in Informal Settlements of Kumasi, Ghana." *SN Social Sciences* 5 (12): 227.
- Nalumu, D. J., and Daniela Perrotti. 2024. "A Review of the Contribution of Nature-Based Solutions to the Urban Metabolism of the Informal Settlements." *IOP Conference Series: Earth and Environmental Science* 1363 (1): 012083. <https://doi.org/10.1088/1755-1315/1363/1/012083>.
- Nampa, I. W., I. W. Mudita, N. P. L. B. Riwu Kaho, S. Widinugraheni, and R. Lasarus Natonis. 2020. "The KoBoCollect for Research Data Collection and Management (An Experience in Researching the Socio-Economic Impact of Blood Disease in Banana)." *SOCA: Jurnal Sosial, Ekonomi Pertanian* 14 (3): 545.
- Nassar, Dina Mamdouh, and Hanan Gamil Elsayed. 2018. "From Informal Settlements to Sustainable Communities." *Alexandria Engineering Journal* 57 (4): 2367–2376. <https://doi.org/10.1016/j.aej.2017.09.004>.
- Okyere, Seth Asare, Louis Kusi Frimpong, Stephen Kofi Diko, Matthew Abunyewah, and Michihiro Kita. 2021. "Situating Everyday Urban Struggles Within the Context of the SDGs in an Informal

- Settlement in Accra, Ghana." In *Sustainable Urban Futures in Africa*, 265–287. New York: Routledge. <https://doi.org/10.4324/9781003181484-13>
- Paller, Jeffrey W. 2015. "Informal Networks and Access to Power to Obtain Housing in Urban Slums in Ghana." *Africa Today* 62 (1): 31–55. <https://doi.org/10.2979/africatoday.62.1.31>.
- Pauleit, Stephan, Teresa Zölch, Rieke Hansen, Thomas B. Randrup, and Cecil Konijnendijk van den Bosch. 2017. "Nature-Based Solutions and Climate Change – Four Shades of Green." 29–49. [https://doi.org/10.1007/978-3-319-56091-5\\_3](https://doi.org/10.1007/978-3-319-56091-5_3).
- Pincetl, S., P. Bunje, and T. Holmes. 2012. "An Expanded Urban Metabolism Method: Toward a Systems Approach for Assessing Urban Energy Processes and Causes." *Landscape and urban planning* 107 (3): 193–202.
- Plano Clark, V. L. 2017. "Mixed Methods Research." *The Journal of Positive Psychology* 12 (3): 305–306.
- Potschin-Young, M., R. Haines-Young, C. Görg, U. Heink, K. Jax, and C. Schleyer. 2018. "Understanding the Role of Conceptual Frameworks: Reading the Ecosystem Service Cascade." *Ecosystem Services* 29: 428–440.
- Roy, M., R. Shemdoe, D. Hulme, N. Mwageni, and A. Gough. 2018. "Climate Change and Declining Levels of Green Structures: Life in Informal Settlements of Dar Es Salaam, Tanzania." *Landscape and Urban Planning* 180:282–293. <https://doi.org/10.1016/j.landurbplan.2017.11.011>.
- Sarabi, Shahryar, Qi Han, Bauke de Vries, A. Georges, L. Romme, and Dora Almassy. 2022. "The Nature-Based Solutions Case-Based System: A Hybrid Expert System." *Journal of Environmental Management* 324: 116413. <https://doi.org/10.1016/j.jenvman.2022.116413>.
- Satterthwaite, David, Diane Archer, Sarah Colenbrander, David Dodman, Jorgelina Hardoy, Diana Mitlin, and Sheela Patel. 2020. "Building Resilience to Climate Change in Informal Settlements." *One Earth* 2 (2): 143–156. <https://doi.org/10.1016/j.oneear.2020.02.002>.
- Schiavina, Marcello, Michele Melchiorri, Christina Corbane, Aneta Florczyk, Sergio Freire, Martino Pesaresi, and Thomas Kemper. 2019. "Multi-Scale Estimation of Land Use Efficiency (SDG 11.3.1) across 25 Years Using Global Open and Free Data." *Sustainability* 11 (20): 5674. <https://doi.org/10.3390/su11205674>.
- Seddon, Nathalie. 2022. "Harnessing the Potential of Nature-Based Solutions for Mitigating and Adapting to Climate Change." *Science* 376 (6600): 1410–1416. <https://doi.org/10.1126/science.abn9668>.
- Smit, Suzanne, Josephine K. Musango, Zora Kovacic, and Alan C. Brent. 2019. "Towards Measuring the Informal City: A Societal Metabolism Approach." *Journal of Industrial Ecology* 23 (3): 674–685. <https://doi.org/10.1111/jiec.12776>.
- Smit, Suzanne, Josephine Kaviti Musango, Zora Kovacic, and Alan C. Brent. 2017. "Conceptualising Slum in an Urban African Context." *Cities* 62: 107–119. <https://doi.org/10.1016/j.cities.2016.12.018>.
- Smit, W., S. Parnell, and W. Solecki. 2018. "Urban Settlements." In *Climate Change and Cities: Second Assessment Report of the Urban Climate Change Research Network*, edited by C. Rosenzweig, W. D. Solecki, P. Romero Lankao, S. Dhakal, and S. Ali Ibrahim, 9–40. Cambridge: Cambridge University Press.
- Smith, S. K., J. Tayman, and D. A. Swanson. 2013. *A Practitioner's Guide to State and Local Population Projections*. Vol. 1. Dordrecht: Springer.
- Takyi, Edward, Henry Mensah, Frank Kwaku Aazore, Dorothy Julian Nalumu, and John Junior Abu. 2022. "Understanding the Urban Planning-Green Space Depletion Nexus: Insights from the Kwabre East Municipality, Ghana." *Urban Forum* 34 (3): 319–342. <https://doi.org/10.1007/s12132-022-09471-x>.
- Teferi, Zafu, and Peter Newman. 2017. "Slum Regeneration and Sustainability: Applying the Extended Metabolism Model and the SDGs." *Sustainability* 9 (12): 2273. <https://doi.org/10.3390/su9122273>.
- Tozer, Laura, Kathrin Hörschelmann, Isabelle Anguelovski, Harriet Bulkeley, and Yuliana Lazova. 2020. "Whose City? Whose Nature? Towards Inclusive Nature-Based Solution Governance." *Cities* 107 (December): 102892. <https://doi.org/10.1016/j.cities.2020.102892>.
- Tutu, Raymond Asare, John Boateng, Edmund Essah Ameyaw, and Janice Desire Busingye. 2017. "Acculturation Inclinations and Subjective Health Status of Internal Migrants in James Town,

- an Urban Slum Settlement in Accra." *Journal of Population Research* 34 (2): 165–183. <https://doi.org/10.1007/s12546-016-9182-z>.
- Tzoulas, Konstantinos, Juanjo Galan, Stephen Venn, Matthew Dennis, Bas Pedroli, Himansu Mishra, Dagmar Haase, Stephan Pauleit, Jari Niemelä, and Philip James. 2021. "A Conceptual Model of the Social-Ecological System of Nature-Based Solutions in Urban Environments." *Ambio* 50 (2): 335–345. <https://doi.org/10.1007/s13280-020-01380-2>.
- UN-Habitat. 2012. *The State of the World's Cities 2012/2013: Prosperity of Cities*. Nairobi: UN-Habitat.
- UN-Habitat. 2016. *World Cities Report 2016: Urbanization and Development – Emerging Futures*. Nairobi: United Nations Human Settlements Programme.
- UN-Habitat (United Nations Human Settlements Programme). 2003. *The Challenge of slums: Global report on Human Settlements 2003*. London: Earthscan Publications for UN-Habitat.
- United Nations. 2019. *The Sustainable Development Goals Report 2019*. New York: United Nations.
- United Nations. 2023. *The Sustainable Development Goals Report 2023*. New York. <https://unstats.un.org/sdgs/report/2023>.
- Wang, Yupeng, and Hashem Akbari. 2016. "The Effects of Street Tree Planting on Urban Heat Island Mitigation in Montreal." *Sustainable Cities and Society* 27 (November): 122–128. <https://doi.org/10.1016/j.scs.2016.04.013>.
- Wolff, Erich, Hanna A. Rauf, and Perrine Hamel. 2023. "Nature-Based Solutions in Informal Settlements: A Systematic Review of Projects in Southeast Asian and Pacific Countries." *Environmental Science & Policy* 145 (July): 275–285. <https://doi.org/10.1016/j.envsci.2023.04.014>.
- Wolman, A. 1965. "The Metabolism of Cities." *Scientific American* 213 (3): 178–193.