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Research article

Dialogues on nature-based solutions and informal e-waste management

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ABSTRACT

Urban informality research has traditionally emphasized precarity and uncertainty amidst climate change. However, could nature-based solutions (NbS) advance sustainable informal futures? This paper, through the lens of informal electronic waste (e-waste) management and using a qualitative case study approach, investigates how NbS can contribute to climate change management in informal urban settings. Conducting nine key informant interviews and an interview of 183 informal e-waste actors in Kumasi (Ghana), we address three questions: a) How do informal e-waste practices influence climate change? b) What are the conditions of NbS in informal urban environments? and c) How can NbS be used as a tool to improve informal e-waste practices? Findings indicate that informal e-waste practices contribute both to local livelihoods and environmental degradation with associated climate vulnerability, yet remain excluded from formal planning. We show that NbS, when contextually adapted and inclusive of informal actors, can serve as a strategic entry point for ecological restoration and urban resilience. A focus on informal e-waste practices is profoundly important for understanding the complexities of and adapting to climate change in a deeply informal city. City authorities working collaboratively with informal e-waste workers and communities is foundational for transitioning to NbS futures. Our novel contribution relates to the integration of NbS into informal e-waste discourse and the urgency for policymakers to rethink how informality intersects with climate change.

1. Introduction

In the realm of climate change research, countless narratives have emphasized the disproportionate impacts on the global South. For example, existing socioeconomic precarity and inadequate mitigation infrastructure are more pronounced in informal settlements in global South cities compared to those in the North (Intergovernmental Panel on Climate Change [IPCC], 2022; Cobbinah and Finn, 2022). Urban informality, particularly informal economies and settlements, is also frequently confronted with limited resources to cope with climate-induced vulnerabilities (Sharma et al., 2022; Parvin et al., 2023; Cobbinah et al., 2021). Importantly, urban informality remains a defining characteristic of urbanity in the global South (Cobbinah, 2025), as empirically substantiated evidence shows that informal economies alone offer employment to over 60 % of urban workers (OECD, 2023). Considering the livelihood-intensive and spatio-political nature of urban informality, residents and actors of informal settlements and economies, respectively, wield a significant influence on how cities function and adapt to external shocks and environmental pressures in the global South, including climate change (Kathage, 2018). This prompts a rare cogitation: could nature-based solutions (NbS) deliver positive influence on climate change management in informal urban environments? Here, we explain NbS as the use of ecosystems and natural processes to mitigate climate risks and enhance urban resilience (IUCN, 2020).

Recent scholarship has provided preliminary evidence that electronic waste (e-waste) is shaping the frontiers of informal economic activities and growth in informal settlements in African cities. For example, a significant proportion of the working population engaged in the informal economy in African cities are into e-waste recycling/processing (Asibey et al., 2021, 2023; Oteng-Ababio et al., 2014), driven by global supply chains and the demand for electronic components (Daum et al., 2017; Andeobu et al., 2021) as well as the global decarbonization agenda (Finn and Cobbinah, 2024). Key concerns associated with informal e-waste processing include deteriorating environmental conditions and vulnerability to climate change risks, in addition to exclusion from planning decisions by city authorities (Cobbinah et al., 2022; IPCC, 2022; Agyei et al., 2025). Furthermore, informal e-waste practices contribute to climate disasters with devastating impacts on the

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environment and residents (Ministry of Inner-City and Zongo Development, 2019; Asibey and Yeboah, 2024). For example, an informal e-waste processing site in Ghana's national capital, Accra, is famous for significant environmental deterioration and residents' exposure to pollution, which creates both a precarious working location and huge vulnerability to climate change impacts, particularly flood events (Asibey et al., 2023). Various analyses based on informal e-waste practices in African cities also imply climate vulnerability and precarious working environment, despite increasing growth in interest in e-waste processing, prompting questions about how to address the environmental and climate threat (Borthakur, 2015, 2020). We argue in this paper that NbS can be an essential component of climate change management in informal e-waste processing sites.

Despite numerous indications from both practice and research implying that NbS play an important role in climate change mitigation and adaptation, this environmental management tool has been surprisingly overlooked in urban studies literature on climate change and informal e-waste management. Previous literature has long emphasized the role of NbS in addressing the material, socio-spatial, and environmental challenges exacerbated by climate change, via green technology adoption, and circular economy models (e.g., Brown et al., 2014; IUCN, 2014). Recent studies have increasingly acknowledged the importance of green infrastructure projects (e.g., Kumar et al., 2021). To date, there is a noticeable lack of attention given to their relevance and application in deeply informal urban environments to reduce their susceptibility to climate-related shocks. Hence, it is necessary to investigate how NbS can influence climate change management in informal e-waste-dominated settlements that minimize ecological damage and ensure economic sustainability.

This paper situates informal e-waste processing within a broader discourse on NbS and climate adaptation, and responds to three questions: a) How do informal e-waste practices influence climate change? b) What are the conditions of NbS in informal urban environments? and c) How can NbS be used as a tool to improve informal e-waste practices? These questions are answered using a case study of Kumasi, Ghana, exploring locally grounded, ecologically viable, and socially inclusive pathways for urban resilience. We use three interrelated conceptual framings: urban informality, ecological resilience, and NbS. Urban informality is approached not simply as a planning deficit but as a dynamic system of adaptation and spatial negotiation that responds to state failure and market exclusion (Roy, 2009). Informal e-waste actors, therefore, are seen as embedded in complex livelihood strategies that intersect with environmental risks and opportunities.

In parallel, ecological resilience provides a lens for understanding how degraded urban ecosystems and vulnerable populations can recover or reorganize in the face of climate change stress through low-tech, context-specific interventions. The NbS concept, while gaining prominence in global climate adaptation discourse, often lacks grounding in informal and resource-constrained settings. We draw on critical perspectives (e.g., Seddon, 2022) to understand how NbS can be reimagined as an inclusive and scalable tool when adapted to the realities of urban informality. By integrating these frameworks, we explore how informal e-waste management practices can either undermine or support climate adaptation goals, and the role of NbS in mediating the stressor.

We make two significant contributions to urban studies and climate change literature. First, our work introduces NbS perspective to informal e-waste management literature by demonstrating that NbS hold considerable potential in minimizing ecological damage and fostering economic growth. We invite other researchers to creatively engage with NbS in managing the several challenges confronting urban informality. Our research is among the few studies to empirically explore the role of NbS in the informal e-waste management economy. Second, our research advances theoretical understanding of the 'informal economy' idea by moving beyond the traditional economic activities involving household consumables to e-waste recycling and processing (Asibey et al., 2021) and shifting focus towards broader climate change and environmental threats. Policy-wise, our analysis offers insights and lessons for policymakers to reconsider their approaches to managing informality and addressing climate change by focusing on initiatives that advance ecological integrity and promote inclusive and sustainable economic futures.

2. Finding the congruence: informal e-waste economy, climate change and NbS

The growth in the generation of e-waste continues to be a major concern for recipient countries lacking appropriate infrastructure and use of sustainable technologies (Daum et al., 2017; Asibey, 2024; Bimpong et al., 2023). In 2021, e-waste was estimated at 52.2 million tons, out of which only 17.4 % was formally collected and recycled (D'Almeida et al., 2021; WHO, 2023). The remaining is disposed of at landfills, leading to a rapid emergence of an increase in landfills (Andeobu et al., 2021), particularly within informal settlements in global South cities. Across many African countries, the sector has become a major source of livelihood for thousands of people (Grant and Oteng-Ababio, 2016; Asibey et al., 2020).

Despite measures to govern this waste stream, a significant fraction of it goes unregistered (Maes and Preston-Whyte, 2022). Most recipient countries import repairable ones for sale because they are less expensive, while those damaged are destroyed and their valuable contents removed using crude techniques, and the unwanted parts dumped in the open environment (Asibey, 2024). Environmentally, many of these sites emerge in or around ecologically sensitive and unapproved areas such as wetlands, major dump sites, old and/or abandoned industrial areas, and unused state lands, where their activities deplete the once-abundant green infrastructure (Cobbinah et al., 2021; Adu Boateng et al., 2023). Many of these areas, largely because of improper e-waste handling practices and poor attitude towards the environment, experience frequent and intense climate-induced disasters, specifically flooding.

Expectedly, climate change has become a major challenge confronting African cities (IPCC, 2022; Adu Boateng et al., 2023; Cobbinah and Finn, 2022), where they are experiencing unprecedented impacts (IPCC, 2019). While Africa's contribution to global GHG emissions is negligible (less than 5 %), its cities remain among the most vulnerable to climate change impacts. Yet, climate resilience in African cities is frequently fraught with unhealthy politics, which complicate climate management efforts (Cobbinah and Finn, 2022), particularly in informal settlements where there is evidence of increasing e-waste volumes with poor management practices. E-waste has a significant but often overlooked impact on climate change. Its improper management—through unregulated landfill disposal and open burning—releases potent GHGs like CO_2 and CH_4, directly contributing to global warming. Additionally, discarded refrigerants and insulating foams contain HCFCs and HFCs, which are released into the atmosphere when not properly handled (Fawole et al., 2023). Moreover, rudimentary recycling practices release heavy metals and brominated flame retardants, which can degrade ecosystems and reduce their ability to function as carbon sinks (Andeobu et al., 2021).

A review of various global interventions highlights a growing commitment to achieving the goals of the COPs, SDGs 11 and 13, and other climate-related agendas. Among these, NbS stands out as a sustainable and efficient approach to improving urban ecological landscapes while addressing climate impacts. According to the European Commission (2015), NbS are "actions that are supported and inspired by, or copied from nature, emphasizing the connection between biodiversity conservation and sustainability and climate-resilient development objectives delivering creative, and realistic solutions". Despite its potential, the adoption of NbS faces several hurdles, particularly in efforts to restore degraded ecosystems. In Africa, cities struggle with severe air, water, and soil pollution, making environmental remediation costly and complex, especially in e-waste-affected communities. Several obstacles hinder progress; the rising e-waste volumes due to rapid

industrialization and uncertainty about future trends, a lack of knowledge on effective remediation and restoration measures, and concerns about the risks and uncertainties associated with integrating NbS into urban planning (Kumar et al., 2021; IUCN, 2014).

Generally, the intersection of informal e-waste processing, climate change, and NbS reflects a confluence of systemic environmental degradation, vulnerability, and opportunity (Fawole et al., 2023). Despite the threats, NbS remains an underutilized approach in informal waste contexts. While often framed in Eurocentric declarations, NbS, when locally contextualized, offers a promising, low-cost, and adaptive approach to restoring degraded e-waste landscapes and improving community resilience. Practices like phytoremediation, constructed wetlands for wastewater treatment, and green buffer zones can mitigate pollution, restore ecological functions, and reduce climate vulnerability. These strategies align with existing global goals (e.g., SDGs) and commitments (e.g., the UNFCCC commitments), but are rarely implemented in informal environments where they are urgently required.

The limited adoption of NbS in African cities transcends policy preference but stems from structural and epistemic barriers. These include limited awareness, inadequate institutional frameworks that recognize informal contributions to waste recovery, and non-consideration of NbS in urban planning systems. NbS is often viewed through a technocratic lens without local contextualization of global South informality realities. Unlike conventional engineered responses that often require high capital and external expertise, NbS supports decentralized, participatory, and multifunctional solutions that can embed sustainability with existing informal waste recovery systems (Bimpong et al., 2023; D'Almeida et al., 2021; WHO, 2023). Importantly, the circular logic appears to be already embedded in informal e-waste processing, such as reuse, repair, and material recovery, which echoes the principles of NbS (Asibey et al., 2020). The challenge lies in enhancing these practices with ecological safeguards. Thus, NbS should not be viewed as a parallel intervention, but rather as a complementary strategy that can harness the adaptive capacities of informal actors, restore damaged ecosystems, and support locally appropriate climate responses.

It is within the foregoing background that this paper analyzes how NbS, when locally foregrounded and institutionally established and supported, can offer synergistic solutions to both e-waste pollution and climate risk in African cities. There has been limited insight into how NbS can enhance e-waste management, restore ecological landscapes, and contribute to climate adaptation, leading to uncertainties about its effectiveness. Frequently, there is a lack of clarity on how NbS initiatives engage with vulnerable informal communities to reduce their exposure to climate-related hazards while assuring livelihood support. While NbS is increasingly promoted as a key strategy for climate adaptation and ecosystem restoration, critiques have emerged regarding its conceptual vagueness, technocratic framing, and limited applicability in informal or resource-poor settings in the global South.

With limited attention to the institutional, spatial, and socio-political complexities of informality in African cities, this study draws on critical perspectives to assess the potential, limitations and necessary conditions for applying NbS in informal contexts where planning systems are fragmented and local actors lack formal recognition or technical capacity. Cities, by recognizing and integrating informal practices such as e-waste management, can align climate adaptation efforts with ecological restoration. As cities grapple with the challenges of climate change and informality, NbS presents an inclusive and holistic strategy that balances environmental sustainability with social justice. Our research uses a case study of an informal e-waste management site in Ghana to explore how NbS can address both human-induced and natural hazards in these settings.

3. Study area and research methodology

3.1. Study area context

This study was carried out at the Dagomba Line e-waste processing site (DEPS) in Aboabo, arguably the largest e-waste processing site in the city of Kumasi. As one of the fastest-growing Ghanaian cities, Kumasi has an annual growth rate of 5.7 %. Rising land values and the inability of many migrants to secure land through formal means have led to the expansion of informal settlements across the city. About 54 % of the population comprises migrants, often engaged in the informal economy and reside in informal settlements. The city hosts some of the largest informal settlements in Ghana, including Aboabo, where the e-waste processing site is located.

Administratively, the e-waste site falls within the Asokore Mampong Municipality (see Fig. 1). With a growth rate of 4.6 % and a high population density of 12,744 persons/km^2, its rapid expansion is closely linked with Kumasi's urbanization. About 70 % of its working population commutes to Kumasi's central business district for economic activities, reinforcing the municipality's role as a dormitory town within the city. Rapid growth has, however, presented significant urban development challenges, including congestion, increased informal e-waste processing, housing shortages, and encroachments on road reservations and other ecologically sensitive areas. Research (e.g., Asibey et al., 2020, 2022; Atiemo et al., 2016) and participant observations indicate a rapid growth and spread of e-waste activities, with disproportionately high and visible environmental hazards.

3.2. Research method

The study adopted a qualitative case study approach, which allowed for an in-depth understanding of local practices, governance structures, and community perspectives on the complex and dynamic nature of informal e-waste processing. The study was designed as an embedded case study, where e-waste processing served as the focal case, and various respondents served as embedded units of analysis. A multi-method approach was subsequently employed, incorporating participant observation, semi-structured interviews, and document review and analysis.

A desk review and analysis of relevant published and unpublished documents was first undertaken, focusing on works on climate change and adaptation strategies in informal settings, the role of e-waste processing in urban resilience, and the opportunities and barriers to implementing NbS in informal urban economies across cities of the global south. Based on insights from the review, relevant respondents were identified and engaged in interviews for primary data.

In-depth semi-structured interviews were conducted with purposively selected relevant informants to understand their perspectives on climate change, informality, and NbS. The respondents included city officials of the Waste Management Department, Development Planning Unit, Environmental Health and Sanitation Unit, the Physical Planning Department, the Department of Parks and Gardens of the Asokore Mampong Municipal Assembly, and the Environmental Protection Agency. A representative from each of these agencies was interviewed, due to their important roles in development, land use planning, informality, climate change management, and the creation and management of NbS. Additionally, community leaders and two executives of the Dagomba Line Scrap Metal Association were engaged in interviews. A total of nine key informant interviews were thus conducted.

Additionally, 183 informal e-waste workers/actors were surveyed based on their engagement in e-waste processing and insights into the sector's influence on the urban landscape. The survey focused on perspectives on the emergence and spread of the e-waste enterprise; the influence of e-waste on climate change, in terms of associated threats and opportunities; the current state and understanding of NbS; and how NbS can productively engage with the informal economy (e-waste) to

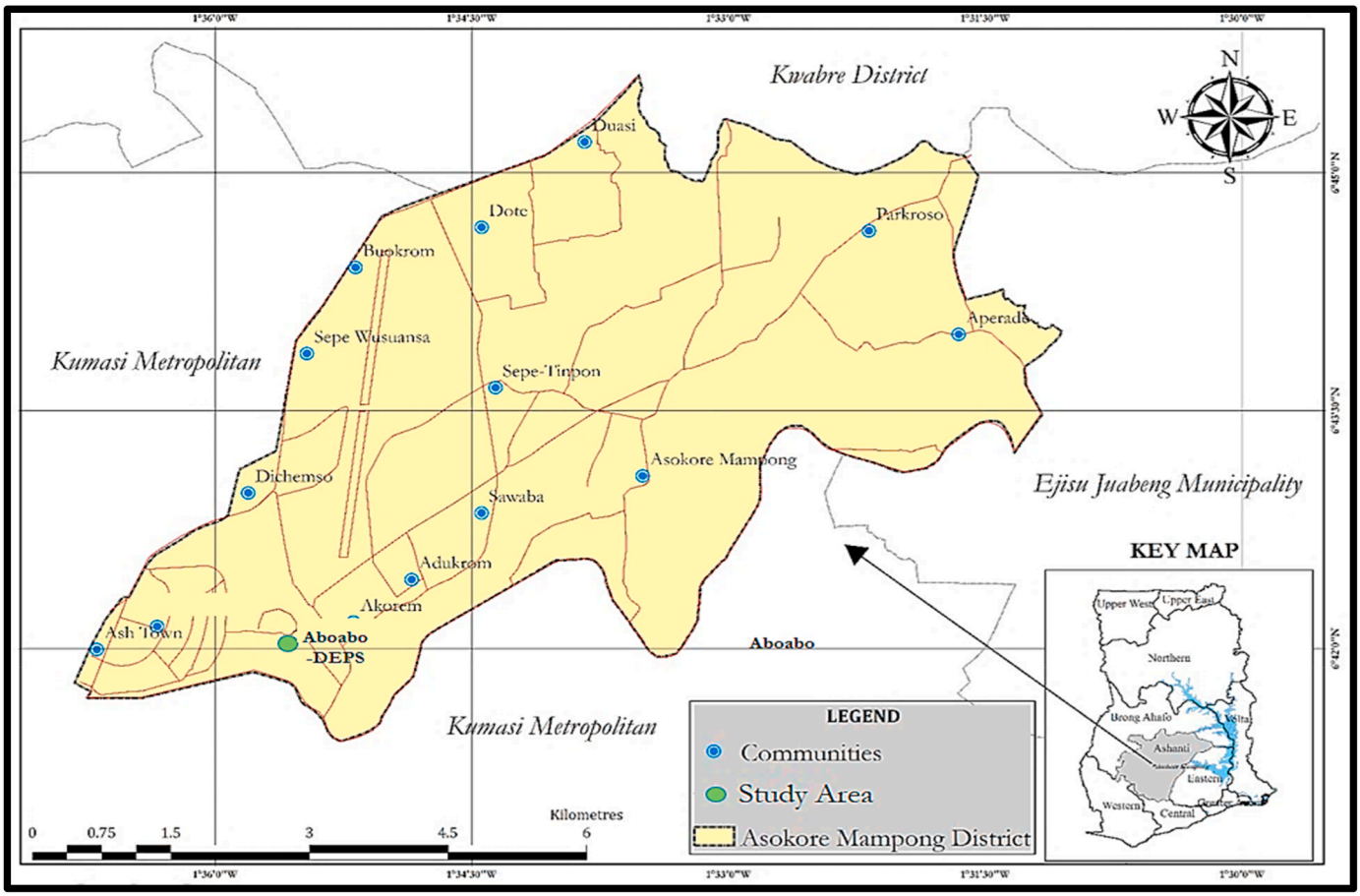

Fig. 1. Case study area in Context.

address climate change. The interviews with the research participants were conducted between November 2023 and March 2024.

To complement the interviews, participant observation was carried out. This provided first-hand insights into the practices of the actors, the environmental impacts of the enterprise, and the interactions among the workers and city officials. Field notes were taken on the conditions of existing infrastructure, informal governance structures, e-waste processing activities, conditions of water bodies and other environmental compartments, and the adaptive strategies employed by the workers.

A thematic analytical approach was used to code, categorize and interpret the data. The analytical process involved: transcription and familiarization where the interview recordings were transcribed verbatim; coding and categorization for emerging themes; and theme identification where key themes were developed based on patterns in the data, including e-waste and its influence on climate change, current state and understanding of NbS in informal urban settings, and urban planning approaches to and challenges in integrating NbS in climate mitigation and adaptation in informal e-waste processing settings. The findings were compared across the different stakeholders to highlight converging and diverging perspectives. The major themes subsequently adopted to present the data were: spread and influence of e-waste on climate change; the current state and understanding of nature-based solutions; and how NbS can productively engage with informal e-waste to address climate change.

4. Results

4.1. Sociodemographic characteristics of the e-waste workers

Approximately 83 % and 17 % of the e-waste actors were males and females, respectively, indicating a male-dominant sector. With a mean age of 36 and an average household size of 5.9, 67 % of the actors had attained formal education. 71 % of the actors were engaged in multiple roles, specifically, scavengers, dismantlers, refurbishers/recyclers. The lowest, average, and highest years of involvement in the sector were 4, 11, and 18 years, respectively. As a migrant town, ethnically, about 88 % of the actors belonged to groups primarily originating from northern Ghana—Gonja, Dagomba, and Mole Dagbani—with a strong sense of unity and social cohesion. Approximately 6 % of the actors were non-Ghanaians from other West African countries, specifically, Nigeria, Burkina Faso and Togo. With an average monthly enterprise income of GHS3,200 (USD207.12[1]), approximately 9 % earned above GHS10,000 (USD647.25), while most (74 %) earned between GHS1,000 and 2000 (USD64.73 – USD129.45). The enterprise's average monthly income far exceeds the national average monthly income of about GHS600 (USD38.83). These figures highlight the important economic contribution of the sector to the actors. Despite this income potential, work conditions remain hazardous and unregulated.

The survey data further revealed the approximate composition of e-waste processed at the site: 35 % of household appliances (e.g., TVs, refrigerators, fans); 13 % mobile phones and accessories; 24 % computers and peripherals/accessories; 17 % batteries (lead-acid, lithium-ion); and 11 % miscellaneous and cables. This profile underscores both the economic significance of the sector and the urgent environmental risks, particularly from toxic components. These details and those provided in the next section offer a clearer context of the site's operations and the livelihood it supports. Kindly see the Supplementary

[1] An exchange rate of USD1 to GHS15.45 as of 16th February 2025.

material for a flowchart to help understand the structure of our analysis.

4.2. E-waste and climate change in Kumasi: agency and workers' perspectives

4.2.1. Emergence and spread of the e-waste sector

In the context of this study, DEPS serves as a critical case study for understanding the current state and implications of NbS in informal climate change adaptation and mitigation. The influx of e-waste at the study site is mainly driven by consumerism, globalization and technological advancements, as commonly observed in other African cities (D'Almeida et al., 2021). This has created a complex interaction between environmental standards, local economies and climate change dynamics. Consultations with city officials and community leaders revealed that Dagomba Line's development has been shaped by spatial, sociocultural, economic, and political factors, yet remains largely disconnected from formal urban planning systems. Despite its well-developed local plan in 1980 (Fig. 2) (Korah et al., 2017), numerous unauthorised structures have been erected, particularly in restricted areas such as floodplains.

Existing economic activities provide essential livelihood opportunities for residents. However, the unregulated developments have reduced accessibility and damaged utility infrastructure, coupled with encroachments and degradation of the urban landscape, posing significant challenges to sustainable neighbourhood development. Dagomba Line exemplifies the intersection of formal urban planning and informal spatial adaptations, where residents independently modify their surroundings in response to municipal inefficiencies.

Historical accounts suggest that as a migrant enclave, its first settlers were migrants from Ghana's Northern, Upper East and Upper West regions. Over time, other migrants relocated to the area due to its proximity to Kumasi's CBD, available economic opportunities, and lower rent, driving its expansion. Residents and workers have erected makeshift structures serving as both residences and workshops, highlighting the complex interplay between residential, commercial, and industrial uses in informal urban settings. The interview findings revealed that e-waste processing evolved spontaneously and informally, in the mid-2000s, when workers originally operated at Suame Magazine (about 6 km away from the site), a well-known informal scrap processing and automobile repair hub in Kumasi. However, due to security concerns, unfair trade practices, and land issues, they relocated their operations to the current site. Over time, other actors from similar backgrounds and interests in e-waste and general scrap processing relocated to the site, contributing to the expansion of e-waste processing in the areas, underscoring the adaptability of informal economies, while also raising concerns about urban planning and environmental sustainability.

Workers involved in this sector spread across the landscape and formed an informal network that thrives on recovering valuable materials from discarded electronics. The key informants and actors reported that the site has witnessed a rapid expansion of informal recycling activities, where the influx of e-waste from both international and local sources has created a dense network of dismantling, burning and metal extraction sites, spread across the area (Fig. 2).

The proliferation of e-waste activities is driven by economic survival, as thousands of informal workers depend on metal extraction for their livelihood. However, the expansion of these operations has had significant environmental and climate-related consequences, considering the numerous workshops and spots where dismantling and burning of e-waste occurred. Their activities have contributed to vegetation loss, which plays a critical role in local climate regulation and as well and point to the pervasive nature of e-waste activities and their tendency to spread beyond designated areas, exacerbating environmental degradation. Aside from the site, there are many spots scattered across the city where actors are involved in various activities along the e-waste chain.

4.2.2. Influence of e-waste on climate change in Kumasi: threats and opportunities

Directly related to findings in Section 4.2.1, city officials emphasized

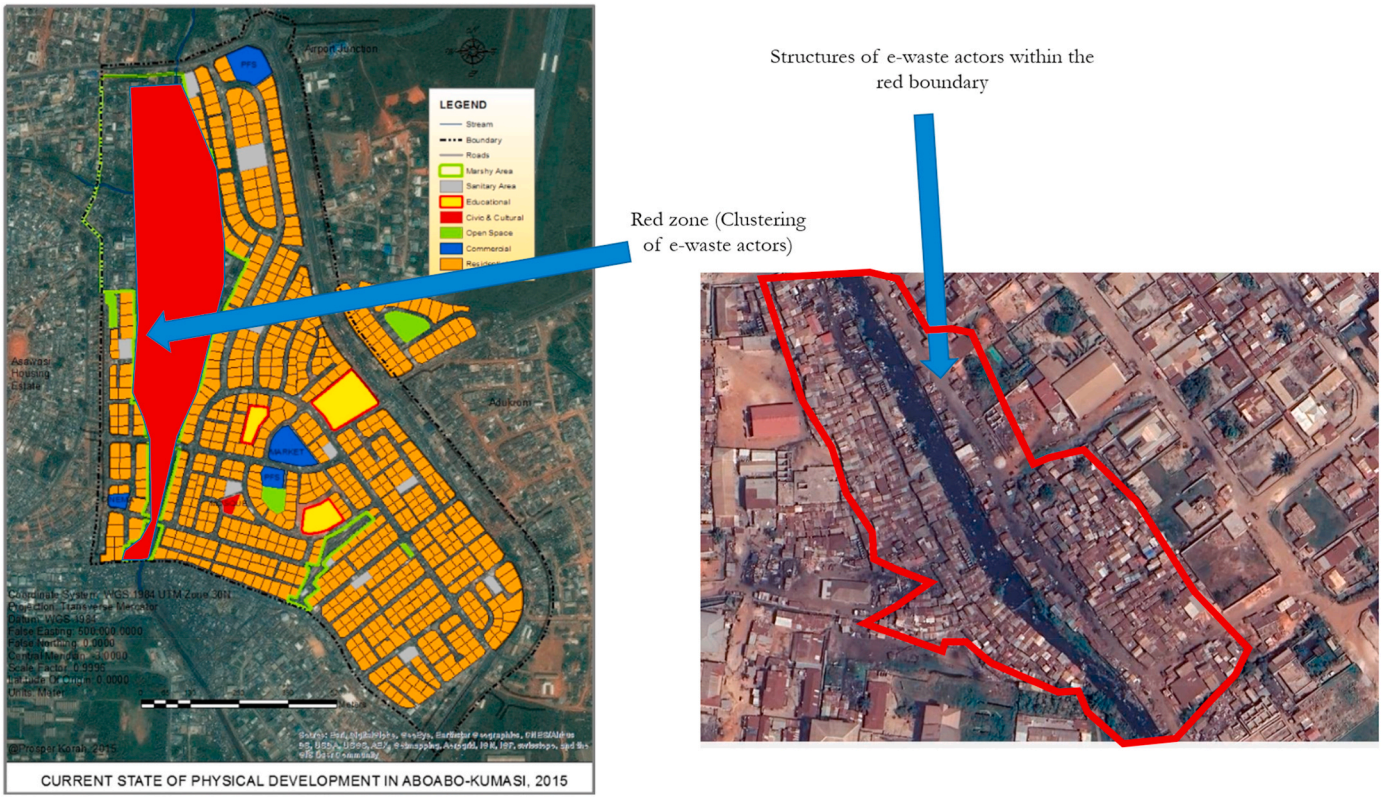

Fig. 2. Spread of e-waste activities across the landscape.

the gravity of the e-waste sector, highlighting its detrimental impacts, both locally and globally. They mentioned that the environmental damage and climate change caused by e-waste activities were undeniable. It must be emphasized that the site and the community remain one of the most vulnerable areas to perennial flood impacts in the city. An official narrated that the open burning of insulated wires and other electronic components releases toxic fumes, including furans, dioxins, and heavy metals, all of which contribute to air pollution and GHGs, a major contributor to climate change (Fig. 3a and b). This was observed across the site. Such emissions endanger public health and contribute to atmospheric pollution and climate change (rising temperature/heat). Soil and water contamination resulting from the improper disposal of e-waste has worsened environmental stress. It was reported that heavy metals seep into the ground, degrading soil quality and making natural regeneration more challenging:

> *"E-waste contains toxic substances, which can leach into the soil and water, exacerbating climate change. The problem or reality is that the soil here has become toxic. Even if we try to replant trees or restore greenery, it will take years for anything to grow properly because of the contamination"* [Official #3]

This perspective underscores the notion that e-waste not only affects immediate health concerns but has far-reaching consequences for climate change management.

Despite the threats to environmental degradation, the city officials indicated that e-waste processing presents an opportunity for sustainable practices and climate change. It was specifically highlighted that the recycling of electronic components served dual purposes: recovering valuable materials and reducing waste. To the officials, the sector has demonstrated some form of efficiency in recovering valuable materials from discarded electronics, reducing the need for new raw material extraction. This dual potential highlights the need for deliberate and targeted interventions—implementing eco-friendly dismantling techniques, enforcing waste segregation policies, and promoting circular economy principles—to turn the site into a model for responsible recycling.

However, interview findings with the e-waste actors revealed limited awareness of the interplay between e-waste processing and climate change. The actors largely recognized the environmental pollution, but did not necessarily associate their actions with climate change. For most actors (83 %), pollution was seen as an immediate, visible and localized issue rather than a contributor to climate change dynamics, which was deemed as a distant and abstract phenomenon.

Some actors further stated that their activities have contributed to reducing e-waste and scraps in communities, indicating that the e-waste sector is beneficial to the general waste management sector. This perspective reflects a disconnect between local pollution concerns and broader climate change discussions, with many actors perceiving industrialized nations and bigger industries as the primary drivers of global warming. The sentiments again reveal a gap in understanding the long-term, cumulative effects of emissions from e-waste processing.

Fig. 3b. A worker manually dismantling e-waste and scrap items at the site.

The perspectives on e-waste pollution as a localized issue were observed to be further reinforced by economic realities. Most actors prioritized income generation over environmental concerns, regarding e-waste processing as a necessary means of survival. Even when acknowledging pollution, the actors often shifted the responsibility for environmental management to city and national authorities or external stakeholders.

> *"We don't burn the items because we want to harm the environment. We do it because that is how we get the copper, and that is what pays for our food, rent, and other items. If the government or bigger industries want us to stop burning, they should bring us machines that can efficiently and timely do the work cleanly"* [An informal e-waste actor]

Local appreciation of promoting environmental sustainability among the actors was intrinsically linked to their lived experience of climate change hazards, specifically, perennial flood occurrence in the area. Most (88 %) indicated that climate change has, over the years, intensified the risks they face in their activities. Specifically, they mentioned that rising temperatures, flood occurrence, and unpredictable weather patterns directly affect their activities, from the destruction of their items after flood occurrence to impacts on their health. As earlier indicated, the informal e-waste sector, although economically important,

Fig. 3a. Smoke emission from the burning of e-waste.

poses severe health and environmental risks (Daum et al., 2017). The actors, therefore, adapt their practices in response to the pressing environmental realities, often from necessity, rather than conscious planning. To them, inadequate resources and infrastructure in the formal sector compel them to innovate to cope with their immediate challenges. For instance, the actors have developed methods to physically separate unwanted materials from recyclable components. These grassroots innovations indicate the potential of informal actors to not only survive but also contribute to the circular economy and climate mitigation.

While interviews and observational data revealed significant volumes of e-waste processed daily at the site, formal statistics on annual e-waste volumes specific to the area are currently unavailable. Likewise, air quality monitoring data disaggregated at the neighbourhood or processing site level do not exist within local government or environmental agency records. This lack of formal monitoring reflects a broader institutional gap in environmental data in informal urban spaces.

4.3. Current state and understanding of nature-based solutions in Kumasi

As scholars shift focus toward sustainable and tangible solutions, NbS has emerged as crucial to managing the complex and interconnected environmental (e.g., e-waste processing and associated risks), material and spatial difficulties posed by climate change (Velayo et al., 2024). However, NbS remains largely overlooked in urban studies, particularly in informal urban environments. Although NbS takes various forms (e.g., use of biodegradable materials, vegetation to combat erosion, natural filtration systems to address contaminated sources, etc.), they were largely non-existent at the study site, and with different levels of knowledge among city officials and e-waste actors.

4.3.1. Current state of NbS in Kumasi

The study findings showed two major realities: NbS were largely non-existent, and the few that naturally existed have been significantly degraded. Despite the urgent need for ecological interventions, the reality on the ground at the e-waste site reflects a significant neglect of NbS. Several parts of the community's landscape are characterized by pollution from e-waste, scrap metals, plastics, and general solid waste, coupled with encroachment on ecologically sensitive areas and haphazard developments, with little space for integrating NbS. Despite reports and observations of the heavy environmental burden posed by informal e-waste recycling, there is little evidence of active NbS interventions to mitigate these impacts.

Primarily, the implementation of the commonest and structured NbS actions, such as vegetation buffers, wetland conservation, and phytoremediation, was absent. First, it was observed that the study site lacks such protective greenery; the absence of which has led to uncontrolled dispersion of hazardous pollutants from open-air burning practices, which was confirmed by city officials. It was again observed that the water channel/body running through the site was severely polluted with discarded materials, heavy metals, and other contaminants, destroying natural aquatic vegetation that could have contributed to filtering pollutants (Fig. 4a and b; Fig. 5a and b). Additionally, the e-waste processing activities are dispersed across the ecologically sensitive area (wetland) of the community, yet there was no effort to integrate wetland-based filtration systems to mitigate the pollution. This neglect has exacerbated the environmental degradation and exposure to climate risks in the area. Last was the non-existence of phytoremediation efforts, although scientific evidence (IUCN, 2020; Seddon et al., 2021) shows that plants such as *Vetiver* grass have the potential to absorb heavy metals from contaminated soils. There was no evidence of deliberate phytoremediation actions at the site, leaving the soil highly toxic and unsuitable for plant and animal life.

In instances where naturally existing elements could have provided environmental benefits, activities of e-waste actors and residents had led to their destruction. At some operational spots at the site, existing

Fig. 4a. Open disposal of unwanted EEE in the environment/water channel.

Fig. 4b. A neglected, polluted and contaminated water channel from open disposal.

Fig. 5a. Encroachments on a section of greenspace in the case study area.

Fig. 5b. Encroachments on a section of greenspace in the case study area.

vegetation (lawns, trees, and shrubs) had been transformed or cleared to accommodate e-waste dismantling, recycling, and open burning, reducing the community's capacity for natural regeneration. Some dominant views from the e-waste actors and city officials reflect the quotes below:

> *"We used to have trees and some green patches around these areas. Over time, however, they have all been cleared to accommodate e-waste activities. Now, instead of shade and fresh air, we have smoke and toxic dust everywhere*" [Official #1]

> *"Well, there was some grass and even a few trees here some years back, but we needed more space for our work. We had fewer options but to remove them. Now, as you can see, the ground is always dry, gets easily muddy when it rains, and the air feels worse …"* [An e-waste actor]

The city officials further mentioned that the presence of mercury, lead, cadmium and other hazardous elements in the soil has rendered the area unsuitable for plant life. They specifically remarked that any previously existing plant species (about ten years ago) that could have contributed to pollution reduction and soil stabilization have been systematically eliminated due to their continuous exposure to toxic chemicals.

As reported, NbS were largely absent at the site, with natural elements significantly degraded due to sustained pollution, encroachment, and land use pressure. Despite these challenges, the physical characteristics of the site, such as flat terrain, proximity to a water body, and pockets of unused or degraded land, offer some ecological potential for NbS interventions like phytoremediation, constructed wetlands, and green buffers. However, suitability remains conditional on substantial investment in site remediation, soil detoxification, and environmental restoration.

Effective implementation of NbS in such a setting would require coordinated multi-stakeholder efforts, including funding for green infrastructure, provision of basic amenities (e.g., sanitation and water access), and structured re-skilling programs for informal workers. This can include training in safe dismantling, environmental awareness, and practical engagement with NbS techniques such as planting and waste segregation. We acknowledge that the current mismatch between NbS approaches and the lived realities of informal e-waste actors—particularly the limited knowledge and operational constraints—may create incompatibilities. Nonetheless, these should not be interpreted as fixed barriers but as gaps that could be addressed through participatory planning, inclusive education, and technical support. In this regard, building trust, demonstrating the co-benefits of NbS, and enabling gradual behavioural shifts are important steps toward compatibility.

4.3.2. Understanding NbS in the context of e-waste and climate change

To deepen the analysis of divergent understandings of NbS between city officials and informal e-waste workers, insights from the institutional analysis and development (IAD) framework (Ostrom, 2007, 2019). The framework emphasizes how different actors operate within distinct action areas shaped by formal rules (e.g., planning regulations), informal norms (e.g., livelihood strategies), and shared or asymmetric access to information and resources. In the case of this study, formal actors operate within institutional logics that prioritize policy alignment, measurable indicators, and formalized NbS planning approaches, often modelled on Global North frameworks. Their understanding of NbS is thus technocratic and structured around formal environmental planning tools.

Knowledge of NbS among city officials was high, where they mentioned that NbS generally contributes to mitigating climate change impacts and offering ecological and health benefits to individuals and communities. NbS in e-waste management, according to an official, is about integrating natural systems and processes to mitigate environmental harm, recover valuable materials and support sustainable livelihoods. NbS was admitted to help mitigate climate change by reducing GHG emissions and enhancing carbon sinks.

> *"NbS are strategies that are natural actions—wetland restoration, green infrastructure, afforestation, agroforestry practice, etc.—aimed at enhancing ecosystem services such as carbon sequestration, flood regulation, and temperature moderation/cooling"* [Official #4]

The officials further indicated that NbS prepares communities to adapt to climate impacts by reducing exposure and vulnerability. Notable strategies mentioned were wetland restoration, floodplain management, urban green spaces, mangrove restoration, and sustainable water management. Relatedly, the officials highlighted several forms of NbS which are relevant for the e-waste sector. Notable mention was green buffer zones and urban forests (planting trees and vegetation [bamboo and *Moringa oleifera*]) around informal e-waste processing sites to help reduce air pollution, absorb heavy metals and create healthier urban environments.

Other forms indicated were the construction of wetlands for wastewater treatment and phytoremediation using plants like reeds (*Phragmites*), cattails (*Typha*), Vertiver grass, and Indian mustard to improve biodiversity, provide ecosystem services, but most importantly, filter heavy metals and pollutants from the wastewater produced by informal e-waste dismantling. To Official #3:

> *"Plants like Vertiver grass and Indian mustard have the potential of absorbing heavy metals such as cadmium, mercury, and lead from contaminated soils in e-waste processing sites. The plants, from what I know, help detoxify areas that are polluted by informal e-waste recycling, making them safer for other land uses"*

Additionally, some officials mentioned agroforestry and land reclamation using agroforestry systems, integrating fast-growing trees, medicinal species, and nitrogen-fixing plants to restore soil health. To the officials, this approach could support sustainable livelihoods for informal workers through alternative income sources. Lastly, the officials highlighted bioleaching for metal recovery and the use of eco-friendly bio-based packaging for electronics as forms of NbS, which are crucial for addressing the environmental and climate risks associated with unsafe e-waste processing activities. Despite this extensive knowledge, all officials remarked that NbS was largely non-existent at the processing site, except for a few green buffer zones at the site, material recovery, and resource repurposing, underscoring the disconnect between knowledge and practice.

In contrast, informal e-waste actors engage in highly localized, experiential practices driven by survival needs, with limited exposure to environmental discourse or ecological training. They prioritize short-term economic returns over long-term ecosystem benefits, explaining their low awareness and limited engagement with NbS concepts.

Interviews with the e-waste actors revealed a limited understanding of NbS. Generally, while all actors recognized the environmental hazards (not necessarily climate change hazards) associated with their work, they did not necessarily frame their mitigation and adaptation strategies within the NbS framework. Only a few (17 %) mentioned that NbS were strategies that use natural processes to address environmental challenges. Notable NbS mentions were vegetation (grass/lawns), trees, and gardens, which to them act as measures to protect the environment, minimize the flooding and heat impacts, and improve the general ecological landscape. The quote below represents a general view of some actors' interpretation of NbS.

> *"I think NbS means making use of nature (vegetation, forest, wetlands, trees, grass, and water) to mitigate environmental problems such as heat, flooding …. they are meant to conserve and protect environmental resources and as well, mitigate the many risks associated with environmental challenges"*.

Although some of the e-waste practices, such as material recovery and resource repurposing, align with NbS principles, they were not explicitly recognized as such by the actors. It was further observed that while some adopted basic personal protective equipment/clothing, systemic interventions that integrate NbS into their activities and the site remain absent. The limited infrastructural support and policy engagement left many of the informal actors to navigate the risks independently. Analysis of the interview data revealed a diverse understanding of NbS in the context of climate change and e-waste processing. This divergence highlights not just a knowledge gap, but a structural disconnect between parallel institutional systems. Bridging this gap requires the design of translational spaces where informal actors can access NbS-related knowledge and where planning institutions recognize and adapt to informal norms and practices. Such institutional learning is essential for inclusive NbS integration in cities shaped by informality.

4.4. How NbS can productively engage with informal e-waste to address climate change

This section analyses the perspectives of the research participants on the urban planning inadequacies that prevent fruitful engagement with the informal economy and suggestions on NbS-e-waste integration to address climate change.

4.4.1. Urban planning inadequacies that impede engagement with the informal sector in Kumasi

The findings reveal that informal e-waste workers possess valuable knowledge of local waste streams and resource recovery skills that could support sustainable practices and resilience. However, several urban planning challenges hinder their engagement in NbS for climate adaptation. These included limited stakeholder engagement, lack of formal recognition and support from city authorities, regulatory constraints, resource scarcity, and inadequate infrastructure for recycling activities.

The e-waste workers reported that their exclusion from urban planning and waste management strategies stems from a longstanding perception of their sector as an obstacle rather than an asset. City officials acknowledged that overlooking informal practices results in missed opportunities to align urban planning with NbS objectives. Many workers face hazardous conditions without proper resources or training, exacerbating environmental and health risks. Most workers further mentioned that in addition to their activities, urban planning strategies inadequately address their existence and needs, resulting in exposure to toxic substances. An executive of the Dagomba Line Scrap Metal Association stated that:

> *"The informal sector remains largely unaccounted for in urban planning initiatives, leaving a significant gap in the planning and implementation of sustainable solutions such as NbS"*

This exclusion is particularly concerning in a context like Kumasi, where over 60 % of the urban workforce operates informally, and planning authorities struggle to keep pace with the rapid growth of the population and increasing service demands. In Kumasi and some of Ghana's major cities, informal e-waste recovery sites serve as both vital economic spaces and environmental risk zones. Yet they remain invisible in formal development frameworks.

The financial implications of this neglect are considerable. Without investment in safe recycling infrastructure or environmental remediation, the city thus incurs costs in the form of public health burdens, polluted land and water bodies, and diminished climate resilience. Simultaneously, opportunities for job creation through green entrepreneurship, skills development, and circular economy innovation are missed. Making these sites visible to political and private decision-makers is therefore crucial, not only to manage risks but also to unlock their potential as hubs for inclusive urban regeneration, climate adaptation, and sustainable economic transition.

Regulatory barriers further restrict integration. Although existing legal frameworks, such as the Hazardous and Electronic Waste Control and Management Act, Act of 2016 (917), and Legislative Instrument 2250, aim to improve the sector, they often fail to recognize the complexities of the informal sector. City officials admitted that regulations are formulated without input from informal workers, citing the technical complexity of policy development. As a result, rigid licensing requirements and stringent environmental standards exclude informal actors, perpetuating unsustainable practices. Despite efforts, such as GIZ-supported initiatives for sustainable e-waste management (Bimpong et al., 2023), informal sector actors remain largely excluded from planning and implementation.

The lack of designated spaces for informal recycling and insufficient waste management infrastructure poses significant challenges. Without proper collection or processing facilities, workers resorted to environmentally harmful practices, leading to pollution and difficulties in monitoring, training, and engagement. Additionally, resource scarcity limits effective NbS implementation. Officials highlighted that rapid increases in e-waste generation require substantial investments in green infrastructure, environmental remediation, and workforce training. However, budget constraints hindered the development of systems that could support informal recyclers. Furthermore, without adequate financial resources, the officials found it difficult to engage informal e-waste actors who operate outside regulatory frameworks, leading to delays or total neglect of NbS initiatives in informal e-waste sites.

Finally, a deficit in technical expertise impedes NbS integration. Some officials and informal workers lack the necessary knowledge to design and implement sustainable and NbS-e-waste-related management strategies. This gap in expertise, according to the officials and actors, impedes the integration of NbS, such as recycling methods or using recovered materials in their activities. For instance, workers engaged in the informal e-waste sector often rely on rudimentary techniques to extract valuable metals but generate substantial environmental hazards. The analysis showed that perspectives on resource scarcity diverge. While some viewed the lack of funding as a barrier that could be overcome through innovative partnerships, others contended that the technical expertise deficit was more complex and required systemic change. This underlines the necessity of addressing educational deficiencies (through training and education programs) as foundational for future progress.

From the above, it is evident that there is a persistent disconnect between formal and informal waste management systems in many Global South cities, where informal actors, despite their critical roles, remain marginalized in planning frameworks (UN-Habitat, 2018). This was evident at the Dagomba Line site, where local views reflected a broader structural pattern of exclusion. In Nairobi, for example, the Dandora dumpsite supports thousands of informal workers, yet they remain unrecognized in municipal waste planning. In Lagos, informal recyclers handle a significant share of the city's waste, but face eviction

threats and poor working conditions due to a lack of integration (Ohajinwa et al., 2017). Similarly, in Delhi, the informal waste sector is highly organized and economically vital, yet continues to operate outside formal policy frameworks, limiting opportunities for safer and greener practices (Borthakur, 2015).

These cases underscore that the exclusion of informal actors is not merely a local governance failure but part of a systemic challenge in urban environmental management. Literature increasingly highlights that integrating informal systems can improve waste recovery efficiency and support inclusive urban sustainability (Asibey et al., 2021, 2023; Daum et al., 2017). Bridging this divide is essential for effective NbS and climate adaptation strategies.

4.4.2. Managing climate change in Kumasi: towards NbS – informal e-waste integration

The participants highlighted that NbS could play an important role in the environmental performance of informal e-waste processing through urban planning integration; inclusive policy formulation, enforcement, and participation; and the development of appropriate NbS.

The officials acknowledged that there have been efforts toward climate adaptation and ensuring environmental protection and sustainability through NbS. Notable measures mentioned were wetland conservation and restoration, safeguarding street trees and planting on road medians, distributing seedlings to residents, and public environmental sensitization. They, however, mentioned that these efforts have been slow, inadequate and do not necessarily target informal e-waste sites. On the way forward, the officials first mentioned that NbS must be embedded into broader e-waste-related urban planning frameworks to ensure they address both socio-economic and environmental concerns. The failure of urban planning to recognize the informal sector was revealed to have limited green infrastructure interventions. The officials reiterated the need for urgent steps to integrate NbS into the environmental management of the Dagomba Line and other e-waste sites across the city. An affordable potential solution mentioned was phytoremediation. Similarly, composting organic e-waste was reported to have the potential to reduce landfill burden and generate valuable compost for greens paces. Additional pathways mentioned were implementing green buffer zones to create protective tree belts around the site to reduce pollution and developing constructed wetlands to serve as natural filtration systems to improve water quality and restore aquatic biodiversity.

> *"Establishing urban green corridors, buffer zones, and phytoremediation sites near informal e-waste processing hubs, including the Dagomba Line e-waste site, can help mitigate environmental harm while creating healthier workspaces."* [Official #1]

These methods were reported to be particularly effective in informal settings where capital investments are lower and land availability is often higher. The integration of such techniques, according to some officials and actors, demands close collaboration and coordination, considering that workers' indigenous knowledge and experience are essential in adapting these solutions to local contexts.

Furthermore, the participants emphasized continuous monitoring and evaluation as necessary to ensure the effectiveness of NbS in achieving environmental and social goals. The respondents specifically mentioned tracking the environmental solutions of to-be-implemented solutions and assessing the well-being of informal actors. Some officials further strongly highlighted that regulations should be designed to incorporate informal e-waste workers in sustainable waste management strategies. To them, without inclusive policies, the workers will continue to operate in environmentally harmful ways, reducing the effectiveness of NbS.

The contribution of local planning authorities, CSOs, NGOs, and relevant environmental sustainability groups cannot be underemphasized. It was reported that environmental activists and groups engaged with some e-waste workers some years ago, mainly to educate them on safer handling and encourage environmentally friendly practices. A notable mention was organized workshops on the importance of safe dismantling and recycling, and the potential of creating a sustainable local economy through responsible e-waste processing. Although such efforts are important in bridging the gap between economic necessity and environmental (NbS) awareness, they were found to have achieved minimal success. Most informal e-waste actors interviewed, confirmed by executives of the association, explained that the workshops were organized through and for members of the association, who only constituted about 15 % of the entire e-waste actors. To these respondents, their non-involvement largely stems from their exclusion from the planning of these workshops and the late relay of information on such events. Key informants emphasized the need to strengthen existing collaborations and explore new partnerships with local environmental sustainability groups to enhance NbS efforts through critical insights and resources.

Environmental advocacy groups can drive legislative changes by promoting frameworks that integrate informal practices into collaborative waste management solutions. On this, the participants asserted that the successful integration of NbS with informal e-waste processing requires a multi-faceted approach involving urban planners, policymakers, environmental experts, and informal e-waste workers. They specifically called for building trust and a participatory approach that engages all stakeholders in planning and implementation processes. Open communication, addressing concerns of the workers, and ensuring equitable benefit sharing are deemed crucial to foster a sense of ownership, increase the likelihood of successful implementation, and provide workers with access to better technology and training, enabling them to improve their practices and contribute to more sustainable and environmentally friendly e-waste management.

All participants, due to the limited knowledge of informal actors on NbS and the influence of their activities on climate change, called for inclusive education campaigns reaching all e-waste workers, not just association members, to enhance awareness of their impact on climate change and encourage NbS adoption. They also called for training on eco-friendly recycling, environmental regulations, sustainable resource recovery, and land use to transform their operations into safer, more sustainable practices and integrate them in NbS planning.

The analysis indicates a significant absence of NbS, with e-waste processing and other human activities exacerbating environmental degradation at the site. If unaddressed, these issues will continue to pose severe ecological risks. Integrating NbS into informal e-waste activities presents both challenges and opportunities for mitigating climate impacts. Recognizing and supporting informal actors while promoting sustainable practices is crucial. Collaborative approaches involving informal e-waste workers, environmental groups, and planning authorities can facilitate inclusive discussions on effective waste management. Additionally, skills training and education can empower informal workers to adopt NbS and advocate for their inclusion in formal sustainability efforts.

5. Discussion: placing NbS in informal e-waste discourse on climate change

This study explores the complexities and opportunities of addressing climate change through NbS in informal urban environments, focusing on the Dagomba Line e-waste processing site in Kumasi, Ghana. Informal e-waste processing is not just an economic activity but is deeply embedded in the social and environmental fabric of urban communities (Andeobu et al., 2021; Maes and Preston-Whyte, 2022). While the sector contributes to economic well-being (Bimpong et al., 2023), it also poses significant environmental hazards, including pollution and GHG emissions from unregulated landfill disposal and open burning (Ohajinwa et al., 2017; Asibey et al., 2021). These practices accelerate climate change, a trend observed across Global South cities (Grant and Oteng-Ababio, 2016; Borthakur, 2015, 2020). The clustering of e-waste

activities in ecologically sensitive areas further degrades urban landscapes and increases risks for local communities.

Despite high awareness of these environmental threats, informal actors had limited knowledge of the sector's contribution to climate change. Actors recognized pollution but did not link their activities to broader climate impacts, a common trend among informal workers with limited exposure to non-visible environmental effects (Ohajinwa et al., 2017; Grant and Oteng-Ababio, 2016). Despite these challenges, the informal sector presents an opportunity for sustainability. Its ability to efficiently recover valuable materials reduces the need for raw material extraction and waste generation (Nartey et al., 2016; Borthakur, 2020). These findings highlight the need for targeted interventions to transform informal e-waste processing into a model for responsible recycling.

NbS has emerged as a critical approach to managing the environmental and spatial challenges posed by informal e-waste activities (Velayo et al., 2024). Case studies demonstrate the effectiveness of integrating NbS with recycling, such as constructed wetlands to treat e-waste wastewater, green infrastructure and improved waste management to mitigate environmental hazards, enhance urban resilience, and promote public health (Kabisch et al., 2023; Velayo et al., 2024). However, NbS remains largely absent in informal settings due to limited knowledge, resource constraints, and weak urban planning responses. Rapid urbanization and the informal nature of e-waste processing further complicate its integration into existing frameworks. A major challenge is the exclusion of informal actors from urban planning processes, a pervasive issue across cities in the Global South (WHO, 2023; UN-Habitat, 2018). Without their inclusion, policies fail to reflect the realities of informal work, leading to inequitable and ineffective solutions. Many informal workers are economically marginalized and face hazardous conditions, yet their contributions remain unrecognized in formal discussions (Bimpong et al., 2023). Nonetheless, their resilience and adaptability underscore their potential role in sustainable NbS implementation.

Recent scholarship has advanced the concept of NbS as a multifunctional approach to climate adaptation, ecosystem restoration, and urban resilience (IUCN, 2020; Kabisch et al., 2023). However, critiques have emerged regarding the uncritical promotion of NbS, particularly in informal or low-capacity urban contexts. Scholars caution against greenwashing and the risk of superficial, technocratic interventions that overlook power dynamics, land tenure, and the lived realities of marginalized communities (Seddon, 2022; Nature-based solutions initiative, 2024). Others advocate for participatory approaches that involve local communities in NbS design and management, ensuring cultural relevance and effectiveness (Kumar et al., 2021; Velayo et al., 2024). Although NbS holds promise for mitigating the climate impacts of e-waste, its implementation requires careful planning, inclusive governance, and community engagement.

The third research question—how NbS can improve informal e-waste practices—revealed both potential and constraints. Although the site lacks formal green infrastructure or ecological planning, opportunities exist to introduce NbS incrementally through phytoremediation, green buffer zones, and flood mitigation using local vegetation (IUCN, 2020; Seddon et al., 2021). However, these possibilities are contingent on broader institutional support, participatory planning, and re-skilling of workers. NbS cannot be imposed as a one-size-fits-all solution; they must be adapted to local needs, land conditions, and governance realities.

In response to calls for more tangible economic justification, it is important to clarify the rationale for NbS in comparison to other feasible approaches, namely manual e-waste recovery and conventional engineering interventions. Manual e-waste recovery, as currently practised at Dagomba Line and other informal hubs in Ghana (Daum et al., 2017; Grant and Oteng-Ababio, 2016), is primarily labour-intensive and driven by survival needs. Although this method allows for low-cost material extraction (e.g., copper, aluminium, plastics), it remains environmentally hazardous, health-compromising, and spatially disordered (Finn and Cobbinah, 2024; Fawole et al., 2023). The findings found that over 70 % earned between GHS1,000 and 2000 (approx. USD65–130), a relatively high income compared to Ghana's minimum wage, but it comes at the cost of polluted soils, degraded wetlands, and hazardous emissions. Moreover, the open burning, dismantling, and waste dumping practices undermine long-term urban sustainability and public health.

In contrast, NbS interventions, while initially requiring basic investment and technical support, offer multiple long-term co-benefits: soil detoxification and water purification, restoration of ecosystem services, opportunities for green job creation, and enhanced integration of informal spaces into urban resilience frameworks (IUCN, 2020, 2014; Brown et al., 2014). Globally, cost-benefit analyses of NbS in comparable low-income urban settings suggest that their benefit-cost ratios range between 1.5 and 10, depending on the scale and time horizon (Seddon et al., 2020). Although such modelling is beyond the current study's scope, these values reinforce the notion that NbS can yield substantial returns when co-benefits are considered.

Additionally, conventional engineering solutions (e.g., lined landfills, air filters, concrete drainage) often demand capital-intensive inputs, rely heavily on external expertise, and offer limited adaptability to informality. In Kumasi's context, where fiscal constraints, fragmented governance, and informality dominate, the feasibility of large-scale grey infrastructure remains low. While manual recovery remains a viable livelihood strategy, it is insufficient to address the environmental and climate risks posed by informal e-waste processing. Rather, NbS should be seen as a complementary and transformative layer, able to both improve the ecological base of these activities and unlock sustainable adaptation pathways. This comparative analysis further supports the argument that locally adapted NbS can provide a strategic, inclusive, and economically justifiable approach to managing e-waste pollution and climate risks in rapidly urbanising, informal African contexts.

Broadly, our results align with ecological resilience theory, demonstrating how informal systems adapt to and shape environmental stressors, albeit in ways that can both support and undermine urban sustainability. The informal e-waste sector reflects a form of adaptive, bottom-up resilience, but in the absence of institutional support, its contributions remain ecologically costly and socially precarious. Additionally, from an inclusive urbanism perspective, the current planning regime in Kumasi overlooks the knowledge, practices, and spatial claims of informal actors, thereby limiting opportunities for co-producing sustainable solutions like NbS. Recognizing informal e-waste actors not merely as polluters but as potential partners in environmental stewardship can enable new pathways for climate adaptation and urban regeneration.

6. Conclusion

Focusing on informal e-waste processing at the Dagomba Line site in Kumasi, this study explored the complexities of how NbS can productively engage with informal urban environments in adapting to climate change in a deeply informal city. The paper does so by studying (i) the spread and influence of e-waste on climate change, (ii) the current state and understanding of NbS, and (iii) how NbS can productively engage with informal e-waste to address climate change. The premise is that for NbS to be beneficial and contribute to climate mitigation and adaptation, more attention should be given to the deeply interwoven and precarious informal economy.

The research showed that informal e-waste processing is prevalent, where a significant proportion of people engage in the sector due to economic necessity. The improper e-waste processing methods lead to severe environmental and health hazards. Despite high awareness of environmental threats, informal actors had limited knowledge of the sector's contribution to climate change. The study further identified various urban planning inadequacies in planning for, implementing and integrating NbS into informal e-waste recycling to address climate change risks and other environmental hazards. Notable among them are

limited formal recognition of informal actors and support from city officials, regulatory constraints, resource scarcity, fear of uncertainties associated with NbS, and lack of designated places for informal recycling activities and inadequate waste management infrastructure. The study underscores the importance of acknowledging the role of informal economies in urban resilience. This case study underscores the urgent need for a multi-faceted approach that acknowledges the realities of informality while seeking to mitigate the impacts of climate change through NbS in the Global South.

We advocate for a shift in urban planning paradigms to incorporate the realities of informal economies. City authorities can create more inclusive and effective climate adaptation and mitigation strategies if they engage informal e-waste workers and communities. Only through a collaborative and inclusive approach can the transformative potential of NbS in tackling the pressing global climate challenge be unlocked. Additionally, promoting research and innovation in environmentally friendly technologies tailored to informal settings, strengthening institutional frameworks that support collaboration and equitable resource allocation, and integrating NbS into local, national, and international e-waste management frameworks are critical.

We call for establishing demonstration plots using locally available species like *Vetiver* grass and Indian mustard to remediate polluted soils by the local planning authorities and local NGOs. This measure provides cost-effective soil restoration while providing environmental education and visibility. Of much significance, empowering informal e-waste workers through capacity building and formal recognition is paramount and essential for ensuring the long-term success of any initiative. Directly in line with this is developing skills training modules on NbS and safe recycling for informal actors. This will allow NbS to play an important role in addressing the climate change implications of the global e-waste crisis while facilitating informal workers' economic opportunities and enhancing the technical capability among actors.

As climate change intensifies, informal e-waste management will become increasingly relevant in urban sustainability dialogues. The transition to circular economics presents a unique opportunity to integrate NbS with informal practices, aligning resource recovery, environmental restoration, and waste reduction with global sustainability goals. The study contributes novel insights into how NbS may intersect with informal e-waste management in urban Ghana. However, several limitations are noted. First, data constraints, particularly the absence of disaggregated environmental and economic statistics, restricted the depth of quantitative analysis. Second, the focus on a single case study site, while offering rich context, limits broader generalizability. Third, the cross-sectional nature of the research does not capture seasonal or long-term dynamics. Lastly, limited engagement with national policy institutions constrained analysis of institutional pathways for scaling NbS interventions.

Future research could address these gaps by conducting longitudinal studies to monitor environmental and livelihood changes; developing economic models tailored to informal and circular systems; exploring participatory NbS design with informal actors and planners; comparing cases across cities to test transferability of findings; and supporting policy experiments that link NbS with urban informality and climate resilience. These directions will help deepen understanding and enhance the practical relevance of NbS in informal urban contexts. Addressing climate change through NbS in informal e-waste settings requires inclusive interventions that recognize the voices and experiences of marginalized groups (UN-Habitat, 2018; Castellanos et al., 2022). We conclude by emphasizing that for NbS to be effective in managing climate change impacts and improving activities, they must be carefully and consciously integrated into the fabric of informal economies, ensuring that the concerns and needs of those involved are heard and addressed.

CRediT authorship contribution statement

Michael Osei Asibey: Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Patrick Brandful Cobbinah:** Writing – review & editing, Writing – original draft, Visualization, Validation, Funding acquisition, Conceptualization.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2025.126697.

Data availability

The data that has been used is confidential.

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