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The informal paradox: electronic waste and the toxic circular economy in Ghana

Brandon Marc Finn[1] ✉, Patrick Brandful Cobbinah[2] & Dimitrios Gounaridis[1]

Decarbonization and the circular economy are heralded as sustainable pathways to address climate change, but their consequences in the Global South are often overlooked. Countries like Ghana face significant environmental and health challenges because of the green transition. In Accra's informal settlements, electronic waste recycling offers economic opportunities but exacerbates pollution and public health risks. This study examines Agbogbloshie, an informal settlement in Accra, Ghana, that is home to one of the world's largest electronic waste sites, to explore the informal paradox between economic opportunity and toxic exposure in the Global South. Using geospatial analysis of the population and time-series $PM_{2.5}$ data (2000–2020) in conjunction with 55 stakeholder interviews, we show that while electronic waste recycling provides much-needed livelihoods, it does so at the expense of the health and well-being of workers and residents alike. These dynamics reflect complex trends linking informality to global supply chains and circular economies.

Decarbonization is a frequently invoked concept in urban sustainability, used to describe perhaps the world's most important socio-environmental and political strategies in the battle against climate change[1]. It is driving a substantial increase in demand for critical minerals[2], met through expanding new mines globally and harnessing circular economy models where products and minerals are recycled before being re-incorporated into supply chains[3].

There are real risks of the 'green transition' being enabled by long-standing global inequalities[4]. A significant consequence of decarbonization and the shifting production geographies it relies upon is the growing importance of informality in the flow of these minerals – from extraction to waste management and recycling. Informality refers to economic, housing, or governance activities that fall outside of formal regulation and oversight. The life cycle of critical minerals such as copper, cobalt, and lithium is closely linked to informality through multiple nodes of their supply chains[4,5].

The links between informality and supply chains are typically documented in their first stage, where artisanal and small-scale miners constitute a global workforce of over 40 million people[6,7]. These links remain largely understudied at the end-of-life stages of mineral supply chains. In contrast to the regulated e-waste management systems with robust policy and infrastructure in Global North countries[8], the situation in Global South countries is often reversed, where weaker capacities result in informal, unregulated recycling practices. Pioneering scholarship[1,9,10] has assessed how functional supply chains create socio-economic and spatial inequalities related to land use, urbanization, and public health at the point of provenance for supply chains and the importance of linking such research to their 'final' stage. This paper builds on this work by focusing on Ghana to assess the relationship between electronic waste (e-waste), urbanization, and exposure to toxicity, including air pollution.

In Africa, informal actors often control the e-waste market by recycling valuable materials from e-waste using rudimentary methods, including open burning and acid leaching[3,11]. Global annual e-waste production was 62 MT in 2022 and is predicted to rise to 82 MT by 2030[12,13]. The estimated value of the metals present in global e-waste stocks in 2019 was USD 65 billion[13]. The Global South has become a destination for over 80% of the e-waste from Global North countries, often obscurely labeled as used and usable electrical and electronic equipment[8]. This phenomenon continues to grow, as electronic waste is produced globally. An estimated 82.6% of the global e-waste generated in 2019 was not formally documented, collected, or recycled. This e-waste is then typically processed informally, without regulation, occupational safety, or registration[14].

In addition to Ghana, other prominent informal e-waste sites are located in China, Nigeria, the Philippines, and India[13]. In Africa alone, the amount of imported electrical and electronic equipment constitutes about 60% of the total e-waste production in the region, as most products have either passed or are nearing the end of their useful life[15]. In Ghana, where about 15% of global e-waste is dumped[8], informal recycling is the most common method[16]. For informal communities working with and living near e-waste sites such as Agbogbloshie, their livelihoods and settlements present a complex trade-off between relative economic opportunity and exposure to chronic health and environmental harm, which we call the informal paradox.

[1]School for Environment and Sustainability, University of Michigan, Ann Arbor, MI, USA. [2]Faculty of Architecture Building and Planning, The University of Melbourne, Parkville, VIC, Australia. ✉e-mail: brafinn@umich.edu

In the past two decades, scholarship has examined the environmental health[17], ecological, spatial[18,19], and socio-economic dynamics[20] of e-waste in Ghana[21]. Research has framed the Agbogbloshie and Old Fadama communities as catalysts for understanding broader informal settlement complexities, dynamics, and operations[22,23]. Scholars, government officials, and urban planners have interrogated e-waste activities in Ghana through the lens of sustainability, formalization, and planning inadequacies[24–26]. Consistent with the growth and resilience of the informal urban sector, scholarship has interrogated eviction and demolition practices by the government, livelihood conditions of residents, waste management, and, more recently, e-waste processing and recycling in the region[27]. Recent innovative scholarship has applied material flow analyses to track e-waste flows to assess data in Agbogbloshie[28,29]. Research has demonstrated the links between e-waste and informal livelihoods[30], air pollution, and climate change[31]. Despite these advances, comprehensive approaches to the inherent multidimensional challenges associated with e-waste management remain lacking in Ghana. This has led to explicit calls for scholars to advance interdisciplinary and systematic analyses of informality, e-waste, and air pollution in the region[20,32,33].

Agbogbloshie (Fig. 1) and Old Fadama face enormous urban and environmental challenges that have emerged through the growing demand for recycled metals[31]. This is a dynamic economic zone marked by ongoing land rights struggles and a mix of multiple residential, industrial, and commercial activities[34]. These sites represent the 'final' node of the supply chain for minerals, where open burning is used on electric appliances, cords, and other materials to retrieve copper, aluminum, and lithium-ion batteries[35,36]. Informal e-waste workers ensure that these materials are not simply dumped and discarded, but are re-articulated back into circular mineral supply chains.

Although the history of land management politics of both Agbogbloshie and Old Fadama informal settlements dates back to the colonial era (before 1957), e-waste processing in the area is a relatively recent phenomenon commencing in the early 1990s following city authorities' relocation of hawkers and the yam market in Accra to the banks of the Korle Lagoon as part of the city's decongestion efforts[37,38]. An influx of migrants[39] from northern Ghana is also linked to the changing environment and urban form in Agbogbloshie, as they moved to this area to escape inter-tribal conflicts and famine, and seek alternative livelihood sources for their declining agricultural opportunities[40].

Activities in Agbogbloshie fit comfortably within circular economy frameworks[41], as e-waste processing seeks to reuse and recycle goods that would otherwise be dumped and discarded. However, the social and environmental externalities associated with this stage of mineral supply chains – the end-of-life phase of a product's life cycle - show that the simple existence of a circular economy is often synonymous with social and environmental injustices.

The e-waste site in Agbogbloshie (Fig. 2) provides direct employment for about 6000 people. An estimated 90% of e-waste workers reside in the Old Fadama and Agbogbloshie informal settlements[42]. Approximately 30,000 people in the Greater Accra region are indirectly employed by the Agbogbloshie recycling industry[43]. Despite its severe challenges, Agbogbloshie attracts a steady source of labor because e-waste recycling offers vital sources of economic livelihood and urban settlement.

Our work engages directly with the informal economies central to e-waste recycling, informal settlements that emerge at this supply chain node, and the informal governance mechanisms that regulate these interactions[44]. This paper aims to investigate how informal e-waste recycling in Agbogbloshie reflects the trade-offs between economic opportunity, environmental harm, and global

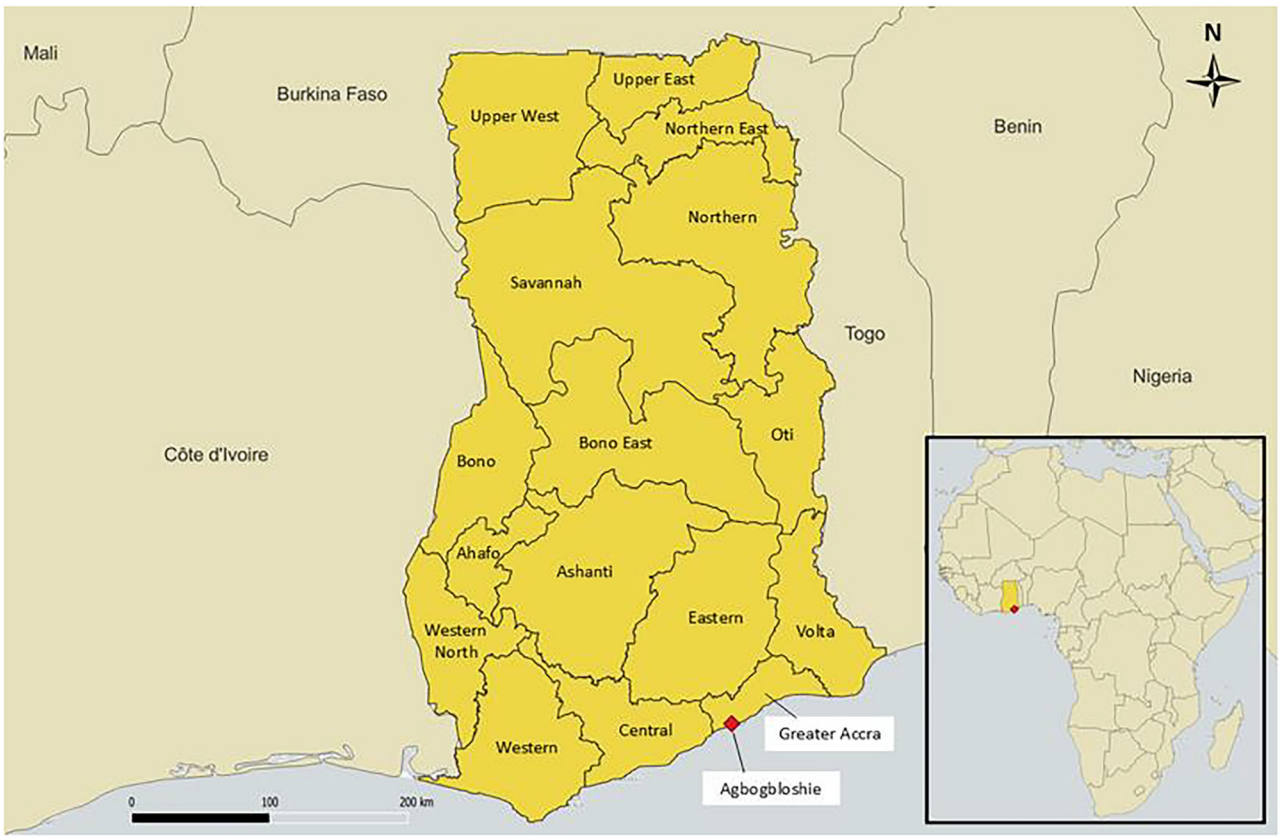

Fig. 1 | Location of Agbogbloshie in Accra, Ghana. This map provides geographic context for the study site within the Accra Metropolitan Area. It was created by the authors in QGIS using openly available administrative boundary data (world and Ghana boundaries, public domain). The location of Agbogbloshie is indicated with a red square.

decarbonization efforts. We hypothesize that the informal e-waste recycling sector exemplifies a broader global trade-off in decarbonization efforts, where the pressing need for critical minerals to support green technologies and global supply chains worsens public health and environmental conditions in areas of the Global South.

In Agbogbloshie, e-waste workers burn plastic casings to recover copper, solder metal over charcoal, and run diesel generators without emission controls, resulting in the presence of very high levels of fine particles ($PM_{2.5}$). For instance, recent studies[45,46] have shown that these workers inhale average $PM_{2.5}$ concentrations of 80–100 μg/m^3 (nearly five times the WHO 24-h guideline) and experience peaks above 200 μg/m^3 during burning tasks. E-waste workers face higher risks of cardiovascular disease[47], disproportionately adverse respiratory health outcomes, and nervous system damage as a result of particulate matter exposure in Agbogbloshie[48]. Despite these hazards, populations in places like Agbogbloshie and Old Fadama continue to grow, as the economic opportunities offered are vital for survival, forcing workers to navigate a precarious balance between livelihood gains and long-term exposure to toxic waste.

Fig. 2 | E-waste site and adjacent informal settlement in Agbogbloshie. This figure shows a photograph taken by the first author during fieldwork in 2023. The image depicts the electronic waste (e-waste) scrapyard in the foreground and the informal settlement in the background, highlighting the close spatial proximity of residential structures to areas where informal e-waste recycling occurs.

We hypothesize that informal economic activities, housing, and governance systems—both locally and internationally—play a central role in mediating the inequalities embedded in decarbonization supply chains. These informal structures sustain the Global South's critical role in meeting the resource demands for decarbonization while deepening vulnerabilities and perpetuating unequal economic and environmental burdens. To test our hypotheses, we demonstrate how urbanization and exposure to air pollution are related in and around Agbogbloshie and how e-waste activities simultaneously expose residents and workers to livelihood opportunities and social and environmental harm. This work brings needed attention to the overlooked human and environmental costs of global supply chains at the end of product life cycles. By centering a site deeply entangled in the circular economy, we highlight how informal communities in the Global South absorb the burdens of sustainability transitions while remaining largely excluded from their benefits. These dynamics are not isolated but emblematic of broader patterns in cities facing similar pressures worldwide.

Results

To test the hypothesized trade-offs associated with e-waste work and urban settlement in Agbogbloshie and Old Fadama, we measured the correlation between urban demographic growth in the region and $PM_{2.5}$ concentrations between 2000 and 2020. Our analysis reveals that demographic growth, driven by the need for housing and economic opportunities, coincides with

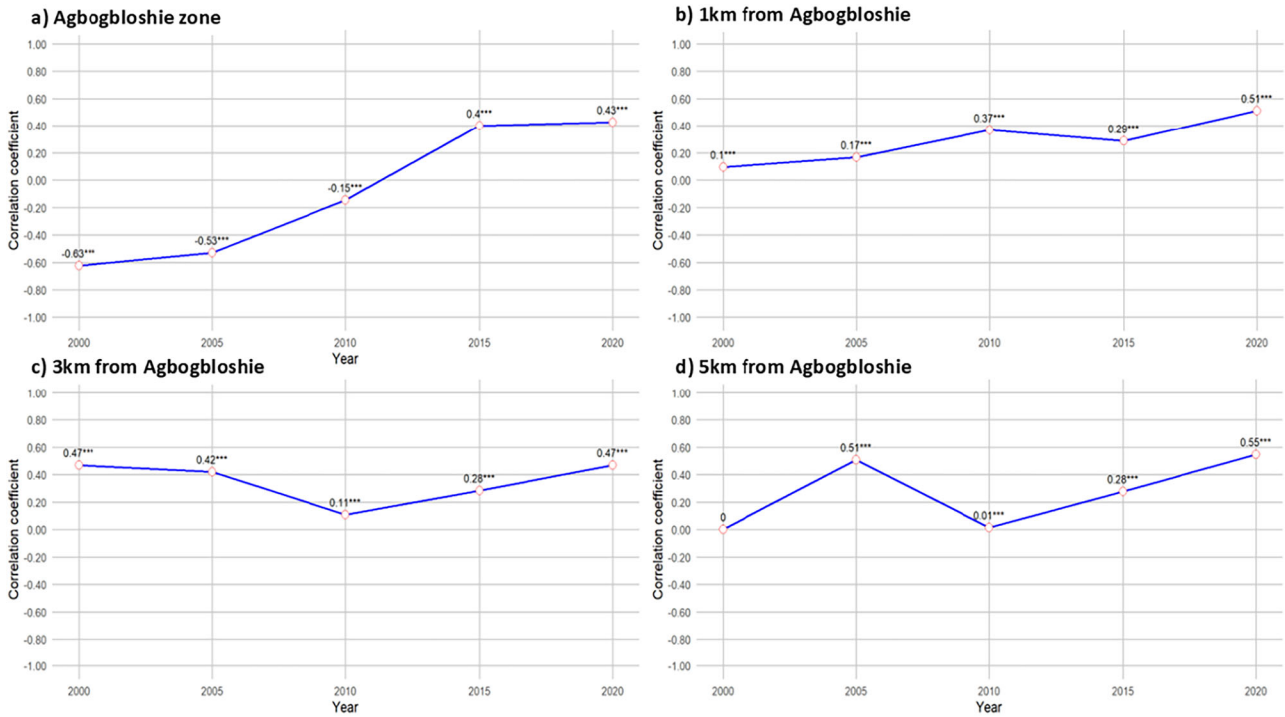

Fig. 3 | Correlation between population density and concentrations of fine particulate matter smaller than 2.5 microns in diameter ($PM_{2.5}$), 2000–2020. This multi-panel figure presents Spearman correlation coefficients between population density and $PM_{2.5}$ concentrations across Agbogbloshie and surrounding zones. Statistical significance is indicated with asterisks, where a single asterisk represents $p < 0.05$, double asterisks represent $p < 0.01$ and triple asterisks represent $p < 0.001$. The figure demonstrates that population growth is increasingly associated with higher $PM_{2.5}$ concentrations near the e-waste site.

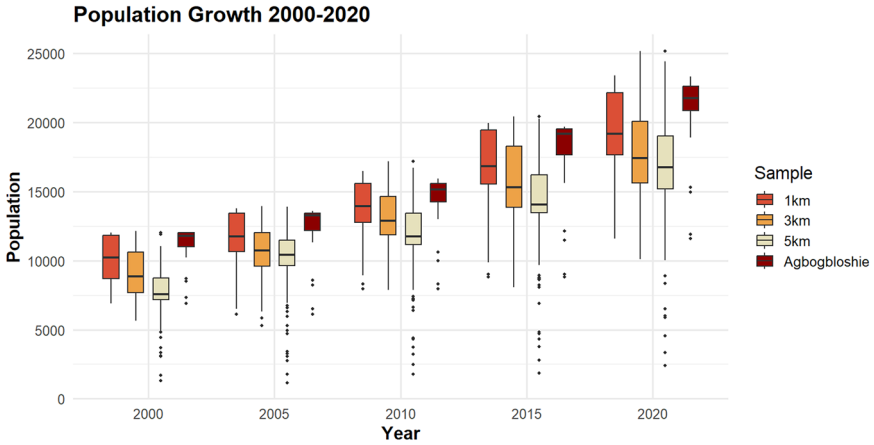

Fig. 4 | Population growth across Agbogbloshie and surrounding zones, 2000–2020. This graph illustrates population growth across four concentric zones: Agbogbloshie (dark red), 1 kilometer (red), 3 kilometers (orange), and 5 kilometers (beige). Population estimates were derived from the WorldPop dataset and processed in QGIS. The figure shows that all zones experienced steady population growth over the two-decade period, including within Agbogbloshie itself.

worsening environmental conditions, as reflected by rising $PM_{2.5}$ levels linked to e-waste processing (Fig. 3).

Opportunity and toxicity

Figure 3 shows a clear temporal increase in the correlation between population counts and $PM_{2.5}$ concentrations within Agbogbloshie and its surrounding zones. In Agbogbloshie, the relationship shifts from negative in 2000 to strongly positive by 2020, reflecting increasing population density despite worsening air quality (Fig. 3a). A similar upward trend is observed in the zone 1 km from the Agbogbloshie area, indicating that population growth continues close to e-waste processing activities (Fig. 3b). In contrast, correlations in the 3 km and 5 km zones remain consistently positive and statistically significant throughout the study period, suggesting a more stable dynamic further from the e-waste epicenter (Fig. 3c, d). This trend is further substantiated in Fig. 4, which shows a consistent increase in population across all spatial zones, including Agbogbloshie. Despite rising pollution levels, settlement density continues to grow. While informal e-waste operations significantly contributed to an increase in $PM_{2.5}$, it is worth acknowledging that it is not the only cause, as pollution from vehicular traffic and poor waste management practices remain major contributors[49]. These findings highlight the complex trade-offs between economic opportunity and exposure to environmental hazards in rapidly urbanizing regions.

We conducted qualitative interviews with 55 respondents to understand what drives people's decisions to engage in e-waste recycling activities and assess the trade-offs between economic opportunity and toxicity. The qualitative responses focused on the lived experiences of the people working in this informal sector and/or living in the informal settlements adjacent to it. The e-waste sector, comprising collection, transportation, and treatment, presents different risks to workers. Interviews indicate that the collection primarily involved young males who justified this practice due to the physical strength required to collect or scavenge e-waste across neighborhoods over several days. The e-waste treatment stage, which involves sorting, dismantling, shredding, burning, repairing, and refurbishing, is also predominantly staffed by young males. However, older males and some women are also involved, with the main risks being exposure to pollutants and physical harm due to inadequate protection. Longer-term residents, who often have shops at the e-waste site, are more likely to be involved in the treatment of e-waste than in collection, compared to recent residents. Interview responses add subjective details to the trade-offs identified in our statistical analysis and largely explain the motivation for the steady population increase.

While long-term environmental, health, and human outcomes are fundamentally worsened by life and work at Agbogbloshie, interviewees pointed out that a lack of economic opportunities elsewhere makes e-waste work beneficial and preferable to chronic vulnerabilities such as hunger and absolute poverty. This finding mirrors previous work[1], where communities know they are being exposed to conditions that may be toxic over the long term, but that chronic health risks are a less important factor than meeting one's immediate survival needs. Respondents framed their work in Agbogbloshie as preferable to the alternative options in the regions they had migrated from, typically but not exclusively from northern Ghana.

Long-term costs and livelihood creation

A consistent and generalizable tension is associated with urbanization and informal settlements, wherein people incur long-term costs to support immediate survival. Agbogbloshie's informal economy enables people to save small amounts of money to send to their families living elsewhere. It offers, however complicated, perhaps the only means of upward economic mobility for residents. For instance, a 19-year-old male stated that e-waste work enables him to work freely because he understands the business:

> *'I can gather metals and sell them to bigger companies. After that, I can feed myself and send money to [my] family'.*

Workers are exposed to harmful chemicals in lithium-ion and lead car batteries, and some showed the interviewers evidence of chemical and fire burns resulting from their past work. Speaking on the dangers inherent within the informal e-waste industry and the mastery that comes after years of repeating the same tasks, a 34-year-old male respondent who works as a scrap metal buyer commented that:

> *'the hunter does not fear guns, the same way we don't fear the weapon we work with'.*

This quote captures some of the tensions of fieldwork uncovered at the Agbogbloshie and Old Fadama sites. People utilize the informal economy and informal housing for rational personal and professional reasons, even if these modes of urban life carry particular acute and long-term dangers and hazards. However, the ongoing e-waste recycling and burning create a toxic environment for everyone working and living in the area, as well as across the city. A 19-year-old female who works selling beverages to the community commented that it is:

> *'tough to work here. I face many challenges, like when men try to take advantage of me or the smell in the air. It makes me cough so much. I am not sure if it is asthma or the air.'*

E-waste operations have important cultural and gender dimensions. Many male spouses request or insist that their female partners not participate in e-waste activities because of society's ridicule of female workers,

associated health challenges, increasing household demands on women, and the generally high-intensity nature of the e-waste operations. Women face gender discrimination in Agbogbloshie, and pregnant women face extreme vulnerability to toxic exposure at and near e-waste sites[50].

The salience of informality

Informal economic processes enable the e-waste circular economy in Ghana. In Agbogbloshie and Old Fadama, e-waste workers are pathologized and complain of being viewed as unwanted and a drain on Ghanaian society. A 26-year-old male stated that:

> *'here, we work hard, do what we can. There is nobody to support us, we are treated like we are not wanted and must find something different. But what?'*

Interviews with e-waste workers show that the highly informal and precarious nature of their activities has led to a deficiency of government support and resources and a lack of recognition of the complex environmental and health risks associated with their operations, as well as a public perception that they are responsible for environmental hazards in the city of Accra. As a result, residents and workers continue to face inadequate and sometimes harmful regulations and deplorable working conditions.

This occurs despite their importance to the critical mineral circular economy, which feeds back into global supply chains. Interviewees challenged this narrative, pointing out how their work enables economic activity and e-waste processing that would otherwise not occur in Ghana without it being done informally. A 20-year-old male working in e-waste metal separation argued that:

> *'our business is important to the country as a whole because it contributes to the economic growth of the country. The government does not recognize our contribution'.*

Informal housing has proliferated near the e-waste site as people migrate to Agbogbloshie and Old Fadama (see Fig. 2). The informal settlements' residents generally lack formal tenure and spoke of enduring substandard infrastructure conditions. Of the non-expert respondents, 85% said they would benefit from improved housing conditions. Meanwhile, 63% felt mistrust of city authorities, citing the fear of eviction or the lack of municipal involvement in infrastructure, sanitation maintenance, and development.

Informality provides the means and structure for the recovery and valorization of waste in Agbogbloshie and Old Fadama. It is central to the proliferation of the circular economy for minerals in Ghana, but it needs more regularization and professionalization. About 73% of interviewees acknowledged how constraints on capital impact their ability to expand their operations, making working conditions less stable. Informal scrap dealers in Agbogbloshie work by buying and selling car batteries, condemned cell phones, refrigerators, old car parts, and other electronic materials to individuals looking to buy them in bulk. Most (55%) respondents mentioned not knowing precisely what bulk buyers do with the metals and lithium-ion batteries they recover and sell, how these items are treated, or where they end up after they have been purchased.

Discussion

Across the Global South, upward mobility is often only available to vulnerable populations through the informal economy, which offers lower market entry barriers. On the other hand, informality also enables the transnational flow of inequalities and the exporting of negative externalities to the Global South. Informal processes mean that e-waste can be dumped in Ghana without sufficient regulation, with the parties responsible for the flows in and out of the goods bearing little to no responsibility. Informality is entangled in the extreme levels of toxicity in Agbogbloshie and Old Fadama because of a lack of regulation and policy oversight. Environmental pollution is severe in the region and will only worsen unless interventions tackle the unregulated global practices of e-waste management, dumping, and processing.

Our findings demonstrate the tensions in the global shift toward decarbonization and its entanglement with informality in the Global South. Informal e-waste processing and recycling present upward mobility opportunities to vulnerable populations as they migrate to cities like Accra in search of work. It also creates severe and long-term challenges, principally through embedding social and environmental toxicity at the heart of the circular economies upon which decarbonization initiatives are advanced. Consequently, informal workers and residents breathe the toxic fallout of these supply chains, trading their long-term health for the raw materials that power the world. They bear the hidden human cost of circular supply chains that are not just.

Despite their frequent lack of oversight, city authorities have an essential impact on the informal processes present at Agbogbloshie. Respondents consistently complained of a city demolition campaign at the e-waste site in 2021, where thousands of informal housing structures were destroyed, and e-waste workers were displaced from their employment sites without consultation. Residents decried the displacement because it led to a loss of income, disrupted important relationships necessary for the efficient functioning of the e-waste supply chain, and moved e-waste processes into a more confined area.

If attempts to implement policy or regulation at the Agbogbloshie e-waste site are to be successful, they must start by understanding the centrality of informality to all processes at, near, and beyond the site. Despite the essential social and economic functions of informality, it also complicates how we understand the interaction between governance and global production networks, which take products from their end-of-life stage and reincorporate them into global supply chains. Informal systems are often complex and challenging to trace. The informality embedded in economies, settlements, and governance regimes makes the codification of information incredibly challenging[51]. The opacity of these systems ultimately undermines the capabilities of suppliers (e-waste workers) to pursue recourse and occupational protections. This inhibits e-waste workers from mobilizing the value of their labor at this 'final' stage of the supply chain and exacerbates its negative sustainability and health-related externalities.

Our research reveals that informal processes significantly challenge orthodox industrial ecology and urban sustainability approaches. Resolving these issues remains a largely unexplored realm of research. The circular economy of e-waste relies on informality through its multiple forms. On the one hand, e-waste items are shipped to and imported into Ghana without being fully tracked and registered[18,19]. This is partially due to the mislabelling of exports from countries worldwide, and partly to opaque official processes that lack transparency among Ghanaian officials. This makes it difficult to track how much e-waste is imported into Ghana. Similarly, once the e-waste is processed, informality prevents transparent records of the minerals exported from Ghana. These exports then return to the formal supply chains that underpin decarbonization. Scholars have drawn attention to Agbogbloshie and Old Fadama's vital role in sustaining the livelihoods of many and providing a relatively cheaper residential option, particularly for migrants. Yet, there remains limited government attention and support for these communities[52,53].

To resolve these tensions, it is essential not to resort to simplistic interventions that either underestimate the salience of informality to e-waste processing or pathologize the people living in Agbogbloshie and Old Fadama. It is equally important not to underestimate the human and environmental vulnerability embedded in the informal e-waste business. Our findings point us to advocate a governance middle ground on informality when dealing with the informal paradox in practice. This middle ground is sensitive to the imperative of enhancing the codification of information and data to enhance transparency and reduce the complexity of information related to informality.

Such a middle ground could constitute private and public initiatives that incentivize transparency at the point of sale of e-waste in Agbogbloshie. Our findings identified and interviewed larger-scale scrap dealers (intermediaries) as the 'point of inflection' between formality and informality in the e-waste industry. These dealers should be required to record the weight and amount of metal purchased from each e-waste worker. The amounts paid for each transaction should be recorded, and the individual trader should also be identified.

The success of a middle-ground policy would depend on acknowledging and understanding the informal paradox outlined in this paper. Without informal e-waste work, many people would lose their only livelihoods. However, the informal nature of e-waste work undermines long-term social and environmental outcomes in and beyond Agbogbloshie. To resolve these issues, new approaches must bring together different stakeholders, such as Ghana's Environmental Protection Agency, which could co-develop certification schemes with local communities in Agbogbloshie and non-governmental organizations in the region. The Accra Metropolitan Assembly is the central planning agency for Ghana's capital city, and it has had a historically antagonistic relationship with Agbogbloshie's workers and residents because of previous demolitions of the area[54]. These two parties, however, would function much better if their interactions and goals were aligned through a middle-ground approach that prioritizes working with and advancing the health and well-being of extant informal groups and communities.

Government regularization strategies could go beyond simple demolition and eviction strategies and incentivize individual e-waste workers to register their work with the government, enabling them to have a permit as registered informal e-waste workers. This permit should require minimum standards of work on-site. Such standards could include wearing protective equipment and abiding by e-waste best practices that exclude harmful acts like burning and dumping non-valuable e-waste into open pits or the nearby lagoon. E-waste workers may be incentivized to abide by this process because their transactions with large-scale scrap workers will be transparent and recorded, facilitating the trade of these goods at market rates. This will prevent individual e-waste workers from being undercut by larger-scale scrap yards, which our respondents complained did not deal transparently or equitably in their transactions[10].

Informal governance is an important yet under-theorized aspect of the inequalities created and sustained through supply chains. Intermediaries are one such example of informal governance at this scale. With most formal firms considering e-waste as a secondary activity, they rely on informal governance structures such as middlemen and intermediaries to accumulate recycled metals[26]. E-waste intermediaries are larger scrap dealers with more mechanized machinery that are better able to recycle in more substantial volumes. While informal governance provides opportunities and flexibility for e-waste workers to operate and increase production, knowing that there is an available market, it also presents challenges in relation to fair pricing, record keeping, and enforcing safe working environments. For example, intermediaries were unwilling to disclose the details of their suppliers (typically e-waste workers in Agbogbloshie). They did not keep a record of who they purchased their materials from. They disclosed that, after processing, they exported their materials to companies in Lebanon, India, and China, but did not have publicly available documentation codifying these transactions. Government agencies such as the Council for Scientific and Industrial Research (CSIR) have begun initiatives to purchase e-waste recycled output from workers at Agbogbloshie. Respondents complained that CSIR did not offer market-rate prices and that the transactions were undesirable because they lacked trust and ease. Prices also change without explanation or transparency from intermediaries.

Given the salience of informality to e-waste management specifically and decarbonization more generally, we encourage government agencies to improve the transparency of e-waste imports and exports, with documentation publicly accessible and available. More accountable and transparent actions in Agbogbloshie and Old Fadama will help third-party actors ensure consistency between the imported e-waste and the recovered minerals exported from the country.

This complex context of informal e-waste operations is further entwined in government policy ineptness. The government of Ghana has a top-down management approach toward formalizing e-waste via the E-Waste Management Bill to ban the importation and exportation of e-waste[26]. However, the bill is limited by its support for the Basel Convention, which allows conditions for the importation of hazardous waste. The government empowers public authorities with search, seizure, and arrest powers to ensure closure of sites for hazardous waste disposal[55]. This vague policy environment further legitimizes and complicates the persecution and vulnerability of informal waste workers, compounding city authorities' hostility toward them[26].

Our qualitative findings demonstrate that e-waste workers and members of the informal settlements feel that government agencies prefer to sweep their issues aside, thereby facilitating the global trade of e-waste and the export of toxicity to the Global South without repercussion or accountability. Despite this, almost every respondent affirmed that working in the informal e-waste industry was more profitable than other work they could access in Accra.

While our study offers new insight into the relationship between urban growth and air pollution in Accra's informal e-waste hub, it has important limitations. We relied on globally available satellite and modeled data, which, while robust for trend analysis, cannot capture fine-grained variation in burn intensity, housing ventilation, or infrastructure conditions. These factors likely play a major role in shaping local exposure but require field-based environmental sampling and spatial inventories to assess. Future research should build on this work by incorporating site-specific measurements, activity mapping, and air dispersion modeling to better understand the mechanisms driving $PM_{2.5}$ exposure in and around Agbogbloshie.

Future research will also benefit from employing mixed-method approaches to investigate diachronic changes, thereby better understanding the driving forces behind these transformations and linking this phenomenon to governance, decision-making, and e-waste flows. For instance, the ever-growing demand for commodities from affluent nations has shaped distant landscapes for decades. Since informal settlements are often unaccounted for in national surveys and official censuses, socio-economic aspects, migration flows, and other essential variables are often not sufficiently recorded. Systematic fieldwork and physical audits are required for collecting population-related data. This, in turn, will be integrated with remotely sensed variables to monitor and quantify changes over time. Future scholarly work may aim to improve the data of the informal settlements surrounding Agbogbloshie, with particular attention to longitudinal geocoded socio-economic and demographic data, which needs improvement. Other lines of research would benefit from building on nascent efforts[28,29] to measure informality through novel industrial ecology approaches that track the flows of materials into and out of a given system.

Informality has become the means of dealing with e-waste in Ghana and across many cities in the Global South[56–58]. Informality is also the bedrock upon which people can maintain livelihoods and establish housing for themselves and their families in informal settlements[59]. Informality is pervasive across governance scales, which mediate the flows of e-waste, the regulation of e-waste workers, and urban development in the area.

Our deep learning and remote sensing methods prove a positive correlation between urbanization and increasing $PM_{2.5}$ levels over 20 years. These methods also indicate greater exposure to $PM_{2.5}$ levels broadly across Accra between 2000 and 2020. Our qualitative data demonstrate that people living and working in the area choose it because it enables economic opportunity despite the toxic and worsening environmental conditions. We identify Agbogbloshie's circular economy and the area's informal settlements as directly related to global decarbonization. Our mixed methods approach shows that these supply chains' end-of-life stages build on land use, urbanization, and public health inequalities, just as they do at the start of

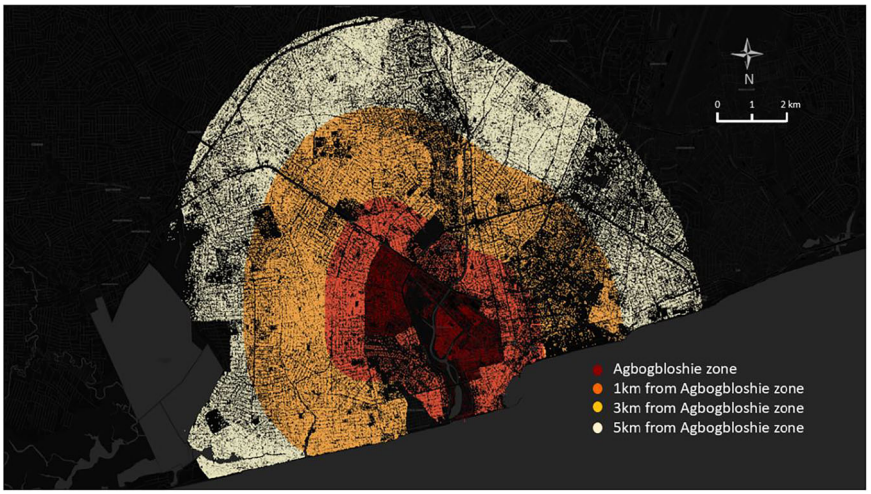

Fig. 5 | Building footprint sample used in the analysis. This map presents 198,048 building footprints extracted from the Open Buildings dataset (© Google/Open Buildings, licensed under CC BY 4.0) within Agbogbloshie and the four concentric zones. Building footprints are shown as dark red points for Agbogbloshie, red points for the 1-kilometer zone, orange points for the 3-kilometer zone, and beige points for the 5-kilometer zone. The data were processed by the authors in QGIS.

mineral supply chains. The paradox of informality plays out on the ground in Ghana, but results from complex economic and political tensions across local and global scales.

Methods

We adopted a sequential research design for this study. In-depth and purposive interviews were conducted first to inform our understanding of local perceptions, motivations, and hypothesized trade-offs between economic opportunity and exposure to toxicity. Insights from the qualitative stage guided the geospatial and statistical correlation analyses, which linked population growth and $PM_{2.5}$ concentration over time and across zones.

Qualitative methodology

Primary data for this study were collected over three weeks in May 2023 in Accra, Ghana. In total, 55 interviews were conducted – 40 with e-waste workers and community members in Agbogbloshie and Old Fadama, and 15 with industry experts in Accra. We adopted a purposive sampling technique, with all respondents working and/or living in the Old Fadama and Agbogbloshie areas. All respondents were between 18 and 55 years old. Of the 40 non-expert interviewees, 33 men and seven women were interviewed, and snowball sampling was used to recruit respondents. Interviews were conducted in both English and Twi, the local language, depending on the participant's preference.

We conducted fifteen expert interviews at the University of Ghana, the Accra Metropolitan Assembly, and the Council for Scientific and Industrial Research—Ghana. Experts were included in the sample based on their research and/or working experience in fields such as e-waste recycling, city planning, and Accra's development policy. The authors attained exemption from the Institutional Review Board office at the University of Michigan (HUM00233020). Informed consent was obtained from each participant included in the sample. Interview field notes and transcriptions were analyzed in the NVivo software package, where emergent themes were coded. Two independent coders engaged with the translated and transcribed text to establish intercoder reliability, before the research team reviewed the emergent themes. We used Braun and Clarke's[60] six-part methodology to adopt the thematic analysis. We read the field notes before categorizing initial themes and discussing and comparing the results. The main themes were formally agreed upon before the 'findings' and 'discussion' sections were developed.

Geospatial analysis

We employed the time slider tool in Google Earth to observe historical land changes surrounding Agbogbloshie. This tool provides access to a long historical RGB optical satellite imagery archive from key commercial data vendors such as Maxar and Airbus, allowing us to visually delineate the Agbogbloshie zone and inspect changes over 25 years. We employed a time-series of high-resolution population counts[61] alongside $PM_{2.5}$ concentration data[62] covering the period 2000–2020 in 5-year increments. The $PM_{2.5}$ dataset, derived from satellite observations and atmospheric modeling, is globally validated and well-suited for assessing long-term exposure trends.

We compiled all data within a GIS environment, sampling population, and $PM_{2.5}$ layers at the location of each building to generate datasets for further statistical analysis. To test our assumption, we analyzed the relationship between population counts and $PM_{2.5}$ concentration over four zones: the Agbogbloshie zone, 1 km from Agbogbloshie, 3 km from Agbogbloshie, and 5 km from Agbogbloshie (Fig. 5). To concentrate only on samples within the urban fringe, we extracted building footprints from the Open Buildings dataset[63] and converted them to centroids. Since the building footprints are a modeled product, we filtered out data with less than 75% confidence. Given that this dataset is not longitudinal, we used it solely for sample extraction, ensuring a focus on built-up areas, excluding vegetation, water bodies, and bare land. For the Agbogbloshie zone, our sample consists of 13,019 buildings; for the 1 km zone, 22,878 buildings; for the 3 km zone, 70,580 buildings; and for the 5 km zone, 91,571 buildings (Fig. 5). Next, we calculated Spearman correlation to assess monotonic trends between population growth and $PM_{2.5}$ concentrations without assuming linear relationships or normal distribution. Given that our analysis used discrete building-level samples without interpolated surfaces or spatial models, spatial autocorrelation diagnostics were not applied.

Data availability

$PM_{2.5}$ concentration levels were used from an open-source database: Shen et al.[62]. Building footprints were extracted from the following source: Sirko et al.[63]. Population count data for Ghana were made available from WorldPop: WOPR (https://wopr.worldpop.org/?GHA/). The data supporting this study's findings are available upon reasonable request from the authors.

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Author contributions

B.M.F.: Conceptualization, Funding acquisition, Investigation, Fieldwork, Qualitative Data Curation, Writing—Original Draft, Writing—Review & Editing. P.B.C.: Conceptualization, Investigation, Qualitative Data Curation, Writing—Original Draft, Writing—Review & Editing. D.G.: Conceptualization; Investigation, Quantitative Data Curation, Writing—Original Draft, Writing—Review & Editing

Competing interests

The authors declare no competing interests.

Additional information

Correspondence and requests for materials should be addressed to Brandon Marc Finn.