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RESEARCH ARTICLE OPEN ACCESS

Advancing Sustainable Development in the Ghanaian e-Waste Sector: A System Dynamics Perspective

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Correspondence: Svenja Klose (svenja.klose@tum.de)**Received:** 26 February 2025 | **Revised:** 21 May 2025 | **Accepted:** 19 June 2025**Funding:** This work was supported by Technische Universität München.**Keywords:** causal loop diagram | e-waste | Ghana | informal sector | system dynamics

ABSTRACT

Ghana is a major e-waste treatment hotspot in the Global South, dominated by the informal sector (IFS). There, sustainable development goals (SDGs) like good health and well-being, no poverty, or sustainable communities remain an area of concern. Therefore, the present study aims at contributing to sustainable development in the Ghanaian IFS. To do so, for the first time, we apply the system dynamics methodology to the Ghanaian e-waste context. The center and strength of the study is a causal loop diagram (CLD) which was developed in a participatory process with stakeholders on-site. The CLD shows how none of the goals stands alone but is embedded in a dynamic relationship with other goals and with the actors and proposed measures in the system. The CLD can be used as a map when designing measures to understand potential consequences for actors and concurrent goals and measures.

1 | Introduction

The rising production and consumption of electronic goods, as well as their uncontrolled disposal, represent both a prevailing trend and one of the most significant global challenges (Baldé et al. 2024). According to the Global E-waste Monitor, the world generated 62 million tons of electrical and electronic waste (e-waste) in 2022—an average of 7.8 kg per capita—which is projected to grow to 82 million tons by 2030 (Baldé et al. 2024). This development can be attributed to increased economic growth, urbanization, and consumption of electronic devices due to the digitalization of everyday life (Hinchliffe et al. 2020; Jain et al. 2023; Narkhede et al. 2024; Shahabuddin et al. 2023). Within this global context, the countries of West Africa are under particularly strong pressure as, apart from the locally

generated e-waste, considerable amounts of non-functional devices are imported while being declared as “used” electrical and electronic equipment (EEE) and thus circumventing the legal framework set by the Basel Convention (Odeyingbo et al. 2017; Schlupe et al. 2012). It is estimated that only 0.7% of the e-waste in Africa gets formally collected and recycled, although e-waste is considered hazardous waste due to the toxic substances such as heavy metals and flame retardants it contains (Baldé et al. 2024). Thus, the vast majority (90%–95%) of e-waste treated in countries of the Global South is handled by the informal sector (Bimpong et al. 2024). In particular, Ghana with the cities of Accra and Kumasi as major e-waste hubs faces major implications for humans and the environment as the informal sector is characterized by high health risks for workers and neighborhoods, poor working conditions and emissions into

Abbreviations: CLD, causal loop diagram; EEE, electrical and electronic equipment; EFET, environmentally friendly e-waste treatment; EFTec, environmentally friendly technologies; e-waste, electrical and electronic waste; EwT, e-waste treatment; F&R, formalization and regulations; FS, formal sector; IFS, informal sector; PPE, personal protective equipment; ScD, scrap dealer; SD, system dynamics; SDG, sustainable development goal; WEEE, waste electrical and electronic equipment.

Vanessa Heinrich and Svenja Klose shared first authorship.

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soil (e.g., heavy metals), water (e.g., acids, nanoparticles), and air (e.g., SO₂, NO_x) (Grant and Oteng-Ababio 2019; Kyere 2016; World Health Organization 2021). Despite the severe health effects and the economic insecurity of the business resulting from the vulnerability to market fluctuations and disruptions, the valuable materials recovered from e-waste recycling provide the livelihoods of actors such as scrap dealers, collectors, dismantlers, and recyclers (Hinchliffe et al. 2020; Schluep 2014). In the context of sustainable development the situation in Ghana is connected to a plethora of the UN sustainable development goals (SDGs), for instance, SDG 1 (no poverty), 3 (good health and well-being), 6 (clean water and sanitation), 8 (decent work and economic growth), 12 (responsible consumption and production), and 13 (climate action). Altering the situation in Ghana, therefore, will have an impact on the achievement of those goals. Measures that may influence the goals include for instance the formalization of the IFS, the provision of a constant income for workers (thus preventing a slipping off underneath the poverty line), fostering safe e-waste treatment practices to increase health and well-being, and reducing emissions from treatments into soil, water, and air. This article includes those and other aspects of the SDGs and investigates their interaction in the Ghanaian e-waste treatment sector.

1.1 | Literature Review and Problem Statement

Since the rapid development of the EEE industry in the last century, fueled by mass production, standardization and decreased prices, e-waste began to accumulate at a noticeable level (Barapatre and Rastogi 2022). In parallel, the research field around e-waste started to evolve reflecting growing environmental, health and economic concerns. Previous, primary research studies often have a narrow focus on a particular sub-topic of the

e-waste ecosystem, as summarized in Table 1. One of the topics that has received strong attention in research is the health and occupational safety of e-waste workers. Systematic reviews from China and Africa reveal that informal e-waste recycling exposes workers and nearby communities to hazardous substances, resulting in serious health risks (Grant et al. 2013; Orisakwe et al. 2019). In China, epidemiological studies report DNA damage, impaired lung and thyroid function, negative birth outcomes, and cardiovascular diseases resulting from heavy metal emissions (Awasthi et al. 2018; Grant et al. 2013). Behavioral and neurodevelopmental effects were also observed. Research in African contexts highlights similar threats. Exposure to toxicants such as heavy metals and dioxins in water, air, soil and food has been associated with respiratory problems, hormonal disruptions, miscarriages, and cancer (Orisakwe et al. 2019). These findings underscore that both direct e-waste handlers and the general population, including future generations, are at risk.

Given the severity and far-reaching nature of these risks and the narrow focus of previous research, a holistic analysis of the system is essential. However, only a few researchers take this approach, considering the interdependencies between the different goals, influencing factors, and stakeholders. Those who adopt such a system dynamic's perspective focus their investigations on India (Dasgupta et al. 2017; Jayaprakash and Pillai 2016), Brazil (Teófilo and Bergiante 2024), China (Miao et al. 2020; Xue et al. 2018), and Indonesia (Attazahri et al. 2021; Hutami et al. 2020; Kemal and Ardi 2022). These studies consistently highlight the interdependence of economic, regulatory, and environmental factors. In India, for instance, simulations show that the informal sector will increasingly dominate recycling, though this raises health and environmental risks if left unregulated (Dasgupta et al. 2017). In Brazil, Teófilo and Bergiante (2024) model feedback loops illustrating how fast

TABLE 1 | Selection of e-waste research areas and key topics.

Research areas	Key topics	Examples
Environment	Pollution Life Cycle Assessments (LCAs)	Awasthi et al. (2018), Ismail and Hanafiah (2021)
Health and occupational safety	Effects of toxins on health Occupational hazards and measures	Grant et al. (2013), Orisakwe et al. (2019)
Recycling technologies and material recovery	Mechanical and chemical recycling Challenges of complex materials	Hossain and Sahajwalla (2024), Yao et al. (2018)
Policies	WEEE Directive, Basel Convention EPR schemes	Leclerc and Badami (2020), Patil and Ramakrishna (2020)
Economy	Market trends in e-waste trade Economic feasibility of formal recycling	Cottes et al. (2023), Petridis et al. (2020)
Society and ethics	Exploitation of workers Ethical considerations	Kelbessa (2023), Kirby and Lora-Wainwright (2015)
Consumer behavior and education	Barriers to recycling Factors influencing consumer choices	Islam et al. (2021), Thukral et al. (2023)
Technology and innovation	Eco-design and modularity AI and robotics in e-waste sorting	Banerjee et al. (2024), Lu et al. (2022)
Digital transformation	Block chain for tracking flows Digital platforms for linking stakeholders	Khan and Ahmad (2022), Sahoo et al. (2021)

device obsolescence and poor disposal drive e-waste growth, while also offering opportunities for urban mining and circular strategies. Miao et al. (2020) demonstrate how in China, coordinated manufacturer-retailer recycling models can improve collection efficiency and reduce price-driven losses. Finally, Kemal and Ardi (2022) show that in Indonesia, regulatory gaps, especially around funding responsibilities, hinder effective management, suggesting that a clear funding scheme policy is essential for improvement. These findings underscore the value of system dynamics approaches in uncovering the complex cause-effect chains shaping e-waste management. They emphasize that sustainable improvements depend not only on technological solutions but also on enabling institutional arrangements, economic incentives, and regulatory clarity. The observed regional differences also point to the need for context-sensitive policies and greater attention to under-researched regions such as Africa, which remains largely overlooked in systems dynamics research despite its pivotal role in international e-waste management (Baldé et al. 2024).

Additionally, several of the studies discussed above research the field of e-waste generation, recycling, and disposal (Kemal and Ardi 2022; Puzzo and Prati 2025; Teófilo and Bergiante 2024; Xue et al. 2018), omitting the implications of the systems' informal nature. Especially informal systems are characterized by highly dynamic structures which contribute to their complexity and sensitivity, and emphasize the need to understand the effects of measures interfering with the system (Harfadli et al. 2024; Wang et al. 2022). This is particularly important to evade undesirable and unforeseen impacts that influence the involved actors negatively and enhance the prediction accuracy of future scenarios. Only if these relations are integrated in current research, decision makers can elaborate tailored measures and programs to successfully tackle environmental and social challenges associated with the informal e-waste sector and enable its smooth transition toward more ecological and social sustainability (Harfadli et al. 2024).

E-waste provides an important source of livelihood for the involved workers and their families (Amankwaa 2013; Oteng-Ababio 2012). While direct studies specifically examining the impacts of increased wages for e-waste workers are limited, a study conducted across five French-speaking West African countries found that insufficient income was significantly associated with higher levels of perceived stress among e-waste workers (Kédoté et al. 2022). The research indicated that workers with inadequate income were 1.46 times more likely to experience stress at work compared to those with sufficient income. Thus, increased wages might positively impact the health conditions and well-being of workers.

However, insights about further interdependencies, especially regarding effects of changes in the wage rate on environmental friendly and safe e-waste treatment (EwT) are lacking for the Ghanaian context. Also, formalization and legislative attempts to transform e-waste management often fail to succeed due to underlying, unconsidered interrelations as a clear root cause analysis is not performed and knowledge about the complex informal system is missing (ALqodsi 2025; Chen et al. 2020; Jangre et al. 2022). Therefore, central cause-effect-chains must be identified for efficient resource allocation especially in developing

countries with limited financial resources to maximize positive long-term impacts and contribute to informed decision-making.

This paper examines three key research gaps: (a) the lack of holistic, system-level analyses that capture the interdependencies across environmental, social, economic, and institutional dimensions; (b) the underrepresentation of African contexts, particularly in system dynamics research despite their relevance in international e-waste flows; and (c) the insufficient integration of informal system complexity, which is essential for understanding the potential impacts of designed measures.

1.2 | Objective of the Research

The primary goal of this study is to provide insights into the interplay of stakeholders and potential consequences of measures implemented, as identified through the development of a CLD based on input from a variety of stakeholders and sources. It intends to diminish negative environmental and social impacts resulting from EwT; thus, it aims to create a solid knowledge basis for decision makers to take efficient action and develop approaches toward further improving the current status quo.

In particular, we address the following main objectives within our study: (a) identifying the main actors and factors that shape the informal Ghanaian e-waste ecosystem; (b) understanding the impacts of health from EwT, emissions from EwT and living standard of scrap dealers (ScDs); (c) providing a dynamic hypothesis of the informal Ghanaian e-waste system behavior; and (d) understanding implications for the achievement of the SDGs and offering guidance for researchers and practitioners in shaping an environmentally and socially responsible e-waste sector in Ghana.

The scope of this study is limited to the informal e-waste sector within Ghana, focusing on local actors, processes, and consequences of e-waste treatment practices and interventions in Ghana. Imports of EEE as well as upstream aspects such as product design are excluded.

2 | Methodology

The methodological framework employed in this study is grounded in System Dynamics (SD), which models the intricate network of interactions among system elements, aiming to offer a comprehensive representation of the cause-effect mechanisms and feedback loops that shape system behavior (Sterman 2000). An overview of SD and its use of Causal Loop Diagrams (CLDs) as a qualitative tool to visualize feedback loops is provided in the following together with a description of the multi-step process used for building the final CLD version.

2.1 | System Dynamics and Causal Loop Diagram

SD has found applications in a variety of socio-economic and environmental fields such as renewable energy supply chains (Saavedra et al. 2018), transition of the automotive sector (Kieckhäfer et al. 2017; Walther et al. 2010), food system

sustainability (Amiri et al. 2020; Espinoza Pérez et al. 2024), and solid waste management (Berenjkar et al. 2021; Rafew and Rafizul 2021). These examples illustrate the versatility and efficacy of the SD methodology indicating its suitability for investigating the complexities of the Ghanaian e-waste management landscape.

Within SD, Causal Loop Diagrams (CLDs) offer a graphical representation of complex systems including their inherent causal connections and reciprocal influences, creating a dynamic hypothesis that reflects reinforcing and balancing loops driving the system behavior (Coletta et al. 2024; Sterman 2000). Given their intuitive nature, CLDs serve as a foundation for the involvement of relevant stakeholders in the development of the model, thereby promoting a “collective system understanding” (Coletta et al. 2021). Hence, as asserted by Mirchi et al. (2012), CLDs present the “conceptual modeling step” in applying SD. Among different fields, CLDs have been successfully applied in policy analysis, sustainable development, and natural resource management (Coletta et al. 2021, 2024; Groundstroem and Juhola 2021; Perrone et al. 2020; Roxas et al. 2019). Furthermore, in the West African context, Adebisi and Olabisi (2022) adopted a CLD to assess organic farming in Nigeria, while Olabisi et al. (2018) employed this method to assess climate risks in the region. However, in the field of e-waste in Africa only one CLD study focusing on the Central African country Cameroon could be identified, showing again the gap of research in this regard (Esopere et al. 2024).

In our study, we decided to focus on the thorough elaboration and validation of the CLD reflecting the current status of the Ghanaian e-waste ecosystem to enhance the understanding of the complex e-waste system and establish a solid basis for future quantitative modeling with the SD methodology.

Among the SD approaches, participatory system dynamics modeling (PSDM) involves relevant stakeholders in the iterative development of the CLD, enhancing a comprehensive understanding of the problem and leveraging on the integration between scientific expertise and stakeholders’ knowledge to capture the full complexity of a system more effectively (Perrone et al. 2020; Voinov and Bousquet 2010). Thus, PSDM is increasingly recognized for improving the accuracy and reliability of SD models by integrating directly involved stakeholders, thereby providing a stronger foundation to guide decision-making in complex and dynamic environments (Hedelin et al. 2017; Hubacek et al. 2017; Inam et al. 2015; Mirchi et al. 2012).

2.2 | The Multi-Step Process Adopted for CLD Development

Building on the principles of ST and PSDM (Coletta et al. 2024; Liebovitch et al. 2020), this study employed a multi-step, mixed-method approach to elaborate a CLD on the e-waste management system in Ghana which is described below and summarized in Figure 1. The essential data is gathered through observations, interviews and workshops during a period from 2023 to 2024 following the approach by Elsawah et al. (2017) for “knowledge elicitation”.

2.3 | Step 1: Pre-Study

The first step consisted of conducting an explorative field study in Ghana in December 2023. Participant observations in the field were performed as this qualitative technique serves as a well-suited method to get a first impression and an overview about the processes involved in informal e-waste management

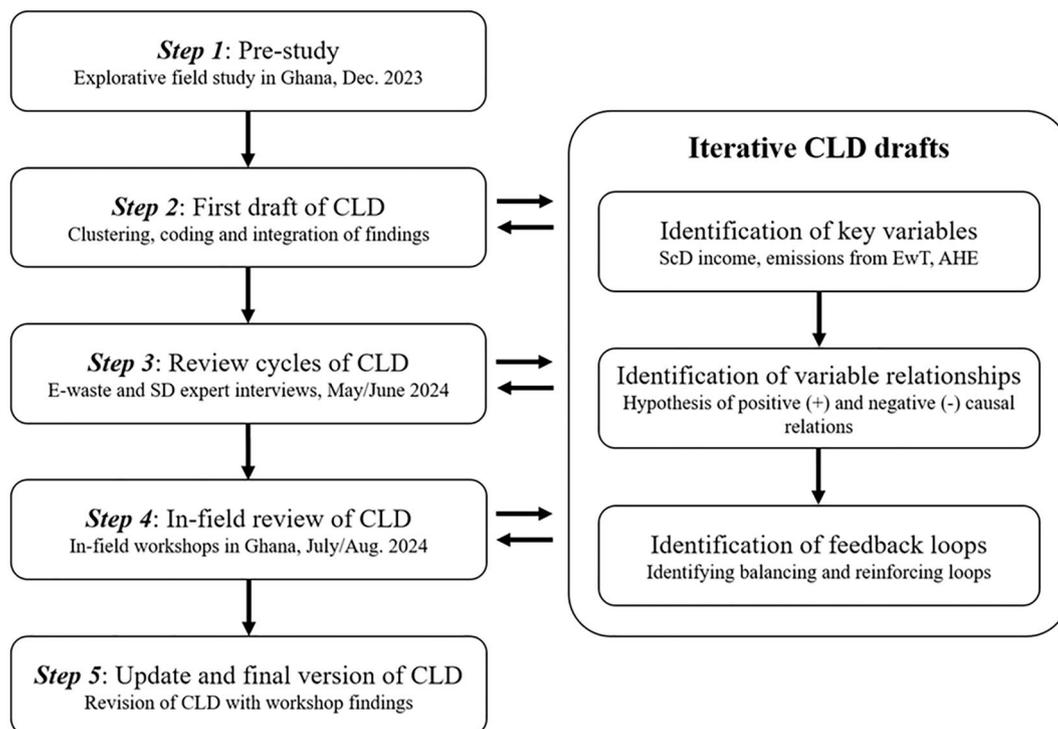


FIGURE 1 | Overview of multi-step process for modeling the CLD of the Ghanaian e-waste sector.

(DeWalt and DeWalt 2010). Local actors were accompanied in their daily routines across several collection and processing sites. The researchers maintained a non-intrusive role, engaging in informal conversations while observing activities to facilitate deeper understanding of the social dynamics, operational practices, and environmental conditions. To minimize the risk of behavior change due to the researcher's presence, the fieldwork was spread over multiple visits and locations, enabling a gradual build-up of trust. While some initial awareness of being observed was inevitable, workers generally returned to their regular practices after becoming familiar with the researcher's presence. Importantly, the focus was not on individual behavior but rather on understanding broader patterns, workflows, and system characteristics of the informal e-waste sector.

Local stakeholders supported with identifying and establishing contacts as well as facilitated trust building with further informants and served as a source of questions addressed in interviews with local scrap dealers and businesses (Kawulich 2005). Additionally, local research institutes, university researchers, and international cooperation agencies were approached to complement the perspectives of the directly involved stakeholders for creating a thorough basis for the further analysis.

2.4 | Step 2: First Draft of CLD

In a second step, insights from the pre-study are clustered by topic and keywords. Data structuring is performed according to consensus coding principles, that is, coding is performed independently by the involved researchers and afterwards discrepancies are discussed and codes are refined (Richards and Hemphill 2018). The findings are then integrated to develop an initial draft of the CLD, using the software Stella Architect 3.4. This involves (i) determining the key variables of interest in the Ghanaian e-waste system in line with the goals of the study (ii) identifying a preliminary set of system elements relevant to the key variables; (iii) formulating hypotheses of the interactions between elements and their relationship to the key variables; (iv) identifying preliminary feedback loops. In line with Coletta et al. (2024), the resulting CLD graphically depicts the system under investigation and illustrates the main interactions among the system variables, setting the stage for the subsequent process integrating further relevant stakeholders for validation.

2.5 | Step 3: Review Cycles of CLD

The third step initiates the iterative and interactive process of reviewing and enhancing the CLD through the engagement of different expert groups via individual interviews (Coletta et al. 2024). This initial cycle of iterations facilitates insightful discussions with specialists in SD who provide critical support in strengthening the underlying methodology of the study, as well as with experts in the e-waste sector, who offer valuable feedback on the variables, the cause-effect mechanisms, and the identified feedback loops. Experts were selected based on their demonstrated expertise through academic publications, professional experience, or active involvement in e-waste management research or system dynamics modeling. Efforts were made to ensure diversity in backgrounds to capture multiple perspectives.

To minimize bias and encourage open, critical input, participants were consulted individually in semi-structured sessions, allowing them to independently assess and comment on the evolving system model and its assumptions. This results in a preliminary version of the CLD intended for in-field validation.

2.6 | Step 4: In-Field Review of CLD

The fourth step is carried out to improve and validate the CLD. To do this, three in-field workshops were carried out, two in Accra and one in Kumasi. The two cities are the major e-waste hubs in Ghana (Asibey et al. 2022). The workshops in Accra involved experts operating in the Ghanaian e-waste sector while the workshop in Kumasi was held with local researchers. No local e-waste workers were directly approached or involved in the workshops. Instead, the workshops relied on the insights of researchers and experts, both of whom were selected based on their academic and field-based experience related to e-waste in Ghana. This ensured that the discussions reflected context-specific expertise while maintaining an academic and analytical perspective. It also enabled the integration of diverse viewpoints into the formulation of a dynamic hypothesis through structured participant input. Participation was voluntary, and prior to the workshops, the purpose of the study and the role of participants were clearly explained to ensure informed consent and foster an open and respectful dialogue.

2.7 | Step 5: Update and Final Version of CLD

The last step is the refinement of the CLD to a final version through an adaptation of the previously established relationships. For this, results from the workshops are used to correct, delete or add relationships and variables. For transparency, the origin of the relationships are highlighted in a separate CLD (Figure 4).

3 | Results

This section presents three main results. First, the Ghanaian e-waste ecosystem is described in detail (Section 3.1). Afterwards, the final CLD with relevant system elements and their interconnections is presented (Section 3.2). Finally, selected loops are reviewed taking two perspectives; analyzing the system excluding measures that address the challenges faced in the Ghanaian e-waste sector (Section 3.3.1), and analyzing the system including measures taken (e.g., training, formalization, etc., Section 3.3.1.1).

3.1 | The Ghanaian e-Waste Ecosystem

In Ghana, it is estimated that around 200,000 people are directly or indirectly involved in the sector scattered all across the country, with the Greater Accra region and its port Tema being the main e-waste hub (Grant et al. 2024; Oteng-Ababio et al. 2014). Thus, the ecosystem's contribution toward poverty alleviation, job creation, and sustainability with regard to material recovery must not be neglected (Oteng-Ababio et al. 2014).

When compared to services provided by local governments or formal companies, the informal sector obtains its unique, strong market position by offering door-to-door collection and remuneration for disposed devices to households and corporate entities (Amoyaw-Osei et al. 2011; Kumi et al. 2019). So-called “condemn” or “boys,” often originating from Northern Ghana, gather e-waste in residential and commercial areas, delivering it to scrap yards (GIZ E-Waste Programme and MESTI-PIU 2022; Kumi et al. 2019). Due to their wide geographical coverage and broad network, they are achieving considerable high collection rates of up to 95% of the total e-waste generated (Amoyaw-Osei et al. 2011; GIZ E-Waste Programme and MESTI-PIU 2022). After collection, the received e-waste is treated for material recovery with simple tools such as a chisel and hammer and often without safety equipment, applying crude techniques like open burning or acid leaching (Amoyaw-Osei et al. 2011). During treatment, non-valuable fractions are simply left on the ground or burned, while the valuable components are sorted, weighed, and resold to foundries, smelters, or exporters (Kumi et al. 2019). Despite the high collection rates, the overall recovery efficiency remains relatively low due to the lack of appropriate technical infrastructure and safe processing methods (Amoyaw-Osei et al. 2011). Thereby, recovery rates depend on the type of material and the product in which it is embedded. Steel can already be recovered quite efficiently with currently used technologies (up to 95%) whereas precious metals like gold or palladium, or lead are still rarely recovered (Prakash et al. 2010). This not only poses environmental and health risks but also results in significant economic losses for the country, as valuable materials are exported for further treatment or lost entirely through improper processing (Prakash and Manhart 2010). A balanced assessment of the system’s performance must therefore consider both the quantity of e-waste collected and the quality of recycling processes (e.g., the number of recycled fractions per item).

For the involved actors, especially for those from the North of Ghana where many people live below the poverty line, the e-waste business provides an attractive source of income of around US \$182–US \$200 per month (GIZ E-Waste Programme and MESTI-PIU 2022). Thus, the pivotal role of the informal e-waste ecosystem in the Ghanaian solid waste management (SWM) system and the national economy as well as its ability to leverage the urban mining potential of e-waste must be acknowledged so that a more differentiated narrative of the e-waste sector can arise (Grant et al. 2024). One of the most infamous places considered “a global e-waste hotspot” was Agbogbloshie, located in Accra, and ranked among the top 10 most polluted sites worldwide (Blacksmith Institute/Green Cross Switzerland 2008; Greenpeace 2008). The academic urban legend—defined as a widely accepted but weakly evidenced narrative repeated in academic and public discourse—surrounding Agbogbloshie emerged from the circulation of exaggerated and poorly substantiated claims (Grant et al. 2024; Rekdal 2014). It likely contributed, among other factors, to the site’s unexpected demolition in 2021, which was driven by the former Greater Accra Regional Minister’s “Make Accra Work” initiative to erase “the world’s largest dumpsite” (Boadu 2022; Facebook 2021; Grant and Oteng-Ababio 2019). Under the guise of redeveloping the area to build a hospital and solving the e-waste challenges, the workshops were razed to the ground (Boadu 2022). However, by

demolishing the site and its structures, the informal activities did not vanish but disintegrated into the neighboring residential area Old Fadama and other areas, which relocated the associated environmental and social challenges in an uncontrolled manner (Grant et al. 2024). Despite this disruption, the reconsolidation of the e-waste sector, including workers acquiring 50 ha 75 km away from Accra to perform their business, highlights their adaptability and resilience, challenging prevalent victim stereotypes (Akese et al. 2022).

Other governmental attempts to mitigate and tackle the challenges related to the Ghanaian e-waste system have failed to address the realities on-site until now (Bimpong et al. 2024; Frimpong et al. 2024; Kumi et al. 2021). Regulatory frameworks such as the Hazardous and Electronic Waste Control and Management Act 917 (2016), the corresponding Legal Instrument (LI) 2250 (2016) and the Technical Guidelines (2018) were designed to transform the e-waste ecosystem but lack completeness and still undergo implementation (Agbesinyale 2023). Furthermore, studies reveal a low level of awareness of Ghana’s e-waste legislation, summing up to 90% of the general public not having heard about it previously (Owusu-Twum et al. 2022). Apart from legislative instruments, the government installed collection spots, the Agbogbloshie Recycling Centre (ARC) for formal e-waste treatment (EwT), training programs, health centers and incentive schemes for informal actors to return collected e-waste to designated sites (Bimpong et al. 2024; Grant et al. 2024).

The governmental activities are complemented by actions induced by organizations applying bottom-up approaches such as legal advice, microfinance schemes or social support to empower the involved actors and trying to shift the paradigm from charity to a collaborative partnership at eye level (Osseo-Asare and Abbas 2012; Stacey and Lund 2016).

However, the global economic, post-pandemic crisis, insufficient funding, externalization of costs to the general public, and further systemic enforcement and monitoring inefficiencies are factors delaying the momentum of the measures to unfold their full potential (Grant et al. 2024; Kumi et al. 2021; Owusu-Twum et al. 2022). Challenges in the e-waste sector remain and are likely to aggravate due to projections of future e-waste quantities (Baldé et al. 2024). The role of the informal Ghanaian e-waste sector must be acknowledged and objectively evaluated, free from stereotypes (Oteng-Ababio 2012; Owusu-Sekyeré and Aladago 2023). Eradicating the informal structures can and must not be the only conceivable way to approach the pressing difficulties on-site. Instead, it is crucial to holistically understand the e-waste ecosystem and its interdependencies, as previous measures have not led to the desired success. A deeper understanding is therefore necessary to develop alternative approaches that enable a smoother transition and more effective solutions by assessing both direct and indirect impacts of interventions.

3.2 | CLD of the Ghanaian e-Waste Ecosystem

Variables and relationships identified during interviews, workshops, and the modeling process result in the dynamic

hypothesis (i.e., the CLD) depicted in Figure A1 (appendix). Three areas stand in the center of interest; ScD living standards, ScD health, and environmental consequences of e-waste activities. ScD living standards are captured in the variable “ScD income”, environmental consequences are expressed in the variable “emissions from EwT” and refer to any substances released from e-waste treatment into ground, water, or air, and “health” captures impacts on health connected to EwT including the occurrence of injuries, diseases, intoxications, or changes in life expectancy. In the following, ScD income, health, and emissions from EwT will be referred to as category 0 variables. The CLD in Figure A1 of the appendix shows how the category 0 variables (dark blue), are affected by influencing variables in the complex Ghanaian e-waste system. Influencing variables vary in their characteristics and can be grouped into the following categories: (1) variables originally influencing health, ScD income, and emissions, when no counter measures are taken, (2) measures to counteract undesirable effects on ScD income, health, or emissions, (3) obstacles to the implementation of measures, (4) enablers to the implementation of measures, and (5) consequences from measures (Figure A1, Table A1 in the appendix).

3.3 | Feedback Loops

Due to the diversity of variables and relations recognized in the diagram that are necessary to provide a thorough overview of the system, there is a great amount of loops that can in theory be identified. Below we show a selection of loops, not with the intention to present an exhaustive list but rather to illustrate the diversity of loops and to highlight some of the effects occurring in the CLD.

3.3.1 | Feedback Loops With Category 1 Variables

ScD income, health, and emissions from EwT (i.e., category 0 variables) may be explained using category 1 variables only (i.e., excluding measures). Table 2 provides a selection of loops that reinforce and balance category 0 variables.

3.3.1.1 | Loops Affecting Health. The loops R1 and R2 reinforce health (Figure 2). In R1, exposure to poisonous chemicals or hazardous treatment practices reduce health and eventually decrease workers' productivity and ScD income. Workers with lower income are, in the hypothesis, expected to treat e-waste less carefully and thus less safely, leading to further reductions in health. This is grounded on the assumption that the fewer income is available, the more imperative the generation of income is in the struggle for survival. As a consequence, own safety during work is ranked lower. On the other hand, the more income is generated, the more might workers allow themselves to reflect on safety requirements, to purchase safety equipment (if available and known of) or to follow procedures that are safer but also more laborious. The relationship between ScD income and safe EwT was both put forward and doubted by workshop participants (conflicting relationships, cf. Figure A2 in the appendix and Section 4.1.2). Further field observations should target this assumption to clarify if the relationship is indeed justified.

In R2, health is directly affected by ScD income. This is because, with an increased income, ScDs have more access to medical treatment and have thereby the possibility to alleviate or avoid adverse effects on health.

IFS size has a balancing effect on health (B1). This is through a highly undesirable cause-effect chain: more actors in the IFS mean more e-waste treated in the IFS, where treatment is predominantly unsafe. This will lead to a decrease in health, for example, through poisonings, sicknesses, and injuries that reduce life expectancy. With a time delay, the greater amount of unsafely treated e-waste may lead to fewer actors in the IFS and thus balance the size of the IFS.

3.3.1.2 | Loops Affecting Emissions. Three loops in Table 2 and Figure 2 affect emissions. For example, R3 impacts emissions via health. Health increases productivity and ScD income. With higher income, ScDs might be more likely to inform themselves about environmentally friendly e-waste treatment (EFET) and possess more capital to invest in tools or materials to perform EFET, resulting in decreasing emissions.

B2 is a balancing loop. Here, increasing health leads to a greater number of ScDs in the IFS (as life expectancy rises and accidents are less prevalent). As there are more ScDs in the IFS, more e-waste is treated in the IFS, and consequently, emissions from EwT rise.

3.3.1.3 | Loops Affecting ScD Income. Visually, the influence of ScD income is striking. Figure 3 and Table 2 show that the income is part of many reinforcing and balancing loops in the system.

When looking at isolated loops, the effects on ScD income are diverse. For instance, R7 is a reinforcing loop. Here, increasing income leads to increased e-waste available to the informal sector. This is because ScDs can now afford to purchase more scrap. Handling and selling more scrap, in turn, will again increase ScD income. Without any external influence, an initial increase of ScD income would thus lead to ever further increased income. This is contrasted by the effects of the balancing loops involving ScD income. For instance, in B4, additional income leads to the capability of purchasing EFET. However, this increases the costs for recycling scrap and can lead to a reduced income. This shows ScD income is involved in both reinforcing and balancing loops. Which of the loops are dominant in a quantitative model remains to be explored. If balancing loops are dominant, ScD income can hardly be changed due to balancing feedback. In contrast, if reinforcing loops are dominant, this can lead to ScD income growth or decline.

3.3.2 | Feedback Loops Including Category 2–5 Variables

3.3.2.1 | Evictions. Evictions are used as an attempt to get rid of undesirable informal EwT activities. In the model, evictions are associated with a couple of reinforcing loops (R8-R13 in Figure 4 and Table 3).

TABLE 2 | Loops with category 1 variables, thus variables originally influencing category 0 variables, that is, ScD income, health, and emissions. Loop names differentiate between reinforcing (R) and balancing (B) loops.

Affected category 0 variable	Loop name	Loop
Health	R1	health $-(+)->$ productivity $-(+)->$ ScD income $-(+)->$ safe EwT $-(+)->$ health
	R2	health $-(+)->$ productivity $-(+)->$ ScD income $-(+)->$ health
	B1	health $-(+)->$ number of ScD in IFS $-(+)->$ e-waste treated in IFS $-(+)->$ health
Emissions from EwT	R3	emissions from EwT $-(+)->$ health $-(+)->$ productivity $-(+)->$ ScD income $-(+)->$ EFET $-(+)->$ emissions from EwT
	B2	emissions from EwT $-(+)->$ health $-(+)->$ number of ScDs in IFS $-(+)->$ e-waste treated in IFS $-(+)->$ emissions from EwT
ScD income	R4	ScD income $-(+)->$ safe EwT $-(+)->$ costs for recycling e-waste $-(+)->$ sales price for recycled e-waste $-(+)->$ fractions recycled per item $-(+)->$ recycled e-waste sold per ScD $-(+)->$ ScD income
	R5	ScD income $-(+)->$ safe EwT $-(+)->$ costs for recycling e-waste $-(+)->$ sales price for recycled e-waste $-(+)->$ ScD income
	R6	ScD income $-(+)->$ number of ScD in IFS $-(+)->$ demand for raw material $-(+)->$ costs for raw material $-(+)->$ costs for recycling e-waste $-(+)->$ sales price for recycled e-waste $-(+)->$ ScD income
	R7	ScD income $-(+)->$ e-waste available to IFS $-(+)->$ ScD income
	B3	ScD income $-(+)->$ safe EwT $-(+)->$ costs for recycling e-waste $-(+)->$ ScD income
	B4	ScD income $-(+)->$ EFET $-(+)->$ costs for recycling e-waste $-(+)->$ ScD income
	B5	ScD income $-(+)->$ number of ScD in IFS $-(+)->$ demand for raw material $-(+)->$ costs for raw material $-(+)->$ costs for recycling e-waste $-(+)->$ ScD income
	B6	ScD income $-(+)->$ e-waste available to IFS $-(+)->$ e-waste treated in IFS $-(+)->$ health $-(+)->$ ScD productivity $-(+)->$ ScD income
	B7	ScD income $-(+)->$ number of ScD in IFS $-(+)->$ demand for raw material $-(+)->$ cost for raw material $-(+)->$ e-waste available to IFS $-(+)->$ ScD income
	B8	ScD income $-(+)->$ number of ScD in IFS $-(+)->$ demand for raw material $-(+)->$ price paid to consumer at door collection by IFS $-(+)->$ cost for raw material $-(+)->$ e-waste available to IFS $-(+)->$ ScD income
	B9	ScD income $-(+)->$ number of ScD in IFS $-(+)->$ sales price for recycled e-waste $-(+)->$ fractions recycled per item $-(+)->$ recycled e-waste sold per ScD $-(+)->$ ScD income
B10	ScD income $-(+)->$ number of SD in IFS $-(+)->$ sales price for recycled e-waste $-(+)->$ ScD income	
B11	ScD income $-(+)->$ safe EwT $-(+)->$ health $-(+)->$ number of ScD in IFS $-(+)->$ sales price for recycled e-waste $-(+)->$ ScD income	

The selected loops show that evictions interfere with other measures; specifically, they reduce the success of formalization and regulations (F&R) via further variables in the system (R8-R11), environmentally friendly technologies (EFTec) available to the IFS (R12), and participation in training (R13) in the respective loops. Simultaneously, evictions can lead to increased emissions (R8-R11), reduced health (R10), and

decreased ScD income (R10). In consequence, evictions may reduce the success of other measures and may affect the key variables of the system in an undesirable way. As soon as the IFS has recovered from an eviction and becomes productive at new sites, the problems leading to evictions (e.g., undesired emissions) arise again or even worsen. Hence, evictions may support a tendency to execute further evictions. Balancing

loops involving evictions are scarce, but B12 is one example. Again, the overall effects of evictions in the system remain to be determined in a quantitative model.

3.3.2.2 | Success of F&R. Like evictions, the success of F&R is involved in more reinforcing than in balancing loops (cf. Figure 5). However, in contrast to evictions, reinforcing loops with F&R have no unintended effects on the key variables once the measure becomes effective (from an isolated perspective).

For instance, in R16, R17, and R21, health and ScD income increase as a result of increasing success of F&R. There are some loops that show how the success of F&R may be fostered (e.g., R14, R15, R18, R19). In those loops, the success of F&R

is for instance supported by payouts from social systems that increase ScD income (R14), and health due to avoided stress from an insecure future (R21), an increased share of the IFS represented by associations, strengthening the position of ScDs (R15), a decreasing dominance of the IFS, providing more e-waste to the formal sector ([FS], R18), or an increasing number of entrepreneurs in the IFS who develop solutions (R19). One of the selected loops affects other measures. This is R20, which can have a positive impact on EFTec available to the IFS; with the increasing success of F&R, trust in the IFS is increased. This attracts investment in the IFS, which in turn makes EFTec available to the IFS. Balancing loops contain variables which impede the success of F&R. This is for instance an initial cost increase due to safe EwT, as required by regulations (B13) or payments to social systems that decrease ScD income (B12).

3.3.2.3 | Environmentally Friendly Technologies. EFTec are predominantly involved in reinforcing loops (R22-R26). Loops R22-R25 affect at least one of the category 0 variables, and this in a desirable way, if more EFTec are available (cf. Figure 6).

For instance, if EFTec become more available to the IFS, R22 decreases emissions and increases health and ScD income, R23 and R24 increase ScD income and R25 increase ScD income while emissions are decreased. In addition, R24 positively influences the category 2 variable “success of F&R”. Thus, in total, EFTec appear to have a desirable impact on the system. Still, some consequences from EFTec are rather undesirable. For instance, one effect of EFTec is that some ScDs are pushed out of the e-waste sector. This is especially true for the most vulnerable group of ScDs whose work can easily be replaced by machines. In R26, fewer actors in the IFS mean increased sales prices for the recycled scrap, thereby a higher income and consequently more EFTec available to those ScDs who managed to remain in the

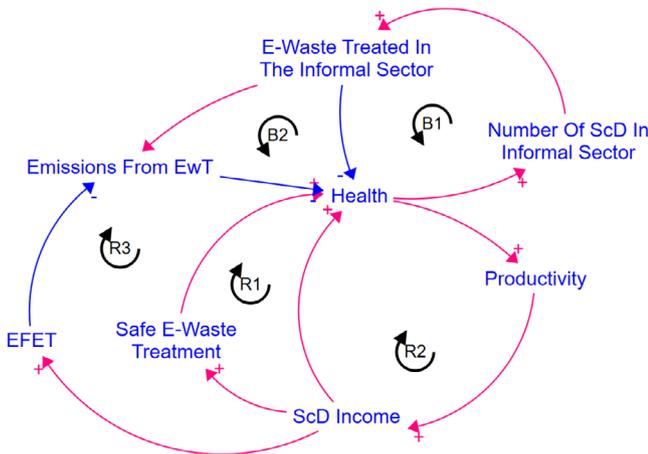


FIGURE 2 | An extract from the CLD of the Ghanaian e-waste treatment system with a focus on loops that involve the category 0 variables “Health” and “Emissions from EwT”.

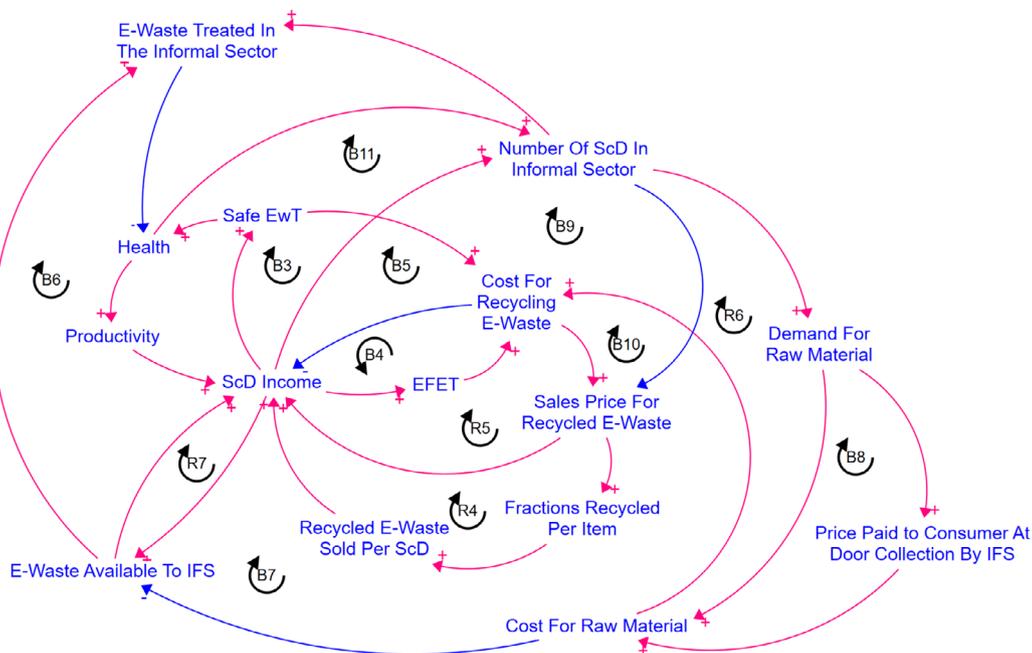


FIGURE 3 | An extract from the CLD of the Ghanaian e-waste treatment system with a focus on loops that involve the category 0 variable “ScD income”.

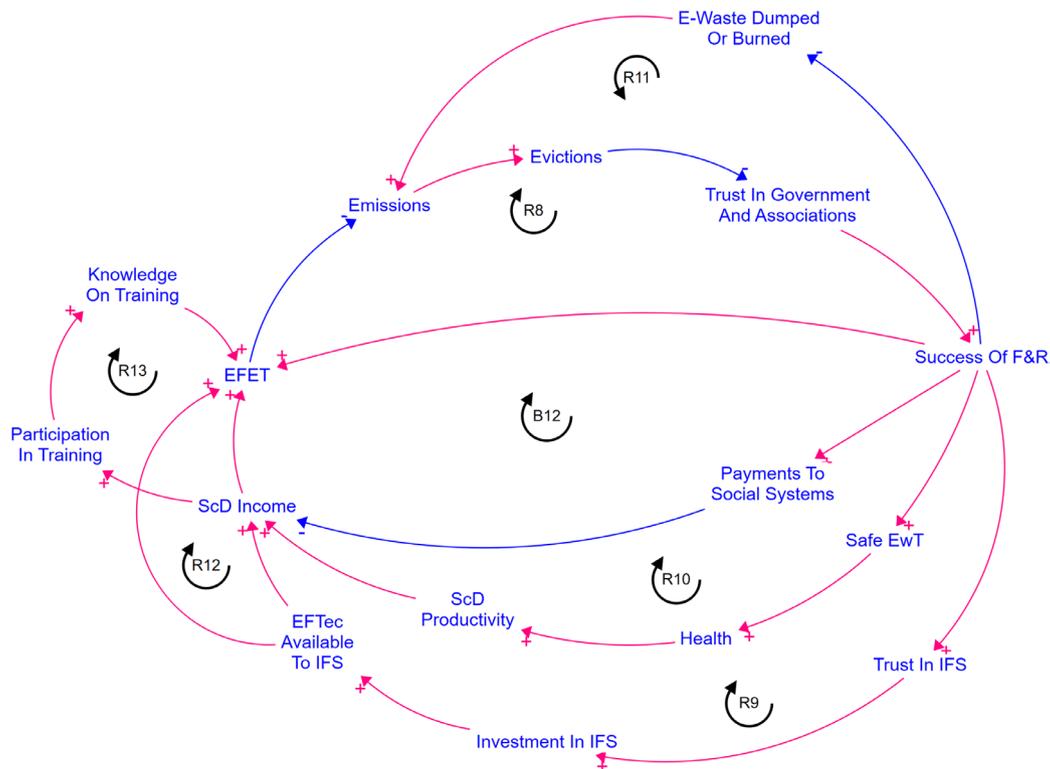


FIGURE 4 | An extract from the CLD of the Ghanaian e-waste treatment system with a focus on loops that involve the category 2 variable “Evictions”.

system. To the more vulnerable group of ScDs, this comes at the cost of a livelihood. Those side effects from EFTec must be kept in mind when promoting technologies to affect category 0 variables. A general point to discuss here is that the variable “EFTec available to the IFS” assumes that the provided technologies are indeed useful and effective in Ghana. The “EF” in EFTec expresses that the technology has actually proven to mitigate environmental impacts in the applied context. This is important to highlight because not every technology is equally suitable for all situations. For instance, technologies might have proven to work in Europe, however, in the Ghanaian e-waste treatment context the same technologies may be less effective (e.g., due to variations in climate, treated waste stream volumes, supply chain contexts, etc.). In contrast to the technologies that are currently available to treat e-waste in the Ghanaian e-waste sector, more efficient and effective technologies are required to support safe and environmentally friendly processes.

3.3.2.4 | Training. In the CLD, training supports knowledge acquisition in all four defined knowledge categories, that is, knowledge on EFET, on safe EwT, on efficiency, and on policies (cf. Figure 7). In five out of the selected six loops this results in desirable effects for emissions from EwT, health, and ScD income (R27-R32). For instance, in R27, knowledge on EFET increases actual EFET which reduces emissions from EwT and increases perceived benefits from EFET. As a result, ScDs are inclined to participate in further training or to recommend trainings to their peers. A counterexample is B16. Here, knowledge on safe EwT does not lead to an increased income due to increased health (as in R32), but to a reduced income due to increased costs required to implement safe EwT.

4 | Discussion

4.1 | Implications

With respect to the SDGs there are both implications for practitioners and for researchers. In the introduction section we highlighted some of the goals that are particularly relevant in the Ghanaian context, for example, SDGs concerning poverty, health, clean air and water, decent work, responsible consumption and production, and climate action. While the presented CLD focuses primarily on ScD income, health and on emissions, the CLD contains variables (e.g., a formalization of the IFS, education or representation of ScDs in associations) that in the understanding of SDGs are parts of goals on their own (e.g., formalization is part of target 8.3, which belongs to the SDG 8, decent work and economic growth). An implication based on this observation is the following. Understanding the variables in the CLD as aspects of the SDGs, the CLD shows clearly that none of the goals stands on its own but is integrated into a dynamic system, interacting with the other goals. This is an important implication for the achievement of sustainable development. For practitioners in the field of implementing the SDGs this means that goal interactions must be a central factor in the creation of measures. For researchers this means, that not only within the e-waste sector in Ghana, but potentially in any other region, sector or research area sustainable development goal interactions may exist and should be known and understood. This could considerably influence the outcome of measures implemented by practitioners. Acknowledging and visualizing these interconnections in a CLD does not identify leverage points with certainty, but it helps to highlight where they may exist and how interventions

TABLE 3 | Selection of loops that involve measures (category 2 variables) to reduce undesirable effects on health, emissions from EwT, and ScD income (category 0 variables). Loop names differentiate between reinforcing (R) and balancing (B) loops.

Implemented measure, i.e., category 2 variables	Loop name	Loop	
Evictions	R8	evictions $-(-) \rightarrow$ trust in government and associations $-(+)$ \rightarrow success of F&R $-(+)$ \rightarrow EFET $-(-)$ \rightarrow emissions $-(+)$ \rightarrow evictions	
	R9	evictions $-(-) \rightarrow$ trust in government and associations $-(+)$ \rightarrow success of F&R $-(+)$ \rightarrow trust in IFS $-(+)$ \rightarrow investment in IFS $-(+)$ \rightarrow EFTec available to the IFS $-(+)$ \rightarrow ScD income $-(+)$ \rightarrow EFET $-(-)$ \rightarrow emissions $-(+)$ \rightarrow evictions	
	R10	evictions $-(-) \rightarrow$ trust in government and associations $-(+)$ \rightarrow success of F&R $-(+)$ \rightarrow safe EwT $-(+)$ \rightarrow health $-(+)$ \rightarrow ScD productivity $-(+)$ \rightarrow ScD income $-(+)$ \rightarrow EFET $-(-)$ \rightarrow emissions $-(+)$ \rightarrow evictions	
	R11	evictions $-(-) \rightarrow$ trust in government and associations $-(+)$ \rightarrow success of F&R $-(+)$ \rightarrow e-waste dumped or burned $-(+)$ \rightarrow emissions $-(+)$ \rightarrow evictions	
	R12	evictions $-(-) \rightarrow$ trust in government and associations $-(+)$ \rightarrow success of F&R $-(+)$ \rightarrow trust in IFS $-(+)$ \rightarrow investment in IFS $-(+)$ \rightarrow EFTec available to IFS $-(+)$ \rightarrow EFET $-(-)$ \rightarrow emissions $-(+)$ \rightarrow evictions	
	R13	evictions $-(-) \rightarrow$ trust in government and associations $-(+)$ \rightarrow success of F&R $-(+)$ \rightarrow trust in IFS $-(+)$ \rightarrow investment in IFS $-(+)$ \rightarrow EFTec available to IFS $-(+)$ \rightarrow ScD income $-(+)$ \rightarrow participation in training $-(+)$ \rightarrow knowledge on EFET $-(+)$ \rightarrow EFET $-(-)$ \rightarrow emissions $-(+)$ \rightarrow evictions	
	B12	evictions $-(-) \rightarrow$ trust in government and associations $-(+)$ \rightarrow success in F&R $-(+)$ \rightarrow payments to social systems $-(-)$ \rightarrow ScD income $-(+)$ \rightarrow EFET $-(-)$ \rightarrow emissions $-(+)$ \rightarrow evictions	
	Success of formalization and regulations (F&R)	R14	success of F&R $-(+)$ \rightarrow payout from social systems $-(+)$ \rightarrow ScD income $-(+)$ \rightarrow success of F&R
		R15	success of F&R $-(+)$ \rightarrow share of IFS represented by associations $-(+)$ \rightarrow success of F&R
		R16	success of F&R $-(+)$ \rightarrow safe EwT $-(+)$ \rightarrow health $-(+)$ \rightarrow productivity $-(+)$ \rightarrow ScD income $-(+)$ \rightarrow success of F&R
		R17	success of F&R $-(+)$ \rightarrow EFET $-(-)$ \rightarrow emissions $-(-)$ \rightarrow health $-(+)$ \rightarrow productivity $-(+)$ \rightarrow ScD income $-(+)$ \rightarrow success of F&R
		R18	success of F&R $-(+)$ \rightarrow e-waste collected by FS $-(-)$ \rightarrow e-waste available to IFS $-(+)$ \rightarrow dominance of IFS $-(-)$ \rightarrow success of F&R
		R19	success of F&R $-(+)$ \rightarrow entrepreneurs in IFS $-(+)$ \rightarrow success of F&R
R20		success of F&R $-(+)$ \rightarrow trust in IFS $-(+)$ \rightarrow investment in IFS $-(+)$ \rightarrow EFTec available to IFS $-(+)$ \rightarrow ScD income $-(+)$ \rightarrow success of F&R	
R21		success of F&R $-(+)$ \rightarrow payout from social systems $-(+)$ \rightarrow health $-(+)$ \rightarrow productivity $-(+)$ \rightarrow ScD income $-(+)$ \rightarrow success of F&R	
B13		success of F&R $-(+)$ \rightarrow safe EwT $-(+)$ \rightarrow costs for recycling e-waste $-(-)$ \rightarrow ScD income $-(+)$ \rightarrow success of F&R	
B14		success of F&R $-(+)$ \rightarrow payments to social systems $-(-)$ \rightarrow ScD income $-(+)$ \rightarrow success of F&R	
Environmentally friendly technologies (EFTec)	R22	EFTec available to IFS $-(+)$ \rightarrow EFET $-(-)$ \rightarrow emissions $-(-)$ \rightarrow health $-(+)$ \rightarrow productivity $-(+)$ \rightarrow ScD income $-(+)$ \rightarrow EFTec available to IFS	
	R23	EFTec available to IFS $-(+)$ \rightarrow ScD income $-(+)$ \rightarrow trust in IFS $-(+)$ \rightarrow investment in IFS $-(+)$ \rightarrow EFTec available to IFS	
	R24	EFTec available to IFS $-(+)$ \rightarrow ScD income $-(+)$ \rightarrow success of F&R $-(+)$ \rightarrow entrepreneurs in IFS $-(+)$ \rightarrow EFTec available to IFS	
	R25	EFTec available to IFS $-(+)$ \rightarrow safe EwT $-(+)$ \rightarrow health $-(+)$ \rightarrow productivity $-(+)$ \rightarrow ScD income $-(+)$ \rightarrow EFTec available to IFS	
	R26	EFTec available to IFS $-(+)$ \rightarrow ScDs pushed out of e-waste sector $-(-)$ \rightarrow number of ScDs in e-waste sector $-(-)$ \rightarrow sales price for recycled e-waste $-(+)$ \rightarrow ScD income $-(+)$ \rightarrow EFTec available to IFS	

(Continues)

TABLE 3 | (Continued)

Implemented measure, i.e., category 2 variables	Loop name	Loop
Participation in training	R27	participation in training $-(+)->$ knowledge on EFET $-(+)->$ EFET $-(-)->$ emissions from EwT $-(-)->$ perceived benefits from EFET $-(+)->$ participation in training
	R28	participation in training $-(+)->$ knowledge on safe EwT $-(+)->$ safe e-waste treatment $-(+)->$ health $-(+)->$ perceived benefits from safe EwT $-(+)->$ participation in training
	R29	participation in training $-(+)->$ knowledge on efficiency $-(+)->$ fractions recycled per item $-(+)->$ recycled e-waste sold per ScD $-(+)->$ ScD income $-(+)->$ participation in training
	R30	participation in training $-(+)->$ knowledge on policies $-(+)->$ success of F&R $-(+)->$ EFET $-(-)->$ emissions $-(-)->$ perceived benefits from EFET $-(+)->$ participation in training
	R31	participation in training $-(+)->$ knowledge on policies $-(+)->$ success of F&R $-(+)->$ safe EwT $-(+)->$ health $-(+)->$ perceived benefits from safe EwT $-(+)->$ participation in training
	R32	participation in training $-(+)->$ knowledge on safe EwT $-(+)->$ safe e-waste treatment $-(+)->$ health $-(+)->$ productivity $-(+)->$ ScD income $-(+)->$ participation in training
	B16	participation in training $-(+)->$ knowledge on safe EwT $-(+)->$ safe EwT $-(+)->$ costs for recycling e-waste $-(-)->$ ScD income $-(+)->$ participation in training

might propagate through the system. This enables the design of more adaptive, informed, and resilient policies. Instead of aiming for isolated fixes, policies can be developed in an iterative, inclusive way that accommodates complexity while remaining aligned with broader sustainability goals. In practical terms, this means that policymakers should invest in cross-sectoral coordination mechanisms (e.g., joint planning processes, shared data platforms), regularly consult with local stakeholders including informal sector actors and integrate flexible monitoring systems that allow for timely policy adjustments. Piloting interventions on a small scale before full implementation can help test assumptions and reduce unintended consequences. Further implications for practitioners are explored in the following by taking a closer look at the developed CLD.

4.1.1 | Implications for Practitioners

Apart from the implications outlined above, there are further aspects to be learned by practitioners. When looking for starting points for a positive change in the Ghanaian e-waste sector, category 1 variables (i.e., variables that originally influence category 0 variables, while no measures are taken) are an interesting group to recognize. The CLD shows that category 1 variables mostly consist of market variables, addressing, for example, supply, demand, costs, and prices. Hence, those variables are a potential leverage for improvements in the system. Measures designed to address challenges in the Ghanaian e-waste system could therefore target modifying category 1 variables.

A second aspect to be considered is that, while some balancing loops were identified, a plethora of reinforcing loops exists. For tackling the challenges in the Ghanaian e-waste system, this has two implications. On one hand, situations that are undesirable may further aggravate. Take, for instance, R2. If health decreases, productivity decreases, ScD income decreases, and therefore health further decreases. On the other hand, if health

increases, this can increase productivity and ScD income and consequently further increase health. For the design of measures, this observation means that sometimes an increase or decrease of a variable may propel dynamics in the system in a desirable way and support a quick development toward good health, low emissions, and high ScD income. Modeling the system and thereby adopting an external perspective supports identifying failures and challenges in old paradigms and transcending them.

Another implication is derived from the wide variety of stakeholders acting in the e-waste system in Ghana, which was again confirmed in the participatory stakeholder process. Central actors encompass, for instance, ScDs in the informal sector, the formal sector, universities, entrepreneurs, local leaders, the government, ScD associations, consumers, non-governmental organizations, or industry. This has two implications. First, potential measures to counteract adverse effects on health, emissions, and a low ScD income should recognize those stakeholders. While the ScDs are an obvious and direct stakeholder to address, there are less apparent actors that can strongly influence the system. For instance, targeted university education can result in a higher interest of students in the Ghanaian e-waste sector and consequently produce ideas and solutions to address challenges on-site. While this is a rather long-term approach, it may be a key component of a portfolio of measures to be taken. Additionally, the government may strengthen the enforcement of regulations. Although necessary legislation is already in place, there is still a lack of enforcement. The origin of this mismatch must be better understood, and stakeholders involved in the enforcement of regulations must be instituted accordingly. Also, entrepreneurship can be supported to increase the generation of economically viable solutions in the e-waste sector. This can create formalized jobs and thus reduce the dominance of the IFS, which in turn aids formalization endeavors. Further, the role of local leaders and ScD associations must be recognized. Both stakeholders rely on the trust of ScDs and are at the same time central means of

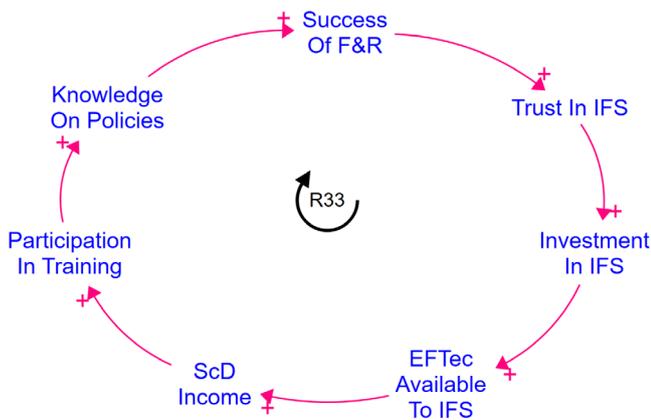


FIGURE 8 | An extract from the CLD of the Ghanaian e-waste treatment system to exemplify a loop with interacting measures.

stakeholder perspectives. This is particularly important in sectors such as informal e-waste management, where actors are affected in varying ways depending on their geographical location, exposure to policy measures, and socio-economic conditions (Owusu-Sekyere and Aladago 2023). Given the trade-off between inclusiveness and complexity, not all potential effects of interventions could be captured in the model. For researchers, this implies two key responsibilities: first, to treat the CLD as a heuristic tool for structuring thinking and generating hypotheses, rather than as a predictive model; and second, to continue validating and updating the model through iterative, participatory processes that include diverse and underrepresented voices. This approach supports adaptive thinking, which can be considered an essential requirement given the highly dynamic nature of the informal e-waste ecosystem.

A final implication addresses data availability in Ghana. During our research, we faced data gaps and uncertainties, making a quantitative model hardly implementable. Therefore, we suggest that more quantitative data is collected in Ghana in a coherent and transparent manner to enable the next steps after a CLD in the SD methodology.

4.2 | Limitations

By engaging a large number of diverse stakeholders in a multi-stage process to enhance the validity of the study, an attempt was made to counteract any potentially arising biases (Bryson 2004; Bryson et al. 2021). However, especially in group settings, potential group biases must be considered as limiting factors when interpreting the results (Gabriel and O'Connor 2022; Mullen et al. 1992; Turner and Pratkanis 1998; de Wilde et al. 2018). Despite encouraging diverse perspectives and promoting critical thinking among participants, biases cannot be avoided completely. Further, researcher biases in observing on-site processes and interviewing stakeholders influenced by subjective, underlying personal assumptions have to be considered. Especially in the participant selection for the workshops, persons with higher education qualifications were disproportionately represented. Integrating more people directly working on the ground holds a promising approach for future research workshops.

One further aspect to be discussed regarding the validation of the relationships is that the proposed relationships represent coarse tendencies only. For instance, although the informal e-waste sector is similarly structured across Ghana, our research results suggest that its actors are characterized by different levels of vulnerability (Owusu-Sekyere and Aladago 2023). In our model, we are not able to cover all possible effects certain measures exert on the target groups, as this comes at the cost of higher complexity. This implies that some of the identified interdependencies might slightly vary for specific cases. Future quantitative analyses will show how far aggregations and simplifications were adequate and where more nuanced representations are required.

Finally, due to the impossibility of including all aspects of the real world, the scope of the study was limited. In our case, there was a focus on dynamics within Ghana. This excludes aspects such as product design that could be another measure to alleviate the situation in Ghana. Also, additional implications of measures can be included in further studies. Such implications could, for instance, recognize the consequences of increasing income opportunities in the IFS, which might attract foreign investors.

5 | Conclusion

For the first time, the complex dynamics of the Ghanaian e-waste treatment system were captured in a CLD as part of the system dynamics methodology. The Ghanaian e-waste management situation has proven to be a complex system characterized by interacting e-waste stakeholders, market variables, and measures, eventually influencing emissions, ScD health, and income. The presented CLD illustrates the interconnectedness of stakeholders and interventions, offering implications for both practitioners and researchers. In the process of developing measures to promote sustainable development in Ghana, the CLD can be used as a mental map to understand the influence of new measures on actors, goals, and existing measures in the system. This can prevent taking action without considering consequences for other system elements. The results encourage paying closer attention to inclusive, collaborative approaches in Ghanaian e-waste management, particularly involving the informal sector, to address economic, environmental, and health challenges. The origin of each of the relationships in the CLD was made transparent to highlight which part of the dynamic hypothesis is backed by the Ghanaian perspective. Further investigations can extend to addressing data gaps through targeted data collection efforts, expanding participant diversity in workshops, and further refining the model. In the presented form, the CLD can be the basis for quantitative modeling in SD to show how the system behaves over time, test the effectiveness of interventions, and identify leverage points for optimized decision-making. In summary, the study underscores the potential of systems thinking and highlights the strengths of collaboration to understand the complexities of the Ghanaian e-waste ecosystem. Eventually, the presented CLD can be a stepping stone in paving the way toward transformative change and long-term sustainable development that balances economic, environmental, and social concerns in the Ghanaian e-waste system.

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Bibliography

- Adebiyi, J. A., and L. S. Olabisi. 2022. "Participatory Causal Loop Mapping of the Adoption of Organic Farming in Nigeria." *Environmental Management* 69, no. 2: 410–428. <https://doi.org/10.1007/s00267-021-01580-w>.
- Agbesinyale, J. 2023. "Ghana vs. e-Waste: Relevance of e-Waste Legislation in Ghana." <https://ddrn.dk/13811/>.
- Akese, G., U. Beisel, and M. Chasant. 2022. "Agbogbloshie: A Year After the Violent Demolition." <https://africanarguments.org/2022/07/agbogbloshie-a-year-after-the-violent-demolition/>.
- ALqodsi, E. M. 2025. "Extended Producer Responsibility in e-Waste Recycling: A Secure Path to a Sustainable Future for UAE." *Sustainable Development* 33, no. 1: 309–318. <https://doi.org/10.1002/sd.3107>.
- Amankwaa, E. F. 2013. "Livelihoods in Risk: Exploring Health and Environmental Implications of e-Waste Recycling as a Livelihood Strategy in Ghana." *Journal of Modern African Studies* 51, no. 4: 551–575. <http://www.jstor.org/stable/43302038>.
- Amiri, A., Y. Z. Mehrjerdi, A. Jalalimanesh, and A. Sadegheih. 2020. "Food System Sustainability Investigation Using System Dynamics Approach." *Journal of Cleaner Production* 277: 124040. <https://doi.org/10.1016/j.jclepro.2020.124040>.
- Amoyaw-Osei, Y., O. O. Agyekum, J. A. Pwamang, E. Mueller, R. Fasko, and M. Schlupe. 2011. "Ghana e-Waste Country Assessment." SBC e-waste Africa Project. https://www.researchgate.net/publication/281381379_Ghana_e-waste_country_assessment. 66, 111.
- Asibey, M. O., A. M. Lykke, and R. S. King. 2022. "Understanding the Factors for Increased Informal Electronic Waste Recycling in Kumasi, Ghana." *International Journal of Environmental Health Research* 32, no. 2: 305–320. <https://doi.org/10.1080/09603123.2020.1755016>.
- Attazahri, A. K., U. S. Putro, and A. Nita. 2021. "Designing Scenarios for Integrated and Sustainable e-Waste Management: Case of Indonesia." *IJSSAM* 5, no. 2: 209–221. <https://doi.org/10.28992/ijssam.v5i2.387>.
- Awasthi, A. K., M. Wang, M. K. Awasthi, Z. Wang, and J. Li. 2018. "Environmental Pollution and Human Body Burden From Improper Recycling of e-Waste in China: A Short-Review." *Environmental Pollution* 243: 1310–1316. <https://doi.org/10.1016/j.envpol.2018.08.037>.
- Baldé, C. P., R. Kuehr, T. Yamamoto, et al. 2024. "Global e-Waste Monitor 2024." https://ewastemonitor.info/wp-content/uploads/2024/03/GEM_2024_18-03_web_page_per_page_web.pdf.
- Banerjee, D., N. Kushwaha, E. Ahmad, S. Quereshi, and K. D. P. Nigam. 2024. "Eco-Design Strategies for Recycling of e-Waste." In *Solid Waste Management. Chemical Approaches*. Boca Raton, edited by G. Chauhan and S. Sevda, 95–120. CRC Press.
- Barapatre, S., and M. Rastogi. 2022. "E-Waste Management: A Transition Towards a Circular Economy." In *Handbook of Solid Waste Management. Sustainability Through Circular*, 1499–1521. Springer. https://doi.org/10.1007/978-981-16-4230-2_68.
- Berenjkar, P., Y. Y. Li, and Q. Yuan. 2021. "The Application of System Dynamics in Different Practices of a Waste Management System." *Environment, Development and Sustainability* 23, no. 11: 15695–15724. <https://doi.org/10.1007/s10668-021-01362-8>.
- Bimpong, F. A. K., M. O. Asibey, and D. K. B. Inkoom. 2024. "Ghana's Recently Introduced e-Waste Regulatory Policy: A Hope for a Better e-Waste Sector?" *Waste Management and Research: The Journal of the International Solid Wastes and Public Cleansing Association, ISWA* 42, no. 11: 1031–1041. <https://doi.org/10.1177/0734242X231204457>.
- Blacksmith Institute/Green Cross Switzerland. 2008. "The Worlds Worst 2013: The Top Ten Toxic Threats. Cleanup, Progress, and Ongoing Challenges." <http://www.worstpolluted.org/docs/TopTenThreats2013.pdf>.
- Boadu, K. A. 2022. "Agbogbloshie Redevelopment Scheme Ready." <https://www.graphic.com.gh/news/general-news/ghana-news-agbogbloshie-redevelopment-scheme-ready.html>.
- Bryson, J. M. 2004. "What to Do When Stakeholders Matter." *Public Management Review* 6, no. 1: 21–53. <https://doi.org/10.1080/14719030410001675722>.
- Bryson, J. M., B. Barberg, B. C. Crosby, and M. Q. Patton. 2021. "Leading Social Transformations: Creating Public Value and Advancing the Common Good." *Journal of Change Management* 21, no. 2: 180–202. <https://doi.org/10.1080/14697017.2021.1917492>.
- Chen, D., D. Faibil, and M. Agyemang. 2020. "Evaluating Critical Barriers and Pathways to Implementation of e-Waste Formalization Management Systems in Ghana: A Hybrid BWM and Fuzzy TOPSIS Approach." *Environmental Science and Pollution Research* 27, no. 35: 44561–44584. <https://doi.org/10.1007/s11356-020-10360-8>.
- Coletta, V. R., A. Pagano, I. Pluchinotta, et al. 2021. "Causal Loop Diagrams for Supporting Nature Based Solutions Participatory Design and Performance Assessment." *Journal of Environmental Management* 280: 111668. <https://doi.org/10.1016/j.jenvman.2020.111668>.
- Coletta, V. R., A. Pagano, N. Zimmermann, et al. 2024. "Socio-Hydrological Modelling Using Participatory System Dynamics Modelling for Enhancing Urban Flood Resilience Through Blue-Green Infrastructure." *Journal of Hydrology* 636: 131248. <https://doi.org/10.1016/j.jhydrol.2024.131248>.
- Cottes, M., M. Mainardis, and P. Simeoni. 2023. "Assessing the Techno-Economic Feasibility of Waste Electric and Electronic Equipment Treatment Plant: A Multi-Decisional Modeling Approach." *Sustainability* 15, no. 23: 16248. <https://doi.org/10.3390/su152316248>.
- Dasgupta, D., A. Debsarkar, T. Hazra, B. K. Bala, A. Gangopadhyay, and D. Chatterjee. 2017. "Scenario of Future e-Waste Generation and Recycle-Reuse-Landfill-Based Disposal Pattern in India: A System Dynamics Approach." *Environment, Development and Sustainability* 19, no. 4: 1473–1487. <https://doi.org/10.1007/s10668-016-9815-6>.
- de Wilde, T. R. W., V. F. S. Ten, and C. K. W. de Dreu. 2018. "The Anchoring-Bias in Groups." *Journal of Experimental Social Psychology* 76: 116–126. <https://doi.org/10.1016/j.jesp.2018.02.001>.
- DeWalt, K. M., and B. R. DeWalt. 2010. *Participant Observer: A Guide for Fieldworkers*. Rowman Altamira.
- Elsawah, S., S. A. Pierce, S. H. Hamilton, et al. 2017. "An Overview of the System Dynamics Process for Integrated Modelling of Socio-Ecological Systems: Lessons on Good Modelling Practice From Five Case Studies." *Environmental Modelling and Software* 93: 127–145. <https://doi.org/10.1016/j.envsoft.2017.03.001>.
- Esohere, Y., H. Yabar, T. Mizunoya, and D. Richards. 2024. "Leveraging Life Cycle Assessment and System Dynamics Model Analysis for an Integrated Household e-Waste Management System in Yaoundé, Cameroon." *Urban Science* 8, no. 3: 77. <https://doi.org/10.3390/urbansci8030077>.
- Espinoza Pérez, L., A. Espinoza Pérez, and Ó. C. Vásquez. 2024. "Evaluation of Mitigation Initiatives for Simultaneous Air Pollution and Municipal Solid Waste Systems: A System Dynamics Approach." *Socio-Economic Planning Sciences* 95: 102010. <https://doi.org/10.1016/j.seps.2024.102010>.

- Facebook. 2021. "Let's Make Greater Accra Work." <https://www.facebook.com/letsmakegawork>.
- Frimpong, L. K., S. L. Mensah, and S. A. Okyere. 2024. "Closing the Policy-Implementation Gaps in e-Waste Management: Implications for Circular Economy and Sustainability in Urban Ghana." In *Urban Slums and Circular Economy Synergies in the Global South*, edited by S. A. Okyere, M. Abunyah, M. O. Erdiaw-Kwasie, and F. G. Boateng, 173–191. Springer. https://doi.org/10.1007/978-981-99-9025-2_10.
- Gabriel, N., and C. O'Connor. 2022. "Can Confirmation Bias Improve Group Learning?: Center for Open Science."
- GIZ E-Waste Programme and MESTI-PIU. 2022. "Baseline Study: Assessing the Baseline of the e-Waste Sector in Ghana." <https://www.giz.de/en/downloads/giz2022-en-baseline-study-ghana.pdf>. (Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH).
- Grant, K., F. C. Goldizen, P. D. Sly, et al. 2013. "Health Consequences of Exposure to e-Waste: A Systematic Review." *Lancet Global Health* 1, no. 6: e350–e361. [https://doi.org/10.1016/s2214-109x\(13\)70101-3](https://doi.org/10.1016/s2214-109x(13)70101-3).
- Grant, R., and M. Oteng-Ababio. 2019. "Electronic-Waste Circuitry and Value Creation in Accra, Ghana." In *Value Chains in Sub-Saharan Africa. I Advances in African Economic, Social and Political Development*, edited by S. Scholvin, A. Black, J. Revilla Diez, and I. Turok, 115–131. Springer. https://doi.org/10.1007/978-3-030-06206-4_8.
- Grant, R., M. Oteng-Ababio, and M. Shin. 2024. "Academic Urban Legend, Agbogbloshie: Sweeping Away the World's Largest e-Waste Dumpsite." *Habitat International* 149: 103097. <https://doi.org/10.1016/j.habitatint.2024.103097>.
- Greenpeace. 2008. "Poisoning the poor. Electronic Waste in Ghana." <https://www.fairphone.com/wp-content/uploads/2013/11/poisoning-the-poor-electronic.pdf>.
- Groundstroem, F., and S. Juhola. 2021. "Using Systems Thinking and Causal Loop Diagrams to Identify Cascading Climate Change Impacts on Bioenergy Supply Systems." *Mitigation and Adaptation Strategies for Global Change* 26, no. 7: 29. <https://doi.org/10.1007/s11027-021-09967-0>.
- Harfadli, M. M'a., B. S. Ramadan, I. Rachman, and T. Matsumoto. 2024. "Challenges and Characteristics of the Informal Waste Sector in Developing Countries: An Overview." *Journal of Material Cycles and Waste Management* 26, no. 3: 1294–1309. <https://doi.org/10.1007/s10163-024-01929-3>.
- Hedelin, B., M. Evers, J. Alkan-Olsson, and A. Jonsson. 2017. "Participatory Modelling for Sustainable Development: Key Issues Derived From Five Cases of Natural Resource and Disaster Risk Management." *Environmental Science and Policy* 76: 185–196. <https://doi.org/10.1016/j.envsci.2017.07.001>.
- Hinchliffe, D., E. Gunsilius, M. Wagner, et al. 2020. "Case Studies and Approaches to Building Partnerships Between the Informal and the Formal Sector for Sustainable e-Waste Management." https://www.step-initiative.org/files/_documents/publications/Partnerships-between-the-informal-and-the-formal-sector-for-sustainable-e-waste-management.pdf.
- Hossain, R., and V. Sahajwalla. 2024. "Current Recycling Innovations to Utilize e-Waste in Sustainable Green Metal Manufacturing." *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 382, no. 2284: 20230239. <https://doi.org/10.1098/rsta.2023.0239>.
- Hubacek, K., F. Ravera, D. Tarrasón, and C. Prell. 2017. "Participatory Modeling." In *International Encyclopedia of Geography*, edited by D. Richardson, N. Castree, M. F. Goodchild, A. Kobayashi, W. Liu, and R. A. Marston, 1–8. Wiley.
- Hutami, A. W. S., A. D. Setiawan, and A. Hidayatno. 2020. "A Conceptual Model for Increasing Consumer Awareness on e-Waste Management in Indonesia." in Proceedings of the 3rd Asia Pacific Conference on Research in Industrial and Systems Engineering 2020. New York, NY, USA.
- Inam, A., J. Adamowski, J. Halbe, and S. Prasher. 2015. "Using Causal Loop Diagrams for the Initialization of Stakeholder Engagement in Soil Salinity Management in Agricultural Watersheds in Developing Countries: A Case Study in the Rechna Doab Watershed, Pakistan." *Journal of Environmental Management* 152: 251–267. <https://doi.org/10.1016/j.jenvman.2015.01.052>.
- Islam, M. T., N. Huda, A. Baumber, et al. 2021. "A Global Review of Consumer Behavior Towards e-Waste and Implications for the Circular Economy." *Journal of Cleaner Production* 316: 128297. <https://doi.org/10.1016/j.jclepro.2021.128297>.
- Ismail, H., and M. M. Hanafiah. 2021. "Evaluation of e-Waste Management Systems in Malaysia Using Life Cycle Assessment and Material Flow Analysis." *Journal of Cleaner Production* 308: 127358. <https://doi.org/10.1016/j.jclepro.2021.127358>.
- Jain, M., D. Kumar, J. Chaudhary, S. Kumar, S. Sharma, and A. Singh Verma. 2023. "Review on e-Waste Management and Its Impact on the Environment and Society." *Waste Management Bulletin* 1, no. 3: 34–44. <https://doi.org/10.1016/j.wmb.2023.06.004>.
- Jangre, J., K. Prasad, and D. Patel. 2022. "Analysis of Barriers in e-Waste Management in Developing Economy: An Integrated Multiple-Criteria Decision-Making Approach." *Environmental Science and Pollution Research* 29, no. 48: 72294–72308. <https://doi.org/10.1007/s11356-022-21363-y>.
- Jayaprakash, P., and R. R. Pillai. 2016. "An Integrated Model for e-Waste Management in India Using Systems Thinking." *Management and Labor Studies* 41, no. 1: 45–57. <https://doi.org/10.1177/0258042X16649464>.
- Kawulich, B. B. 2005. "Participant Observation as a Data Collection Method." *Forum Qualitative Sozialforschung / Forum: Qualitative Social Research* 6, no. 2: 466. <https://doi.org/10.17169/fqs-6.2.466>.
- Kédoté, N. M., G. E. Sopoh, S. B. Tobada, et al. 2022. "Perceived Stress at Work and Associated Factors Among e-Waste Workers in French-Speaking West Africa." *International Journal of Environmental Research and Public Health* 19, no. 2: 851. <https://doi.org/10.3390/ijerph19020851>.
- Kelbessa, W. 2023. "Environmental Injustice and Disposal of Hazardous Waste in Africa." In *The Palgrave Handbook of Global Sustainability*, edited by R. Brinkmann, 1957–1975. Springer International Publishing.
- Kemal, M. I., and R. Ardi. 2022. "A Causal Loop Analysis for Proposed e-Waste Funding Scheme in Indonesia." in Proceedings of the International Conference on Industrial Engineering and Operations Management. Michigan, USA. (IEOM Society International). 1–9.
- Khan, A. U. R., and R. W. Ahmad. 2022. "A Blockchain-Based IoT-Enabled e-Waste Tracking and Tracing System for Smart Cities." *IEEE Access* 10: 86256–86269. <https://doi.org/10.1109/access.2022.3198973>.
- Kieckhäfer, K., K. Wachter, and T. S. Spengler. 2017. "Analyzing Manufacturers' Impact on Green Products' Market Diffusion—The Case of Electric Vehicles." *Journal of Cleaner Production* 162: S11–S25. <https://doi.org/10.1016/j.jclepro.2016.05.021>.
- Kirby, P. W., and A. Lora-Wainwright. 2015. "Exporting Harm, Scavenging Value: Transnational Circuits of e-Waste Between J Apan, C Hina and Beyond." *Area* 47, no. 1: 40–47. <https://doi.org/10.1111/area.12169>.
- Kumi, E., M. Hemkhaus, and T. Bauer. 2019. "Money Dey for Borla: An Assessment of Ghana's e-Waste Value Chain." Berlin. https://adelphi.de/de/system/files/mediathek/bilder/money%20dey%20for%20borla%20-%20assessment%20of%20ghana%e2%80%99s%20e-waste%20value%20chain%20-%20adelphi_0.pdf.
- Kumi, E., M. Hemkhaus, S. Hibler, P. Boateng, and I. Von Falkenhausen. 2021. "Trust Be Key. Exploring Pathways to Formalisation in Ghana's

- e-Waste Sector.” https://adelphi.de/de/system/files/mediathek/bilder/trust_be_key_final.pdf.
- Kyere, V. N. 2016. “Environmental and Health Impacts of Informal e-Waste Recycling in Agbogboshie, Accra, Ghana: Recommendations for Sustainable Management.” Dissertation. In Rheinische Friedrich-Wilhelms-Universität Bonn. <https://bonndoc.ulb.uni-bonn.de/xmlui/bitstream/handle/20.500.11811/6744/4325.pdf?sequence=1>.
- Leclerc, S. H., and M. G. Badami. 2020. “Extended Producer Responsibility for e-Waste Management: Policy Drivers and Challenges.” *Journal of Cleaner Production* 251: 119657. <https://doi.org/10.1016/j.jclepro.2019.119657>.
- Liebovitch, L. S., P. T. Coleman, and J. Fisher. 2020. “Approaches to Understanding Sustainable Peace: Qualitative Causal Loop Diagrams and Quantitative Mathematical Models.” *American Behavioral Scientist* 64, no. 2: 123–144. <https://doi.org/10.1177/0002764219859618>.
- Lu, Y., B. Yang, Y. Gao, and Z. Xu. 2022. “An Automatic Sorting System for Electronic Components Detached From Waste Printed Circuit Boards.” *Waste Management (New York, N.Y.)* 137: 1–8. <https://doi.org/10.1016/j.wasman.2021.10.016>.
- Miao, S., D. Liu, J. Ma, and F. Tian. 2020. “System Dynamics Modelling of Mixed Recycling Mode Based on Contract: A Case Study of Online and Offline Recycling of e-Waste in China.” *Mathematical and Computer Modelling of Dynamical Systems* 26, no. 3: 234–252. <https://doi.org/10.1080/13873954.2020.1762096>.
- Mirchi, A., K. Madani, D. Watkins, and S. Ahmad. 2012. “Synthesis of System Dynamics Tools for Holistic Conceptualization of Water Resources Problems.” *Water Resources Management* 26, no. 9: 2421–2442. <https://doi.org/10.1007/s11269-012-0024-2>.
- Mullen, B., R. Brown, and C. Smith. 1992. “Ingroup Bias as a Function of Salience, Relevance, and Status: An Integration.” *European Journal of Social Psychology* 22, no. 2: 103–122. <https://doi.org/10.1002/ejsp.2420220202>.
- Narkhede, G., V. Dohale, and Y. Mahajan. 2024. “Darker Side of Industry 4.0 and Its Impact on Triple-Bottom-Line Sustainability.” *Sustainable Development* 32, no. 6: 5999–6016. <https://doi.org/10.1002/sd.3009>.
- Odeyingbo, O., I. Nnorom, and O. Deubzer. 2017. “Person in the Port Project: Assessing Import of Used Electrical and Electronic Equipment Into Nigeria.” http://collections.unu.edu/eserv/unu:6349/pip_report.pdf.
- Olabisi, L. S., S. Liverpool-Tasie, L. Rivers, et al. 2018. “Using Participatory Modeling Processes to Identify Sources of Climate Risk in West Africa.” *Environment Systems and Decisions* 38, no. 1: 23–32. <https://doi.org/10.1007/s10669-017-9653-6>.
- Orisakwe, O. E., C. Frazzoli, C. E. Ilo, and B. Oritsemuelebi. 2019. “Public Health Burden of e-Waste in Africa.” *Journal of Health and Pollution* 9, no. 22: 190610. <https://doi.org/10.5696/2156-9614-9.22.190610>.
- Osseo-Asare, D. K., and Y. Abbas. 2012. “Agbogboshie Makerspace Platform.” <https://www.visibleproject.org/project-4/agbogboshie-makerspace-platform/>.
- Oteng-Ababio, M. 2012. “When Necessity Begets Ingenuity: e-Waste Scavenging as a Livelihood Strategy in Accra, Ghana.” *African Studies Quarterly* 13, no. 1&2: 1–22.
- Oteng-Ababio, M., E. F. Amankwaa, and M. A. Chama. 2014. “The Local Contours of Scavenging for e-Waste and Higher-Valued Constituent Parts in Accra, Ghana.” *Habitat International* 43: 163–171. <https://doi.org/10.1016/j.habitatint.2014.03.003>.
- Owusu-Sekyere, K., and D. A. Aladago. 2023. “Material Flow Analysis and Risk Evaluation of Informal e-Waste Recycling Processes in Ghana: Towards Sustainable Management Strategies.” *Journal of Cleaner Production* 430: 139706. <https://doi.org/10.1016/j.jclepro.2023.139706>.
- Owusu-Twum, M. Y., G. Kumi-Amoah, W. K. Heve, et al. 2022. “Electronic Waste Control and Management in Ghana: A Critical Assessment of the Law, Perceptions and Practices.” *Waste Management and Research: The Journal for a Sustainable Circular Economy* 40, no. 12: 1794–1802. <https://doi.org/10.1177/0734242X221103939>.
- Patil, R. A., and S. Ramakrishna. 2020. “A Comprehensive Analysis of e-Waste Legislation Worldwide.” *Environmental Science and Pollution Research* 27, no. 13: 14412–14431. <https://doi.org/10.1007/s11356-020-07992-1>.
- Perrone, A., A. Inam, R. Albano, J. Adamowski, and A. Sole. 2020. “A Participatory System Dynamics Modeling Approach to Facilitate Collaborative Flood Risk Management: A Case Study in the Bradano River (Italy).” *Journal of Hydrology* 580: 124354. <https://doi.org/10.1016/j.jhydrol.2019.124354>.
- Petridis, N. E., K. Petridis, and E. Stiakakis. 2020. “Global e-Waste Trade Network Analysis.” *Resources, Conservation and Recycling* 158: 104742. <https://doi.org/10.1016/j.resconrec.2020.104742>.
- Prakash, S., and A. Manhart. 2010. “Socio-Economic Assessment and Feasibility Study on Sustainable e-Waste Management in Ghana.” (Öko-Institut e.V.). <http://ressourcenfiebers.org/publications/reports/2010-105-en.pdf>.
- Prakash, S., A. Manhart, Y. Amoyaw-Osei, and O. O. Agyekum. 2010. “Socio-Economic Assessment and Feasibility Study on Sustainable e-Waste Management in Ghana.” In *Öko-Institut in Cooperation With Ghana Environmental Protection Agency (EPA) and Green Advocacy Ghana, Ministry of Housing, Spatial Planning and the Environment, VROM-Inspectorate*. Öko-Institut. <http://ressourcenfiebers.org/publications/reports/2010-105-en.pdf>.
- Puzzo, G., and G. Prati. 2025. “Unraveling the Influence of Convenience Situational Factors on e-Waste Recycling Behaviors: A Goal-Framing Theory Approach.” *Sustainable Development* 33, no. 1: 1174–1191. <https://doi.org/10.1002/sd.3164>.
- Rafew, S. M., and I. M. Rafizul. 2021. “Application of System Dynamics Model for Municipal Solid Waste Management in Khulna City of Bangladesh.” *Waste Management* 129: 1–19. <https://doi.org/10.1016/j.wasman.2021.04.059>.
- Rekdal, O. B. 2014. “Academic Urban Legends.” *Social Studies of Science* 44, no. 4: 638–654. <https://doi.org/10.1177/0306312714535679>.
- Richards, K. A. R., and M. A. Hemphill. 2018. “A Practical Guide to Collaborative Qualitative Data Analysis.” *Journal of Teaching in Physical Education* 2, no. 37: 225–231. <https://core.ac.uk/download/pdf/345094936.pdf>.
- Roxas, F. M. Y., J. P. R. Rivera, and E. L. M. Gutierrez. 2019. “Locating Potential Leverage Points in A Systems Thinking Causal Loop Diagram Toward Policy Intervention.” *World Futures* 75, no. 8: 609–631. <https://doi.org/10.1080/02604027.2019.1654784>.
- Saavedra, M., M. Ricardo, O. Fontes, C. Hora de, M. Freires, and F. Gaudêncio. 2018. “Sustainable and Renewable Energy Supply Chain: A System Dynamics Overview.” *Renewable and Sustainable Energy Reviews* 82: 247–259. <https://doi.org/10.1016/j.rser.2017.09.033>.
- Sahoo, S., A. Mukherjee, and R. Halder. 2021. “A Unified Blockchain-Based Platform for Global e-Waste Management.” *IJWIS* 17, no. 5: 449–479. <https://doi.org/10.1108/IJWIS-03-2021-0024>.
- Schluep, M. 2014. “Chapter 29—Informal Waste Recycling in Developing Countries.” In *HANDBOOK of Recycling. State-Of-The-Art for Practitioners, Analysts, and Scientists*, edited by E. Worrell and M. A. Reuter, 439–444. Elsevier. <https://www.sciencedirect.com/science/article/pii/B9780123964595000295>.
- Schluep, M., T. Terekhova, A. Manhart, E. Müller, D. Rochat, and O. Osibanjo. 2012. “Where Are WEEE in Africa?” in 2012 Electronics Goes Green 2012+, 1–6.
- Shahabuddin, M., M. N. Uddin, J. I. Chowdhury, et al. 2023. “A Review of the Recent Development, Challenges, and Opportunities of Electronic Waste (e-Waste).” *International Journal of Environmental Science and*

Technology 20, no. 4: 4513–4520. <https://doi.org/10.1007/s13762-022-04274-w>.

Stacey, P., and C. Lund. 2016. “In a State of Slum: Governance in an Informal Urban Settlement in Ghana.” *Journal of Modern African Studies* 54, no. 4: 591–615. <https://doi.org/10.1017/s0022278x16000586>.

Sterman, J. D. 2000. *Business Dynamics: Systems Thinking and Modeling for a Complex World*. McGraw-Hill.

Teófilo, P., and N. C. R. Bergiante. 2024. “Modeling the Dynamics of Urban Mining e-Waste in the Cities: A System Dynamics Perspective of Rio de Janeiro’s Case.” in International Joint Conference on Industrial Engineering and Operations Management Proceedings: International Joint Conference on Industrial Engineering and Operations Management.

Thukral, S., D. Shree, and S. Singhal. 2023. “Consumer Behaviour Towards Storage, Disposal and Recycling of e-Waste: Systematic Review and Future Research Prospects.” *Benchmarking: An International Journal* 30, no. 3: 1021–1072. <https://doi.org/10.1108/BIJ-12-2021-0774>.

Turner, M. E., and A. R. Pratkanis. 1998. “Twenty-Five Years of Groupthink Theory and Research: Lessons From the Evaluation of a Theory.” *Organizational Behavior and Human Decision Processes* 73, no. 2/3: 105–115. <https://doi.org/10.1006/obhd.1998.2756>.

Voinov, A., and F. Bousquet. 2010. “Modelling With Stakeholders.” *Environmental Modelling and Software* 25, no. 11: 1268–1281. <https://doi.org/10.1016/j.envsoft.2010.03.007>.

Walther, G., J. Wansart, K. Kieckhäfer, E. Schnieder, and T. S. Spengler. 2010. “Impact Assessment in the Automotive Industry: Mandatory Market Introduction of Alternative Powertrain Technologies.” *System Dynamics Review* 26, no. 3: 239–261. <https://doi.org/10.1002/sdr.453>.

Wang, C., F. Zhao, and C. Handwerker. 2022. “Transforming and Integrating Informal Sectors Into Formal e-Waste Management System: A Case Study in Guiyu, China.” *CTR* 2, no. 4: 225–246. <https://doi.org/10.3934/ctr.2022012>.

World Health Organization. 2021. “Children and Digital Dumpsites: e-Waste Exposure and Child Health.” <https://www.who.int/publications/i/item/9789240023901>.

Xue, R., F. Zhang, and F. Tian. 2018. “A System Dynamics Model to Evaluate Effects of Retailer-Led Recycling Based on Dual Chains Competition: A Case of e-Waste in China.” *Sustainability* 10, no. 10: 3391. <https://doi.org/10.3390/su10103391>.

Yao, Z., T.-C. Ling, P. K. Sarker, et al. 2018. “Recycling Difficult-To-Treat e-Waste Cathode-Ray-Tube Glass as Construction and Building Materials: A Critical Review.” *Renewable and Sustainable Energy Reviews* 81: 595–604. <https://doi.org/10.1016/j.rser.2017.08.027>.

Appendix A

Overview of variables of the CLD and their categorization.

TABLE A1 | Overview of variables and their categories in the CLD.

Category	Variables
0	Central variables of interest (dark blue in Figure A1)
1	Variables originally influencing AHE, ScD income, and emissions (orange in Figure A1)
2	Measures to counteract undesired effects on ScD income, health, or emissions (red in Figure A1)
3	Obstacles to the implementation of measures (purple in Figure A1)
4	Enablers to the implementation of measures (light blue in Figure A1)
5	Consequences from measures (green in Figure A1)

Category	Variables
0	ScD income health emissions from EwT
1	<ul style="list-style-type: none"> • number of ScDs in IFS • e-waste available to IFS • immigration • attractiveness of jobs outside e-waste sector • sales price for recycled scrap • ScD productivity • costs for recycling scrap • perceived benefits from safe EwT • perceived benefits from EFET • demand for recycled scrap by industry • recycled scrap sold per ScD • fractions recycled per item • wastes from EwT dumped • amount of e-waste generated • price paid to consumer at door collection by IFS • demand for raw material (= e-waste) • cost for raw material (= e-waste) • e-waste treated in IFS • e-waste collected by formal sector • e-waste dumped or burned • EFET • safe EwT
2	<ul style="list-style-type: none"> • success of F&R • use of PPE • EFTec available to IFS • participation in training • governmental support • evictions
3	<ul style="list-style-type: none"> • corruption • dominance of IFS • fluctuations
4	<ul style="list-style-type: none"> • trust in IFS • trust in Government and associations • trust in leaders • investment in IFS • incentives/sanctions • participation in governmental processes • share of IFS represented by associations • supporting influence from local leaders • effectivity of training • research and university education • education and literacy • entrepreneurs in IFS
5	<ul style="list-style-type: none"> • scrap dealers pushed out of e-waste sector • knowledge on efficiency • knowledge on EFET • knowledge on policies • knowledge on safe ET • payout from social systems • payment to social systems

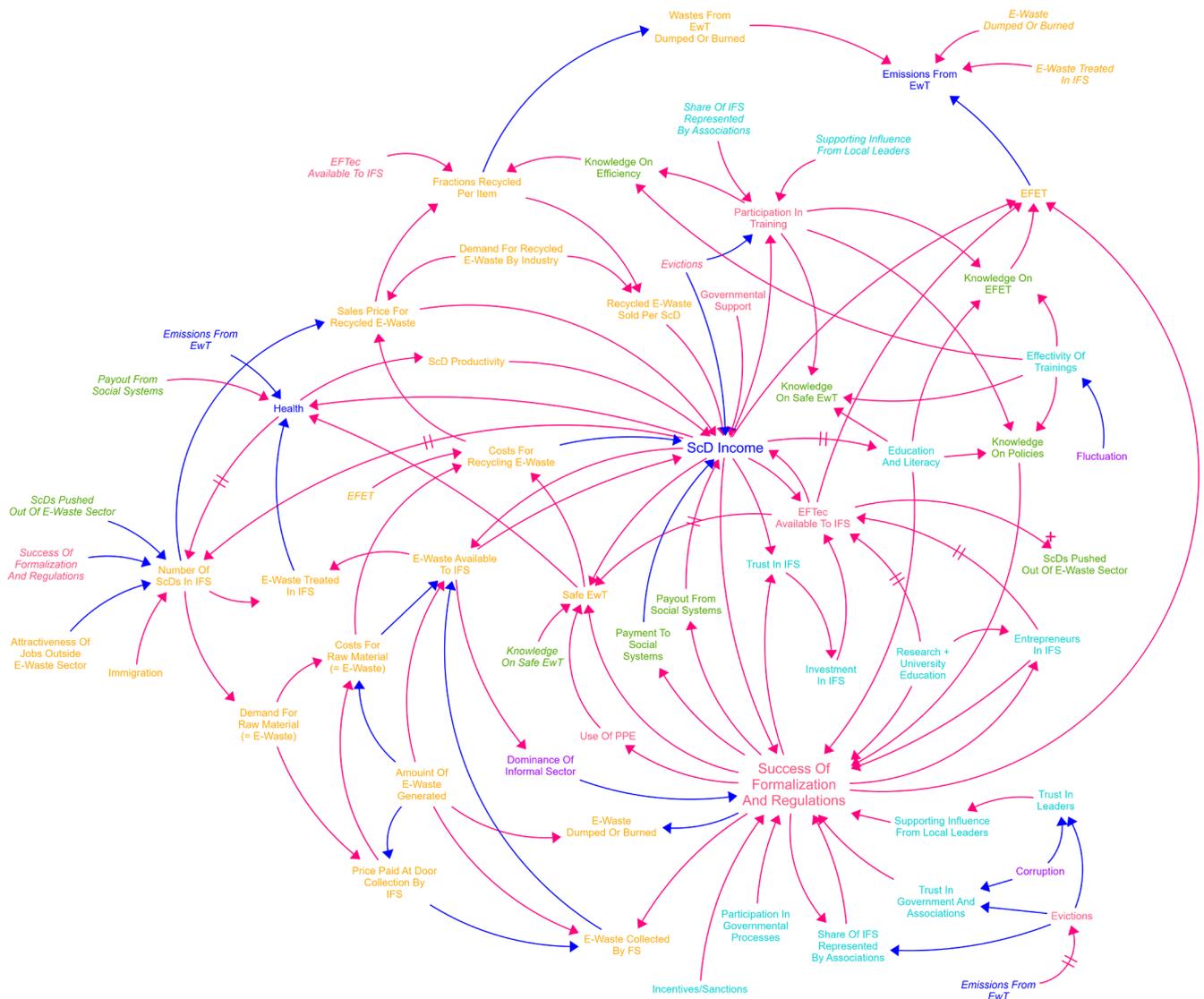


FIGURE A1 | CLD with categorized variables: Dark blue: Central variables of interest (category 0), orange: Variables originally influencing health, ScD income, and emissions, when no countermeasures are taken (category 1), red: Measures to counteract undesirable effects on ScD income, health, or emissions (category 2), purple: Obstacles to the implementation of measures (category 3), light blue: Enablers to the implementation of measures (category 4), green: Consequences from measures (category 5). Red arrows depict positive and blue arrows negative relationships.

