Waste Management 139 (2022) 158–167

Contents lists available at ScienceDirect

Waste Management

journal homepage: www.elsevier.com/locate/wasman

Assessing data in the informal e-waste sector: The Agbogbloshie Scrapyard

Karoline Owusu-Sekyere [a,*], Alexander Batteiger [b], Richard Afoblikame [b], Gerold Hafner [a], Martin Kranert [a]

[a] *University of Stuttgart, Institute for Sanitary Engineering, Water Quality and Solid Waste Management, Bandtäle 2, 70569 Stuttgart, Germany*
[b] *GIZ E-Waste Programme Office Accra, P.O. Box KA 9698, 7 Volta Street, Accra, Ghana*

ARTICLE INFO

Keywords:
E-Waste
Informal sector
Data assessment
Informal waste management
Material flow analysis
Participant observation

ABSTRACT

The Old-Fadama-Scrapyard, better known as Agbogbloshie, is located in Accra, Ghana. Over the last 20 years, the area has developed into a large scrapyard, where the informal sector processes mainly electronic waste (e-waste) and scrap metals. However, unsafe treatment methods, such as the open burning of cables and foams, and the spilling of hazardous liquids onto the ground, cause environmental pollution and create health risks by releasing persistent organic pollutants (POPs) and heavy metals.

There is a recognized lack in literature of data on e-waste mass and material flows due to the lack of applicable methods to measure e-waste quantities in an informally managed treatment system. However, to establish sustainable e-waste management, e-waste mass and material flow data are crucial prerequisites. Therefore, the material flow analysis (MFA) methodology is proposed as a means for data collection within a limited time frame in the informal e-waste recycling context.

In this case study, mass and material flows of e-waste processed at Agbogbloshie were estimated using two different approaches: Firstly, the kind, measures, constitution of load and number of loaded entering and exiting vehicles was observed and documented, and second, to validate the data collected, the mass and material flow of e-waste treatment processes on site were observed and documented.

The resulting annual mass flows range between 13,090 t/a and 17,094 t/a of e-waste. Based on the data for Ghana from the Global E-waste Monitor, an average of 15,092 t/a (approximately 39% of the Ghanaian e-waste generation) is treated in Agbogbloshie.

1. Introduction

E-waste is one of the largest sources of heavy metals and organic pollutants in municipal solid waste (Chi et al., 2011). With an annual growth rate of 3–5%, e-waste is one of the fastest-growing waste streams in the world (Cucchiella et al., 2015). In 2019, approximately 53.9 million metric tons of e-waste were generated globally, and about 82.6% of that is likely dumped, traded, or informally recycled (Forti et al., 2020). African countries are the fastest-growing economies globally, leading to an increase in the use of electrical and electronic equipment (EEE) and a corresponding increase in the generation of local e-waste (Asante et al., 2019). There is an absence of appropriate treatment facilities and legislation, and the e-waste recycling sector in developing countries is largely unregulated (Tsydenova and Bengtsson, 2011). Documented formal collection and recycling in Africa was estimated to be 0.9% (Forti et al., 2020). In most developing countries, the informal sector plays a vital role in the end-of-life management of e-waste (Leigh et al., 2007; Mueller et al., 2008; Widmer et al., 2005). Some recycling methods for e-waste require a certain technical standard due to hazardous components, such as the use of shredding and sorting machines or a controlled atmosphere storage preventing gaseous components (e.g. form refrigerators) to escape to the atmosphere. This increases recycling costs (Achillas et al., 2013). However, most developing and transition countries lack the needed technical standards and treatment systems, such as controlled incineration with flue gas cleaning or end processing for metals and slag (Kumar et al., 2017). In addition, formalized

Abbreviations: EEE, Electrical and electronic equipment; e-waste, Electronic waste; GASDA, Greater Accra Scrap Dealer Association; GPS, Global positioning system; ICT, Information and communication technology; MFA, Material flow analysis; MOU, Memorandum of understanding; PWB, Printed wiring boards; QGIS, Geoinformation system software; STAN, subSTance flow ANalysis: freeware developed at TU Vienna to perform material flow analysis according to the Austrian standard ÖNorm S 2096 (Material flow analysis - Application in waste management.

* Corresponding author.
E-mail address: Karoline.Owusu-Sekyere@iswa.uni-stuttgart.de (K. Owusu-Sekyere).

https://doi.org/10.1016/j.wasman.2021.12.026
Received 28 May 2021; Received in revised form 13 December 2021; Accepted 16 December 2021
Available online 28 December 2021

collection and registration, regulations, and policies are often missing (Sthiannopkao and Wong, 2013).

A sustainable e-waste management system should be based on sufficiently accurate data to estimate the quantities and composition of generated e-waste (Davis, 2021; Kiddee et al., 2013; Streicher-Porte et al., 2005). However, in developing countries, there is a lack of reliable data on treated e-waste quantities and types of devices because of the often complex informal organization of the system (Shittu et al., 2021).

1.1. E-Waste context in Ghana and the Agbogbloshie Scrapyard

Ghana has ratified both the Basel and the Bamako Conventions which regulate the transboundary movements of e-waste, but little implementation has taken place (Amoyaw-Osei et al., 2011; Daum et al., 2017). The Hazardous and Electronic Waste Control Management Act (Act 917) was adopted in 2016, and its implementation was launched by the president of Ghana in 2018 to regulate e-waste management in the country (Asante et al., 2019).

Studies have shown that e-waste collected for recycling in developed countries is illegally processed or disposed of in the developing world, including Ghana (Daum et al., 2017; Odeyingbo et al., 2017; Sander and Schilling, 2010). E-waste frequently enters the country as wrongly declared second-hand goods or working devices for donation and may end up as e-waste. Odeyingbo et al. (2017) show that although the Basel Convention bans the import of e-waste, legal compliance is still a serious problem in exporting and importing countries. Approximately 30–40% of imported second-hand electronics do not function. However, half of them can be repaired and sold locally (Schluep et al., 2012). In addition, imports of e-waste are hard to estimate since they are officially illegal and most of the studies focus on statistics (e.g. sales, stock or import data), which are often inaccurate and give inflated numbers of e-waste quantities (Odeyingbo et al., 2017). Therefore, the main e-waste stream does not come from importing e-waste for dismantling purposes but arises locally from new and used electronic equipment (Amoyaw-Osei et al., 2011; Odeyingbo et al., 2017; Schluep et al., 2012).

Ghana generated 52,000 tons of e-waste in 2019, of which 93–97% was collected and recycled by the informal sector through the well-established door-to-door collection (Amoyaw-Osei et al., 2011; Forti et al., 2020; Kyere, 2016; Schluep et al., 2013). However, unsafe treatment methods, such as the open burning of cables and plastics and the draining of liquids from cartridges or batteries onto the ground, expose workers and locals to hazardous chemicals such as heavy metals, dioxins, furans, and other persistent organic pollutants (Ikhlayel, 2018; Seitz, 2014; Tsydenova and Bengtsson, 2011).

The Old Fadama Scrapyard, better known as the Agbogbloshie Scrapyard, is Ghana's largest e-waste processing site (*notice: this Scrapyard was demolished by the Ghanaian government in July 2021. However, scrap dealers relocated to the surrounding places to continue their work.) The Agbogbloshie Scrapyard occupies about 31.3 ha and is located in the center of Ghana's capital Accra (Amankwaa et al., 2017). Mainly controlled by the Greater Accra Scrap Dealer Association (GASDA), the Scrapyard is highly organized in hierarchies and structures, where e-waste is processed and recycled by more than 300 small informal enterprises or shops (Amankwaa et al., 2017). The workers predominantly originate from the northern regions of Ghana and other countries such as Togo, Benin, and Nigeria (Adanu et al., 2020). While e-waste and scrap workers in Agbogbloshie are mostly young males with an average age of 21 years, women sell water and work as food vendors on site (Amankwaa and Oteng-Ababio, 2014). Manual dismantling is practised to extract valuables such as copper, iron, aluminium, and printed wiring boards (PWBs) from e-waste using unsustainable crude technologies (Adanu et al., 2020). The open burning of cables and waste residues for volume reduction, such as e-waste plastics, car tires, and fridge foams, is a common practice (Fujimori et al., 2016). Supporting occupations such as collectors, dismantlers, scrap dealers, burners, refurbishes and repairers, intermediaries, blacksmiths, and toolmakers can be found on site (Amoyaw-Osei et al., 2011). Informal small-scale enterprises act together within the e-waste process chain. Valuable fractions, such as iron or aluminium, generated by dismantling e-waste and scrap, are treated and extracted for downstream markets (Amoyaw-Osei et al., 2011).

1.2. Methodologies to estimate e-waste quantities and types

The assessment of e-waste quantities and types in developing countries requires a comprehensive and structured approach (Schluep et al., 2013).

There are several classifications for the quantification of e-waste generation. Wang et al. (2013) divided the data assessment into four groups: Disposal Related Analysis, Time Series Analysis (Projections), Factor Models, and Input-Output Analysis.

A widely accepted method for assessing data within complex and inconsistent structures is material flow analysis (MFA) (Duygan and Meylan, 2015; Ibrahim et al., 2013; Jain and Sareen, 2006; Steubing et al., 2010; Streicher-Porte et al., 2005). An MFA is a systematic assessment of material flows and stocks in a defined system that connects sources, pathways, and intermediate and final material sinks. In accordance with the law of conservation of matter, the results of an MFA can be controlled by a material balance (Brunner and Rechberger, 2004). It involves four steps: (i) problem analysis, determination of relevant substances, processes, materials, and system boundaries, (ii) determination and assessment of data, (iii) calculation of mass and material flows, and (iv) interpretation of the results (Brunner and Rechberger, 2004; Steubing et al., 2010).

According to Islam and Huda (2019), an MFA is a data-intensive tool. For data collection of e-waste within an MFA, sales data, stock data, and data on a lifespan basis are used. Data quantity and quality are the biggest challenges, even in developed countries. In developing countries, the informal e-waste sector is frequently ignored due to insufficient data, and further MFA studies in this field are needed. Quantification assessment in developing countries is iterative with a mixed 'top-down' and 'bottom-up' approach. Common methods for uncertainty calculation are difficult to perform when data originates from different and mixed sources, such as measurements and statistics. However, this applies to most existing e-waste studies (Schluep et al., 2013).

To date, e-waste quantities in developing countries have mostly been assessed through lifetime data or import statistics since informal e-waste collection systems are the least documented (Schluep et al., 2013). The quality and the possibility of data collection in the informal sector depend on informal actors' willingness to cooperate. Usually, there are no data on business registrations or public data for informal small-scale businesses. Therefore, further field studies are required.

1.3. Estimations of e-waste generation in Ghana and Agbogbloshie Scrapyard

To estimate e-waste quantities in Ghana and specifically at Agbogbloshie, surveys, statistical data, and socio-economic assessments were used to obtain the necessary data (Amoyaw-Osei et al., 2011; Forti et al., 2020; Prakash et al., 2010). However, a direct comparison of estimated e-waste quantities exhibited considerable differences (see Table 1).

We assume that these significant divergences can be explained by the lack of consistent data, the complexity of informal recycling, and the different types of waste included in the analysis. The deviations of data in the literature limit the use of the data and pose a problem in understanding and improving Ghana's (informal) e-waste system.

Researchers should minimize the time spent on site for data collection because of severe health and safety hazards resulting from unsafe e-waste treatment methods. Additionally, some of the activities in informal scrapyards are illegal, leading to a volatile security situation.

To bridge the data gap, a method that allows a relatively fast and

Table 1
Literature analysis for e-waste treated in Ghana (total) and Agbogbloshie Scrapyard.

E-waste ($\frac{t}{a}$)	Area and frame	Method	Reference	Year
179,000	Total e-waste generation in Ghana	Socioeconomic Assessment	(Schluep et al., 2012)	2009
99,283	Recycled in the informal sector in Ghana (reflects about 93–97% of total e-waste generation)	Survey, Field Study	(Amoyaw-Osei et al., 2011)	2011
26,216	Total e-waste generation in Ghana	Trade statistics	(Baldé et al., 2015)	2014
39,000	Total e-waste generation in Ghana	Trade statistics	(Baldé et al., 2015)	2016
52,900	Total e-waste generation in Ghana	Trade statistics	(Forti et al., 2020)	2019

sufficiently accurate assessment and quantification of e-waste mass and material flows, the types of e-waste being processed, and the associated treatment processes in the informal sector was developed.

2. Materials and methods

A rapid methodology to assess informal e-waste data, minimizing the time used for field studies, was developed. First, the input and output flows were evaluated based on visual inspection. Second, participant observation was used to validate material flows in the informal sector for some indicator fractions. The combination of both is a rapid method for assessing e-waste types and quantities in the informal sector. A flowchart of the methodology is presented in Fig. 1.

2.1. Preliminary assessment

As a first step, an analysis of literature, project reports, and ongoing activities of development partners was conducted. The willingness of the involved actors to provide data and allow researchers to assess site data was a requirement. Without the understanding and approval of the active informal sector actors, there may be non-cooperation and fear of disclosure. Therefore, persons or institutions that can establish trustworthy relationships with informal sector actors were identified. The association's leadership representing informal actors on site (GASDA) was consulted, and the research project was introduced to them. A memorandum of understanding (MOU) was signed between the researchers and representatives of informal actors. To carry out such a study in other scrap yards, ethical clearance in form of a MOU should be obtained between the informal sector and the researchers, to respect the confidentiality of the operators.

Furthermore, the inclusion and cooperation of informal stakeholders is a key requisite in data collection and to ensure the physical safety of the researchers. While establishing contacts with informal actors, several walking tours were performed before data collection started. For further studies, a minimum of two walking tours in the research area is recommended. Data collected on these walking tours included area specifications, such as the size of the Agbogbloshie Scrapyard, number and location of frequently used entrances for transportation of goods, working days of the scrapyard and a rough initial estimate of the number of businesses and workers involved.

2.2. Method A: input-output analysis

At Agbogbloshie, there is no weighing bridge for trucks or mass balances of the involved actors. Thus, a visual inspection coupled with the measurement of the loading volume of transporting vehicles was chosen. For every incoming and outgoing vehicle, the type of load, vehicle size, day, and time were documented. In addition, measurements of the loading areas were taken, and the load composition was inspected and noted.

Waste is often transported as mixed loads to the Scrapyard. Furthermore, informal actors do not differentiate between scrap and e-waste. Informal treatment processes of e-waste, end-of-life vehicles (e.g., cars), and scrap metals are connected and take place in the same small-scale businesses. Therefore, visual inspection and photo documentation of the load of each passing vehicle was necessary to examine the components. Photos allow better traceability if a large number of vehicles must be inspected at the same time.

By estimating the bulk densities of the transported materials, the load and subsequently the mass and material flows were calculated. The bulk densities used for assessment are listed in Table 2.

Using the volumes of the load area of the vehicles and the retrieved bulk densities from Table 2, the mass of the metal fractions from dismantled e-waste on the vehicles was calculated.

The e-waste masses of full devices transported in a vehicle depend on the packing density and the type of device transported. Therefore, the average weights of the devices were used to calculate the e-waste input (see Table 3). Within Method B, for data validation, scrap dealers were interviewed about the average load weight of their scrap on different trucks and the amount of e-waste they bought in tons.

The observation timeframe was regular working hours at the Scrapyard between 6 am and 7 pm. For safety reasons, in Method A, no observations were undertaken at night. However, according to GASDA, no material enters at night, and there was no significant difference between the two assessment methods.

In general, a minimum of two representative workdays for data collection was proposed. To ensure that there were no unusual occurrences on these two working, confirming site visits were done on several other days. From this collected dataset, the mass flows of the detected materials were calculated over one year, within the working days of the Scrapyard.

2.3. Method B: participant observation

In Method B, participant observation was applied for the determination and identification of mass and material flows and recycling processes (Bernard and Gravlee, 2014; Kawulich, 2005). This method is widely used in anthropology and enables researchers to learn about people's natural settings and activities by observing and participating in them (Kawulich, 2005). During data collection, maintaining an objective distance, an open and non-judgmental attitude, and a strong interest in learning about others is considered important (Kawulich, 2005). The formulation of the interview questions, methods, and data collection was undertaken on this basis. Between November 2017 and February 2018, regular scrapyard visits for data collection took place on different weekdays to calculate the material flows and validate the responses of informal shop owners.

In Method B, data collection cannot consider all processes and waste types on a large scrapyard such as Agbogbloshie since the observation time is limited and should be minimized. Therefore, e-waste was selected as the focus and defined as an indicator fraction. The treatment processes relevant to this indicator fraction and their mass and material flows were assessed. The owners of informal small businesses in e-waste management were interviewed on the type and amount of processed material. The interviews included documentation of processed e-waste types and their quantities in tons (t) within a time frame specified by the worker, main output fractions of the process, further processing within the Scrapyard or outside, the treated e-waste type, and estimated weight of the devices.

In future studies, parameters such as the size of the site and the assessment time can be modified. Recording the GPS coordinates of the small-scale businesses (so-called shops or workshops) is recommended.

The number of small-scale businesses involved in a specific treatment process was counted. To determine whether a workshop exclusively

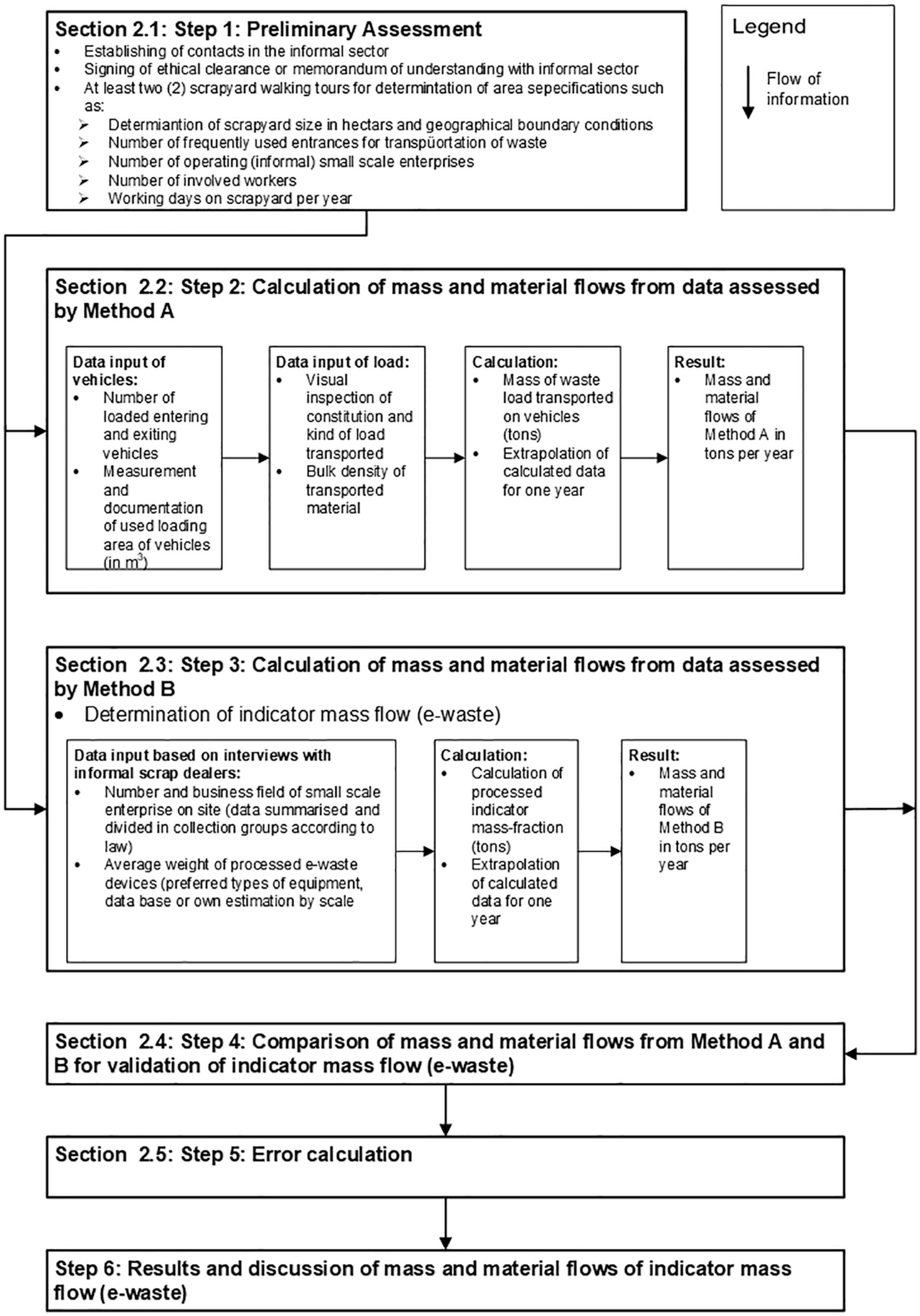


Fig. 1. Description of the developed methodology to assess e-waste quantities in the informal sector. The enumeration indicates the chapter of the paper.

treats one particular type of e-waste (e.g., fridges) or if several types are treated (e.g., laptops, phones, and desktop computers) should be assessed on-site and aligned through further interviews.

Input mass and material flows were calculated using processed units' average weights within one year and the number of shops, as shown in equation (1). Data on average mass from EEE units from the literature were retrieved and compared with the local composition of the processed e-waste evaluated during the interviews (Amoyaw-Osei et al., 2011; DRZ, 2013). This dataset forms the basis for the extrapolation of mass flows and is presented in Table 3.

$$\dot{m}_{po} = N_s \cdot m_d \cdot n_d \quad (1)$$

where is $\dot{m}_{po}$ the processed mass flow of a unit within a year in t/a, N_s is the number of shops per device or good (n), m_d is the average mass of the device or good in (t), and n_d is the number of units (n) processed during a year (a) by an informal small-scale enterprise.

Table 2
Bulk densities estimated for scrap fractions used to determine e-waste mass flow in Method A.

Material	Bulk Density in $[\frac{t}{m^3}]$	Source
Light Steel Scrap E1	0.5	(Bundesverband Sekundärrohstoffe und Entsorgung, n.d.)
Heavy Steel Scrap E3	0.6	(Bundesverband Sekundärrohstoffe und Entsorgung, n.d.)
Aluminium Scrap	0.1	Own calculation through grid boxes
Stainless Steel Scrap	0.5	(Bundesverband Sekundärrohstoffe und Entsorgung, n.d.)
Copper Scrap	0.7	Own calculation through stillage
Brass Scrap	0.65	Own calculation through grid boxes
Municipal Solid Waste	0.1	(Statistisches Landesamt Bayern, 2015)

The timeframe between consecutive purchases of waste usually differs strongly between shops. The e-waste for dismantling is bought depending on the economic situation and availability. Therefore, estimations for the annual processed quantities were based on interviews with the owners of the small-scale enterprises.

The following e-waste collection groups were used to classify the results of method B. The groups are aligned with the Ghanaian Act L. I.2250 (European Parliament, 2012; Government of Ghana, 2016): Group 1, large household appliances; Group 2, cooling appliances; Group 3, screens, monitors and TVs, IT, and telecommunication equipment; Group 4: Lighting equipment; Group 5: Small household appliances; Group 6: Photovoltaic.

The data from Method B were documented and analyzed using Microsoft Excel. The Substance Flow Analysis(STAN) program was used to calculate confidence intervals.

2.4. Validation of indicator fraction

The assessed quantities of the indicator fraction (e-waste) using Methods A and B were compared and reconciled to validate the results. Method B was used as a validation method to confirm the assessed e-waste mass flows in Method A.

By validating the indicator mass flow (e-waste), conclusions on the respective order of magnitude of the other assessed mass flows within Method A could be drawn.

The difference in the indicator mass flow (e-waste) assessed using the two methods was calculated for the validation. The difference can be rated according to the five confidence rating levels for an individual result of the MFA model, from very high (< ± 5%), high (±5% to 33%), medium (±33% to 67%), low (±67% to 95%), and very low (> ± 95%) (Laner et al., 2014).

The difference between the values assessed in Methods A and B should not exceed the maximum confidence level of ± 33%. If the difference between the two methods is greater than this value, the observation time of Method A should be increased. If it is below this value, the actual value of the material flow is expected somewhere between the two values. Therefore, we suggest calculating the average value of the two methodologies.

2.5. Method of error calculation

Collecting data in a given context is subject to uncertainties due to the informal setting or the absence of weighing bridges and other facilities. There are several approaches for calculating the uncertainties within an MFA. The confidence rating of Laner et al. (2014) considers the uncertainty of statistical variation and errors in direct measurements. This method was applied to make a qualitative statement regarding the accuracy of the assessed data. The qualitative and semi-qualitative approach of confidence ratings gives five confidence levels from very high (< ± 5%) to very low (> ± 95%), after which the calculated uncertainties can be rated according to (Laner et al., 2014).

3. Results and discussion

3.1. Preliminary assessment

The study area, the Agbogbloshie Scrapyard in Accra, is shown in Fig. 2. The data for area specifications found in literature could be confirmed through site visits. A size of 31.3 ha, with about 2000 involved workers in more than 300 informal small-scale enterprises was identified (Amankwaa et al., 2017). The system boundary includes areas where e-waste and scrap metals are processed. In other parts of the site, onion sellers or small-scale plastic recyclers (not e-waste plastics) are located.

The Agbogbloshie Scrapyard has two main entrances and is partly surrounded by the Korle Lagoon (see Fig. 2). After two field visits, only a small number of small vehicles were observed using the second entrance. The first entrance was selected for the input–output analysis because of the higher traffic load and limited observation time.

Table 3
Documented data and calculation of e-waste quantities within the collection groups.

E-Waste	Shops counted [No.]	Average weight in [kg]	Number of units processed per year and shop average [pieces]	Throughput estimated $[\frac{t}{a}]$	Source of the average weight of e-waste
Group 1: Large household appliances	20	35	1550		(DRZ, 2013; Own estimation* 2018)
Group 2: Fridge and AC mix	15	50	3100		(DRZ, 2013)
Group 2: Compressors mixed	100	10	1200		(DRZ, 2013; Own estimation* 2018)
Group 3: CRT TV/ Monitor	20	12	3100		(DRZ, 2013; Own estimation* 2018)
Group 3: LCD TV/ Monitor	20	8	3100		(DRZ, 2013; Own estimation* 2018)
Group 3: Printer	20	15		1000	(DRZ, 2013; Own estimation* 2018)
Group 3: Phones	5	0.2			
Group 3: Other	10	2			
Group 3: Laptops	20	2		One shop was estimated to treat 1 t within one week (52 weeks/year)**	(DRZ, 2013; Own estimation* 2018)
Group 3: Desktop Computer	20	18			
Group 5: Small household appliances	80	16	3250		(DRZ, 2013; Own estimation* 2018)

*Own estimation based on data collection of average weights of dismantled devices at Agbogbloshie scrapyard; ** Shops are treating different devices, including fractions and parts of group 3, therefore assessed through interviews,

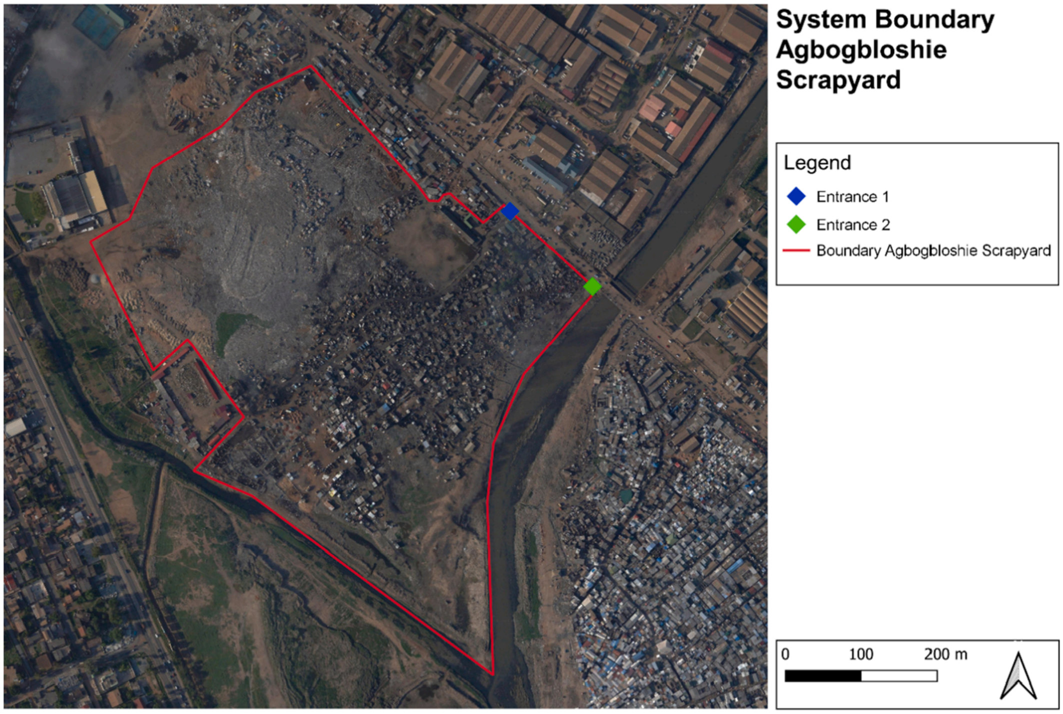


Fig. 2. System boundary of the case study (Source: Google Satellite, QGIS).

For the working days of the scrapyard 310 days per year were estimated due to the subtraction of 29 days for the month of Ramadan and of 26 days for Fridays, where only half day work is done.

3.2. Results of Method A: input - output analysis

Within the assessment period, 328 loaded vehicles entered the Scrapyard, and 92 loaded vehicles exited. The loaded entering vehicles are considerably smaller than the loaded leaving vehicles; thus, material

a) b) c) d)

Fig. 3. Typical informal transportation of e-waste/scrap to the Agbogbloshie Scrapyard, using a) bike transport, b) a so-called push-push, c) a tricycle and d) a small truck and d) entering or leaving the Scrapyard (own pictures).

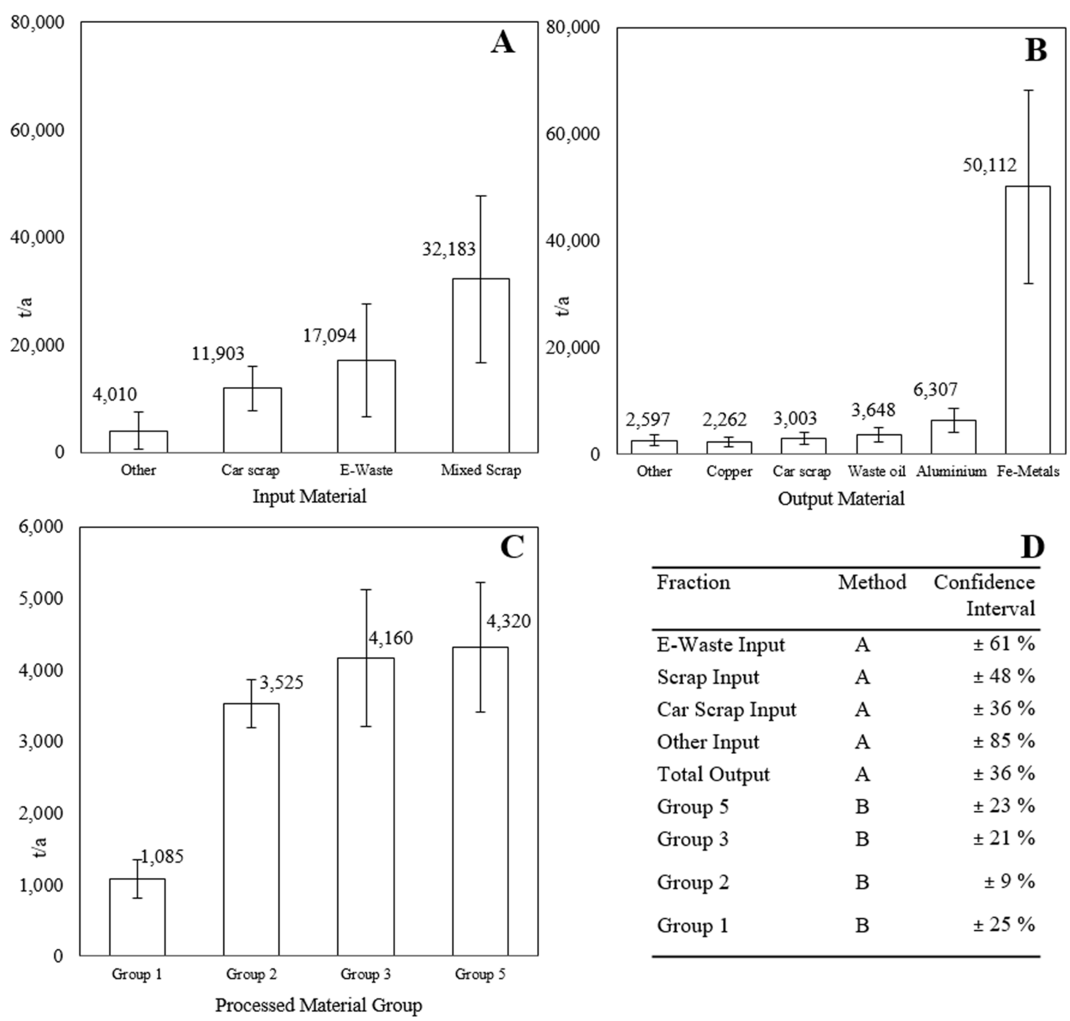
flows are consolidated and aggregated. Most big vehicles, such as trucks, enter empty and most smaller vehicles, such as tricycles, leave empty. For the mass flows only the loaded vehicles were considered. E-waste and scrap metals are usually transported into the scrapyard by bikes, motorbikes, hand carts, or tricycles and originate from household and street collection. Typical vehicles and loads are shown in Fig. 3. The output fractions of the Scrapyard are transported in trucks of all sizes, tricycles, bikes, and motorbikes. Most transport occurs during the late morning and early evening hours. Using Method A, the total inflow mass was calculated as 65,190 t/a. About 26% of all inflow masses is e-waste, which corresponds to 17,094 t/a. The most significant fraction brought to the Scrapyard is scrap metals originating from households or construction sites (49%). The share of car scrap was 20%. Other materials entering the Scrapyard include used oil, food supplies (such as millet, yam, and onions), tyres, and car batteries. The Agbogbloshie Scrapyard primarily deals with scrap metals and their recovery from different sources, such as end-of-life vehicles, household, and construction sites, rather than e-waste, as is often reported.

The total output mass flow is approximately 67,929 t/a, consisting mainly of dismantled iron scrap (74%), aluminium scrap (9%), and used oil (5%), as shown in Fig. 4. It is evident that the materials entering the scrapyard, such as e-waste and care scrap, are predominantly transformed into tradable metal scrap fractions and are sold to downstream traders on sites where they are mixed with scrap metals from other sources. They are not sold directly to the formal sector outside of the Scrapyard. Furthermore, informal collectors focus on e-waste with high intrinsic material values, often with high metal content. The plastic fractions arising from e-waste dismantling on-site are not sold due to limited market access and low plastic prices and remain on the Scrapyard. Therefore, these plastics are mostly burned for waste reduction purposes. In addition, other fractions such as oil and liquids form cartridges, while others are dumped into the ground.

The total observed output volume was approximately 4% higher than the total input mass flow. The reasons for the mass difference of in and output mass flows may be the limited observation time at other entrances, addition or subtraction to stocks on the Scrapyard, errors in data collection due to the counting and weight estimation without the exact weighing of vehicles, as well as non-continuous mass flows.

3.3. Results of Method B: participant observation

The processes observed at the Scrapyard through Method B could be categorized into four groups: pre-treatment processes, further processing, production processes, and administrative and commercial processes. Through interviews, the number of shops and e-waste-related treatment processes was assessed. The documented data are presented in Table 3. The weight of the e-waste devices was estimated according to data from an Austrian recycling enterprise (DRZ) and samples taken from the Scrapyard. Within the assessment, 52 processes related to e-waste treatment were identified in Agbogbloshie. Of these, 33 relate to pre-treatment, such as simple dismantling, 8 relate to further processing (such as the burning of cables or further dismantling), 6 relate to



Fraction	Method	Confidence Interval
E-Waste Input	A	± 61 %
Scrap Input	A	± 48 %
Car Scrap Input	A	± 36 %
Other Input	A	± 85 %
Total Output	A	± 36 %
Group 5	B	± 23 %
Group 3	B	± 21 %
Group 2	B	± 9 %
Group 1	B	± 25 %

Fig. 4. Fractions determined at the Agbogbloshie scrapyard A: input material flows assessed through Method A; B: output material flows assessed through Method A; C: Treated e-waste groups on site assessed through Method B; D: Calculated confidence levels of the assessed data.

production processes (such as the production of tools, cooking pots, and other goods), and 5 to administrative and commercial processes (such as weighing, trading, and transportation).

Manual e-waste dismantling processes aggregate tradeable fractions, such as metals and PWBs. Electronic and telecommunication devices are popular because they contain valuable PWBs. They are sorted into different grades according to the source device. Plastics and glass originating from e-waste are usually dumped or burned; however, certain plastics are collected at the Scrapyard and recycled locally or exported to other countries such as Nigeria.

Summing up the mass flows of the five different category equations assessed through Method B, the indicator mass flow or total e-waste mass flow at the Agbogbloshie Scrapyard is 13,090 t/a.

At the Agbogbloshie Scrapyard, compressors from cooling appliances are usually treated at several shops as a side business. Laptops, phones, and desktop computers are often treated at one shop. The same applies to small and large household appliances. For compressors and parts of information and communications technology (ICT) devices that are less common, estimations of the treated quantity were made based on the interviews. There were no treatment processes evident for the photovoltaic and lighting equipment. The distribution of the mass flows of the e-waste collection groups is shown in Fig. 4. Information on treatment processes in use can inform process-oriented improvement at the Scrapyard, such as introducing an oil collection system for compressor dismantling.

3.4. Validation of the two methodologies

The material flow for the indicator fraction for Method A was estimated at 17,094 t/a. Method B showed a total e-waste mass flow of 13,090 t/a for the Agbogbloshie Scrapyard, 23.4% less than Method A. A maximum deviation of ±33% for both values should not be exceeded to achieve high data quality. This confidence interval was chosen according to the qualitative confidence ratings and recommendations given in Laner et al. (2014) and based on the researcher's judgment of the data reliability and quality. If the deviation of both values is higher than ±33%, the time for data assessment should be increased, and the assessment should be repeated.

The deviation of the assessed data in the case study was within the accepted range of the methodology. Therefore, the real value is assumed to be between the two calculated values, approximately 15,092 t/a. Additionally, the total material likely flowing through Method A was also valid. Therefore, as Method B delivered a lower result, we can assume that the total input and output analysis values are a higher estimate of the material flow treated on the Agbogbloshie Scrapyard.

E-waste volumes are rapidly increasing in Ghana (Daum et al., 2017; Oteng-Ababio et al., 2014; Prakash et al., 2010). Therefore, to establish an adequate treatment facility, the larger value should probably be used in the design. However, the actual value is likely between the values of Methods A and B for the following reasons:

Method B delivered a lower result than Method A due to limited observation timeframes. There might be times, such as during festivals or the rainy season, where less material is brought to the Scrapyard. This seasonal change was not considered in the assessment. In addition, the buying and selling system of waste depends on economic factors of small-scale, informal actors, and the mass flow is not consistent. The data assessed in Method B could be an underestimation since the data are based on statements of the business owners, who find it difficult to accurately estimate processed quantities without formal accounting. In addition, business owners may fear losing business by disclosing data.

The informal e-waste recycling processes and their risks can be assessed through Method B to provide rapid insight into potential environmental and health hazards and to inform more sustainable e-waste management.

3.5. Confidence rating of the results

The data reliability and quality of the case study were rated in the high interval between ±5% and 33%, according to Laner et al. (2014) due to the relatively short observation time, the neglect of seasonal changes, stock situation, and economic influences within the case study area, the reliability of information from the interviews in Method B, the data assessment of visual observation, and average weight estimation of devices.

The confidence levels of the individual fractions were calculated manually for Method A and using the program STAN for Method B. Fig. 4 shows the confidence intervals calculated for Methods A and B. The confidence level of the two methods was ±20%.

By applying the two methodologies and comparing the indicator mass flows, the validity of the analysis is improved. Nevertheless, the assessed data have limited accuracy due to the relatively short observation time of Method A and other influences, such as the language barrier and workers' fear of disclosing information. Nevertheless, the information on e-waste flows in Ghana is considered sufficient. Therefore, a confidence level of ±20% is considered sufficiently accurate for e-waste data collection in the informal sector. Furthermore, a comparison of Methods A and B showed that the indicator flows of e-waste masses are in the same range. Therefore, it is unlikely that other, more extensive, e-waste loads enter the Scrapyard outside of the observation times.

4. Conclusion

Analysis and optimization of waste management systems depend on the availability of relevant basic data, particularly the structure of the waste management system under investigation and quantification of the relevant material and substance flows. In Ghana, data on e-waste quantities and types are limited. In most developing countries, the collection and treatment of e-waste mainly occur in the informal sector, and statistics on stocks and sales data are not readily available. A bottom-up approach to estimate e-waste generation in the informal sector was adopted. Data collection in an informal context is challenging and time-consuming due to the absence of infrastructure (e.g., weighing bridges), the health and safety risks in the area, the legal status of the informal actors, the fear of disclosing data, and inconsistent mass and material flows which are influenced by the availability of goods, economic factors, and seasonal changes.

Data collection through input–output analysis and participant observation delivered acceptable data accuracy to inform the planning of e-waste management systems, with an expected confidence interval of ±20%. A comparison of the data in both methods determined the validity of the collected data. The visual inspection methodology to calculate the in- and output flows delivered robust results and can be easily replicated in other scrapyards. Therefore, the process assessment results of Method B can be used as a reference framework to validate data collected through interviews with other scrapyards.

The estimated e-waste quantity in the case study at the Agbogbloshie Scrapyard is between 13,090 t/a and 17,094 t/a. The average value of 15,092 t/a from the Global E-waste Monitor for Ghana in 2017 indicates that approximately 39 % of the Ghanaian e-waste generation is treated in Agbogbloshie. The Agbogbloshie Scrapyard is considered the most significant informal e-waste processing site in Ghana (Forti et al., 2020). Considering the catchment area, number of inhabitants and the existence of other, smaller scrapyards in the Greater Accra Region, the order of magnitude of this study's results on e-waste quantities are in line with the data provided in the Global E-waste Monitor. Approximately 17% of the Ghanaian population lives in the Greater Accra Region, where the Scrapyard is located (Government of Ghana, 2020). This region has the strongest economy in the country and is therefore assumed to make use of most electrical and electronic devices which later accrues as e-waste.

The presented method in this study aims to do a rapid assessment presenting sufficiently accurate data for waste management purposes. In order to keep the time used for data collection adequate, the timeframe for data collection should be chosen accordingly short but sufficient enough for the purpose of the use of data. The proposed data collection timeframe in Method A is in total at least two days and visits on several other days for the exclusion of extraordinary activities on site during data collection need to be done. For Method B, a further two days of assessment is suggested, based on the boundary conditions such as the number of entrances, size of the area, and expected number of people involved in the treatment processes. Combining Method A and B allows data assessment over a relatively short observation time for the indicator faction e-waste. Nevertheless, the different geographic conditions and the resulting change in the observation time need to be considered when applying this method to other scrapyards.

To improve accuracy, the methods should be combined to account for all waste flows. In addition, the information given by waste workers needs to be cross-checked to minimize the risk of false information due to fear of disclosure. Overall, this research closes a knowledge gap on informal e-waste treatment in Ghana and can be applied to similar scrapyards. This study improves e-waste statistics and serves as a basis for enhancing e-waste management in Ghana.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research was supported by the GIZ Project “Environmentally Sound Disposal and Recycling of E-waste in Ghana”, funded by the German Federal Ministry for Economic Cooperation and Development (BMZ) and supported by the Ghanaian Ministry of Environment, Science, Technology and Innovation (MESTI). We thank our colleagues from the GIZ E-Waste project, especially Markus Spitzbart, who provided insight and expertise that greatly assisted the research.

This work was also supported by the Hans Böckler Stiftung (Funding No. 407867).

References

Achillas, C.h., Aidonis, D., Vlachokostas, C.h., Karagiannidis, A., Moussiopoulos, N., Loulos, V., 2013. Depth of manual dismantling analysis: a cost-benefit approach. Waste Manag. 33 (4), 948–956. https://doi.org/10.1016/j.wasman.2012.12.024.
Adanu, S.K., Gbedemah, S.F., Attah, M.K., 2020. Challenges of adopting sustainable technologies in e-waste management at Agbogbloshie, Ghana. Heliyon 6 (8), e04548. https://doi.org/10.1016/j.heliyon.2020.e04548.
Amankwaa, E.F., Adovor Tsikudo, K.A., Bowman, J., 2017. ‘Away’ is a place: the impact of electronic waste recycling on blood lead levels in Ghana. Sci. Total Environ. 601–602, 1566–1574. https://doi.org/10.1016/j.scitotenv.2017.05.283.
Amankwaa, E.F., Oteng-Ababio, M., 2014. The e-waste conundrum: balancing evidence from the North and on-the-ground developing countries’ realities for improved management. African Rev. Econ. Financ. 6, 181–204.
Amoyaw-Osei, Y., Agyekum, O.O., Pwamang, J.A., Mueller, E., Fasko, R., Schluep, M., 2011. Ghana e-waste country assessment, SBC e-waste Africa Project. Green Advocacy Ghana, EPA Ghana, Empa Switzerland.
Asante, K.A., Amoyaw-Osei, Y., Agusa, T., 2019. E-waste recycling in Africa: risks and opportunities. Curr. Opin. Green Sustain. Chem. 18, 109–117. https://doi.org/10.1016/j.cogsc.2019.04.001.
Baldé, C.P., Wang, F., Kuehr, R., Huisman, J., 2015. The global e-waste monitor -2014. United Nations University, IAS -SCYCLE, Bonn, Germany. doi: 10.1007/s00705-012-1479-4.
Bernard, H.R., Gravlee, C.C., 2014. Handbook of Methods in Cultural Anthropology. Rowman & Littlefield Publishers.
Brunner, P.H., Rechberger, H., 2004. Practical Handbook of Material Flow Analysis. Lewis Publishers.
Bundesverband Sekundärrohstoffe und Entsorgung, n.d. Europäische Schrottsortenliste [WWW Document]. URL https://www.bvse.de/images/pdf/schott-elektro-kfz/schrottsorten.pdf (accessed 12.10.17).
Chi, X., Streicher-Porte, M., Wang, M.Y.L., Reuter, M.A., 2011. Informal electronic waste recycling: a sector review with special focus on China. Waste Manag. 31 (4), 731–742. https://doi.org/10.1016/j.wasman.2010.11.006.
Cucchiella, F., D'Adamo, I., Lenny Koh, S.C., Rosa, P., 2015. Recycling of WEEEs: an economic assessment of present and future e-waste streams. Renew. Sustain. Energy Rev. 51, 263–272. https://doi.org/10.1016/j.rser.2015.06.010.
Daum, K., Stoler, J., Grant, R., 2017. Toward a more sustainable trajectory for e-waste policy: a review of a decade of e-waste research in Accra, Ghana. Int. J. Environ. Res. Public Health 14 (2), 135. https://doi.org/10.3390/ijerph14020135.
Davis, J.-M., 2021. A model to rapidly assess informal electronic waste systems. Waste Manag. Res. 39 (1), 101–107. https://doi.org/10.1177/0734242X20932225.
DRZ, 2013. Dismantling Data Collection Demontage und Recycling Zentrum Wien.
Duygan, M., Meylan, G., 2015. Strategic management of WEEE in Switzerland - Combining material flow analysis with structural analysis. Resour. Conserv. Recycl. 103, 98–109. https://doi.org/10.1016/j.resconrec.2015.06.005.
Parliament, E., 2012. Directive 2012/19/EU of the European Parliament and of the Council on waste electrical and electronic equipment (WEEE). Off. J. Eur. Union 13, 1–24. https://doi.org/10.3000/19770677.L_2012.197.eng.
Forti, V., Baldé, C.P., Kuehr, R., Bel, G., 2020. The Global E-waste Monitor 2020: Quantities, flows and the circular economy potential. United Nations University (UNU)/United Nations Institute for Training and Research (UNITAR) – co-hosted SCYCLE Programme, International Telecommunication Union (ITU) & International Solid Waste Association (ISWA), Bonn/Geneva/Rotterdam.
Fujimori, T., Itai, T., Goto, A., Asante, K., Otsuka, M., Takahashi, S., Tanabe, S., 2016. Interplay of metals and bromine with dioxin-related compounds concentrated in e-waste open burning soil from Agbogbloshie in Accra, Ghana. Environ. Pollut. 209, 155–163. https://doi.org/10.1016/j.envpol.2015.11.031.
Government of Ghana, 2020. Ghana Statistical Service [WWW Document]. URL https://www.statsghana.gov.gh/regionalpopulation.php?population=MTM0NTk2MjQzOS4yMDE1&&Greater Accra&regid=3.
Government of Ghana, 2016. Hazardous, electronic and other wastes control and management regulations L.I.2250 (No. L.I.2250). Accra.
Ibrahim, B.F., Adie, B.D., Okuofu, A.C., 2013. Material Flow Analysis of Electronic Wastes (e-waste) in Lagos, Nigeria. J. Environ. Prot. (Irvine,. Calif). 1011–1017.
Ikhlayel, M., 2018. An integrated approach to establish e-waste management systems for developing countries. J. Clean. Prod. 170, 119–130. https://doi.org/10.1016/j.jclepro.2017.09.137.
Islam, M.T., Huda, N., 2019. Material flow analysis (MFA) as a strategic tool in E-waste management: applications, trends and future directions. J. Environ. Manage. 244, 344–361. https://doi.org/10.1016/j.jenvman.2019.05.062.
Jain, A., Sareen, R., 2006. E-waste assessment methodology and validation in India. J. Mater. Cycles Waste Manag. 8 (1), 40–45. https://doi.org/10.1007/s10163-005-0145-2.
Kawulich, B.B., 2005. Participant observation as a data collection method. Forum Qual. Sozialforsch. 6 https://doi.org/10.17169/fqs-6.2.466.
Kiddee, P., Naidu, R., Wong, M.H., 2013. Electronic waste management approaches: an overview. Waste Manag. 33 (5), 1237–1250. https://doi.org/10.1016/j.wasman.2013.01.006.
Kumar, A., Holuszko, M., Crocce, D., Espinosa, R., 2017. Resources, Conservation and Recycling E-waste: an overview on generation, collection, legislation and recycling practices. Resour. Conserv. Recycl. 122, 32–42. https://doi.org/10.1016/j.resconrec.2017.01.018.
Kyere, V.N., 2016. Environmental and Health Impacts of Informal E-waste Recycling in Agbogbloshie, Accra, Ghana: Recommendations for Sustainable Management. Rheinische Friedrich-Wilhelms-Universität Bonn.
Laner, D., Rechberger, H., Astrup, T., 2014. Systematic evaluation of uncertainty in material flow analysis. J. Ind. Ecol. 18 (6), 859–870. https://doi.org/10.1111/jiec.12143.
Leigh, N.G., Realff, M.J., Ai, N., French, S.P., Ross, C.L., Bras, B., 2007. Modeling obsolete computer stock under regional data constraints: an Atlanta case study. Resour. Conserv. Recycl. 51 (4), 847–869. https://doi.org/10.1016/j.resconrec.2007.01.007.
Mueller, E., Schluep, M., Widmer, R., Gottschalk, F., Böni, H., 2008. Assessment of e-waste flows : a probabilistic approach to quantify e-waste based on world ICT and development indicators. Proceeding R09 Twin World Congr. Resour. Manag. Technol. Mater. Energy Effic. Sept. 1416 2009 Davosswitzerl. 7.
Odeyingbo, O., Nnorom, I., Deubzer, O., 2017. Person in the Port Project - Assessing Import of Used Electrical and Electronic Equipment into Nigeria 35.
Oteng-Ababio, M., Amankwaa, E.F., Chama, M.A., 2014. The local contours of scavenging for e-waste and higher-valued constituent parts in Accra, Ghana. Habitat Int. 43, 163–171. https://doi.org/10.1016/j.habitatint.2014.03.003.
Prakash, S., Manhart, A., Amoyaw-Osei, Y., Agyekum, O.O., 2010. Socio-economic assessment and feasibility study on sustainable e-waste management in Ghana. Öko-Institut e.V. - Institute of Applied Ecology, Freiburg/Darmstadt/Berlin.
Sander, K., Schilling, S., 2010. Optimierung der Steuerung und Kontrolle grenzüberschreitender Stoffströme bei Elektroaltgeräten/Elektroschrott, Umweltbundesamt. Hamburg.
Schluep, M., Müller, E., Hilty, L.M., Ott, D., Widmer, R., Böni, H., 2013. Insights from a decade of development cooperation in e-waste management. First Int. Conf. Inf. Commun. Technol. Sustain. 45–51 https://doi.org/10.5167/uzh-84886.
Schluep, M., Terekhova, T., Manhart, A., Muller, E., Rochat, D., Osibanjo, O., 2012. Where are WEEE in Africa? Electron. Goes Green 2012+, ECG 2012 - Jt. Int. Conf. Exhib. Proc.
Seitz, J., 2014. Analysis of Existing E-Waste Practices in MENA Countries; The Regional Solid Waste Exchange of Information and Expertise Network in Mashreq and Maghreb Countries (SWEEP-Net).
Shittu, O.S., Williams, I.D., Shaw, P.J., 2021. Global E-waste management: Can WEEE make a difference? A review of e-waste trends, legislation, contemporary issues and

future challenges. Waste Manag 120, 549–563. https://doi.org/10.1016/j.wasman.2020.10.016.
Statistisches Landesamt Bayern, 2015. Umrechnungsfaktoren für ausgewählte elektrische Haushaltsgeräte; Außenhandelsstatistik Berichtsjahr 2014 und 2015 [WWW Document]. URL https://www.statistik-bw.de/DatenMelden/Formularservice/33_A_Umrechnungsfaktoren.pdf (accessed 8.3.19).
Steubing, B., Böni, H., Schluep, M., Silva, U., Ludwig, C., 2010. Assessing computer waste generation in Chile using material flow analysis. Waste Manag. 30 (3), 473–482. https://doi.org/10.1016/j.wasman.2009.09.007.
Sthiannopkao, S., Wong, M.H., 2013. Handling e-waste in developed and developing countries: initiatives, practices, and consequences. Sci. Total Environ. 463–464, 1147–1153. https://doi.org/10.1016/j.scitotenv.2012.06.088.
Streicher-Porte, M., Widmer, R., Jain, A., Bader, H.-P., Scheidegger, R., Kytzia, S., 2005. Key drivers of the e-waste recycling system: Assessing and modelling e-waste processing in the informal sector in Delhi. Environ. Impact Assess. Rev. 25 (5), 472–491. https://doi.org/10.1016/j.eiar.2005.04.004.
Tsydenova, O., Bengtsson, M., 2011. Chemical hazards associated with treatment of waste electrical and electronic equipment. Waste Manag. 31 (1), 45–58. https://doi.org/10.1016/j.wasman.2010.08.014.
Wang, F., Huisman, J., Stevels, A.b., Baldé, C.P., 2013. Enhancing e-waste estimates: improving data quality by multivariate Input-Output Analysis. Waste Manag. 33 (11), 2397–2407. https://doi.org/10.1016/j.wasman.2013.07.005.
Widmer, R., Oswald-Krapf, H., Sinha-Khetriwal, D., Schnellmann, M., Böni, H., 2005. Global perspectives on e-waste. Environ. Impact Assess. Rev. 25 (5), 436–458. https://doi.org/10.1016/j.eiar.2005.04.001.