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Environmental Impacts on Soil and Groundwater of Informal E-Waste Recycling Processes in Ghana

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Abstract: This study examines the environmental impacts of informal e-waste recycling processes in Agbogbloshie, Ghana, which is one of the most notorious e-waste recycling sites in sub-Saharan Africa. Despite being unsafe and unorganized, the informal sector is still actively involved in dismantling, extracting, and disposing of e-waste in unauthorized locations on a considerably large scale. However, the academic research on the environmental consequences of informal recycling practices is limited. Soil and groundwater samples for five important and representative informal e-waste recycling processes and one related oil process were collected and analyzed to determine heavy metal-, PBDEs, PCBs, CBs, and PAHs concentrations. Contamination indices were used to assess and compare the effects of informal recycling processes, thereby providing a geochemical evaluation of soil conditions. As a result, the manual dismantling of CRT and ICT devices is the major source of heavy metal pollution. Furthermore, the burning of e-waste plastic for waste reduction purposes and the oil collection process substantially contribute to the input of organic pollutants. Regulatory measures for CRT and ICT recycling would result in an 85% reduction of heavy metals and the enforcement of a compulsory collection system for plastic and oil would eliminate 86% of the organic pollutants.

Keywords: e-waste; sustainable development; informal recycling sector; recycling technology; soil contamination; groundwater contamination

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1. Introduction

In contemporary society, electronic waste (e-waste) presents a multifaceted environmental challenge identified as the fastest-growing waste stream worldwide with an annual growth rate of 3–5% [1–3]. Over the past 12 years, the volume of e-waste has nearly doubled, driven by rapid digital transformation, shifts in consumer behavior, and population growth [1–3]. E-waste consists of discarded electronic devices rich in valuable metals and materials, making recycling beneficial. Effective e-waste management plays a crucial role in advancing the circular economy by reclaiming valuable resources from discarded electronics, thereby enhancing resource efficiency and curbing emissions associated with primary raw material production [4]. However, e-waste also poses significant environmental and health risks, recognized as a hazardous waste stream due to the presence of numerous harmful substances. With over 1000 substances and 69 elements found in e-waste, including heavy metals, flame retardants, polychlorinated biphenyls (PCBs), coolants, and other potentially toxic compounds, the management of e-waste demands careful attention [1,5,6]. The improper handling of e-waste poses a considerable concern, given that pollutants can spread over long distances through dust, eventually contaminating the food chain and endangering the ecosystem and individuals who are not directly involved [7].

1.1. Literature Review

1.1.1. The Global E-Waste Challenge

Global e-waste production reached 62 million tons in 2022 and only 22.3% was formally collected and recycled [1,8,9]. E-waste is typically sorted into six collection categories based on their recycling characteristics, necessitating specialized treatment facilities due to their hazardous components that could pose environmental risks [1]. Although the metals within global e-waste generated in 2022 hold an estimated economic value of USD 91 billion, the requirement for specialized treatment facilities raises the expenses of e-waste recycling, contributing to the estimated annual global economic cost of e-waste management of USD 37 billion [1].

Globally, as of June 2023, only 81 out of 193 countries had established policies, legislation, or regulations regarding e-waste collection and recycling [1]. The absence or poor enforcement of technical requirements and regulatory frameworks for e-waste management in developing countries has led to a heavy reliance on the informal sector, characterized by activities operating outside official governance structures [1,7,10]. In Africa, 99.3% of the e-waste is processed in the informal sector using hazardous methods that are harmful to the environment and health [1,11].

1.1.2. Managing E-Waste in Ghana and the Role of the Informal Sector

In Ghana, 72,000 tons of e-waste were generated in 2023 [1]. As reported by the UN's Global Waste Atlas, the informal sector manages 93–97% of the accumulating e-waste, positioning the country among the top five countries of concern for informal e-waste management [1,12,13]. Furthermore, there is an annual import of 150,000 tons of used electric and electronic equipment (EEE), of which 15–30% is already e-waste, not suitable for refurbishment or reuse. Ghana stands out as one of the most prominent examples among the African nations that deal with high volumes of illegally imported transboundary e-waste from the Global North [14–17]. The e-waste sector in Ghana generates an annual economic value of USD 105–268 million, employing over 20,000 and 35,000 people, whereas more than 121,000 people depend on the industry [14,18,19]. It provides livelihoods for the marginalized population while demonstrating innovativeness, adaptability, and contributions to job creation [19–22]. The sector consists of informal small-scale enterprises employing rudimentary tools, such as hammers and chisels, for manual dismantling to extract valuable components, such as copper, brass, iron, steel, and PCBs [23–25]. Uncontrolled burning is employed to recover valuables such as copper from cables and reduce plastic waste [24]. All types of e-waste are processed, with a preference for e-waste containing higher metal and valuable material content. The Agbogbloshie Scrapyard, Ghana's largest informal e-waste recycling facility in the capital Accra, operated from 1991 until June 2021 before relocating to nearby areas. Other informal scrapyards carry out similar activities in every major Ghanaian city [12,24,26].

1.1.3. Environmental Impact of Informal E-Waste Recycling

E-waste treatment releases hazardous environmental pollutants. Heavy metals are present in components and can be released into the environment through dismantling. Organic components like PCBs, polybrominated diphenyl ethers (PBDEs), and polyaromatic hydrocarbons (PAHs) exist in components or are formed through incomplete combustion of e-waste components, as commonly observed in the informal sector [5,27].

Moreover, the flame retardants in e-waste plastics reduce the burning temperature leading to the formation of dioxin and dioxin-like compounds [28]. Recent studies show a clear link between pollution levels and emissions from informal e-waste recycling worldwide and in Ghana [5,7,29–40]. The pollutants follow various pathways, depositing and diffusing into soil, water, and ambient air, potentially entering the human body through ingestion, inhalation, or dermal contact, leading to diseases such as cancer and others [27,41,42]. The available literature emphasizes elevated concentrations of Pb, Cr, Cu, As, Cd, and Ba in soil samples of informal scrapyards. In Ghana, there are no established limits for heavy

metals in soil. Consequently, the German Federal Soil Protection Ordinance, known for its stringent standards internationally, was utilized to evaluate the findings. Pb concentrations reaching up to 35,300 mg kg^{-1} Pb exceed the limit values of the German Federal Soil Protection Ordinance about 87.5 times [43,44]. For PCBs, a median concentration of 5.5 µg kg^{-1} was found in literature and exceeded the limit value of the German Federal Soil Protection Ordinance almost seven times [36,44,45].

Soil contamination poses threats through direct exposure and the potential for secondary exposure in distant regions facilitated by the long-distance transport of pollutants via soil particles [40]. Soil functions significantly in the hydrological cycle, acting as a filtration mechanism that stores and transports water. Porosity, structure, and hydraulic conductivity affect infiltration, runoff, and groundwater replenishment in terrestrial environment [46]. Once pollutants infiltrate the groundwater system, it can induce extensive and persistent environmental harm. Practical techniques, such as carboxylated-GO and MOF adsorption, have been developed to efficiently remove heavy metals from polluted environments [47]. These methods hold potential for application once the pollutant load and origin are clarified. Therefore, understanding and addressing soil contamination is essential for protecting environmental and human health and promoting overall ecosystem resilience [40,46].

1.2. Knowledge Gap and Research Question

Existing studies have small sample sizes (2–18) taken at distinguished points not lower than 5 cm depth [5,33,36,45,48]. This results in a considerable variation of the pollutant concentration, dependent on the sampling location, ranging from 100 to 14,000 mg kg^{-1} Pb [36]. Additionally, we encountered only one study that evaluated subsoils ranging from depths of 30 cm up to 100 cm, while all other studies focused on sampling from the topsoil layer [43]. Awere et al. [27] confirm this finding, noting that as of 2020, no study had been conducted with sampling depths below 5 cm. This indicates that the concentration of pollutants in subsoils may not be fully understood. Yet, subsoils frequently act as a storage for contaminants that have migrated from the surface over time. Recognizing subsoil pollution levels is essential for thoroughly assessing environmental effects and formulating efficient remediation plans.

It is important to note that the findings obtained from the studies may not be applicable on a larger scale due to some limitations. These limitations include inadequate infrastructure and accessibility, which restricted the extent of sampling. Additionally, the fear of eviction and loss of income from the informal sector, as well as the absence of technical requirements in the country, resulted in the challenging and costly export of samples to other countries with suitable laboratory facilities. As a result, these factors contributed to the limitations identified in the studies [25].

An identified need is to assess the relation between environmental contamination and informal recycling processes, and the pollutant release through informal e-waste recycling processes to implement targeted strategies for mitigating pollution. While several studies, including [7,27,49–52], have highlighted the need for further research into informal e-waste data and sustainability measures, gaps persist in fully understanding the environmental impacts of informal e-waste recycling processes.

A research gap exists in assessing the direct environmental and health implications of specific e-waste treatment processes carried out by the informal sector about the pollutants involved [27]. Andeobu et al. [51] and Bimir [49] emphasized an urgent need the necessity for research due to the lack of data regarding informal e-waste recycling practices in Africa, underscoring the importance of understanding the origins of pollutants. Concerning the research gap in the context of the informal sector in Ghana, we seek to answer the following research questions in our study:

1. How do informal e-waste recycling activities contribute to soil contamination?
2. How do informal e-waste recycling processes affect the quality of groundwater?

3. What is the environmental impact of informal e-waste processes regarding soil and groundwater pollution?
4. Which informal e-waste recycling processes need to be improved in order to derive effective measures for mitigating pollution?

1.3. Objectives

Our study aims to address the described research and knowledge gaps by assessing the environmental impacts and risks of important informal e-waste recycling processes. Specifically, we aim to provide data on soil and groundwater contamination to identify and mitigate major environmental impacts from informal recycling processes. These data are a requirement for enabling the formulation of practical strategies for mitigating significant pollution sources. Specific and methodological aims of the environmental risk assessment are:

- Investigating the contamination in soil and groundwater with heavy metals and organic pollutants arising from informal e-waste recycling processes;
- identifying the processes which offer the best potential for improvement;
- contributing to informed decision-making on informal e-waste recycling processes.

2. Materials and Methods

2.1. Study Area and Geology

This study was conducted at the informal e-waste recycling site Agbogbloshie Scrapyard (5°33′09.6″ N 0°13′32.9″ W) in Accra, Ghana. Soil and groundwater samples were taken in the dry season in February 2021. The scrapyard occupies an area of 31.3 hectares with around 300 small informal enterprises [42]. It processes approximately 15,092 tons of e-waste annually, comprising 8% large household appliances, 27% cooling appliances, 32% monitors and ICT equipment, and 33% small household appliances [42,53]. The assessment area lies in a dry equatorial climate with an average annual precipitation of 1210 mm. The average mean surface air temperature is 27.7 °C [54]. The geological composition of the area comprises the Accraian, Togo, and Dahomeyan formations, containing consolidated and loosely consolidated sediments and soils [55,56]. The distinct layers at the Agbogbloshie Scrapyard were assessed in preparatory work and are described as: The upper layer (0.5 to 0.6 m), characterized by loose, reddish-brown silty sand with clay, with the presence of decomposed waste matter. The middle layer (0.6 to 1.5 m) consists of silty sand embedded in a matrix of deposited rocky aggregates, varying in size from 10 to 40 mm, and also containing waste deposits. The lower layer, (1.4 to 3.5 m) encounters loose to medium-grained clayey silt and silty sand with the presence of waste materials. The subsoils predominantly consist of loose to medium-dense lagoon sands and silts with clays, which overlay interbedded shale and sandstone at depths exceeding 18.0 m [55].

The groundwater level in this area ranges from 0.9 to 2.2 m below the surface, indicating a relatively shallow aquifer [29,55].

The permeability of soil determines its ability to absorb water. Soils with low permeability, such as those found in the Accra metropolitan area, increase the cities vulnerability to flooding [57]. The permeability coefficient for the different soil layers was estimated according to the soil characteristics, assessed in a preliminary investigation [55]. The upper layer of the soil, which is about 0.5 to 0.6 m deep, is made up of loose red-dish-brown silty sand mixed with clay and decomposed waste materials. The average bulk density of this layer is 1693 kg/m^3. The second or subsoil layer, which is around 0.6 to 3.5 m deep, is a medium silty sand containing deposited rocky aggregates ranging in size from 10 to 40 mm and some waste materials. It gradually transitions into loose to medium greyish/brownish/dark spotted medium-grained clayey silt/silty sand with waste materials. The average bulk density of this layer is 1716 kg/m^3 [55].

The typical infiltration rate for the topsoil composition is 1.14 cm/h, classified as hydrological soil group B. In contrast, due to its composition, the subsoil demonstrates a lower infiltration rate of 0.51 cm/h, classified as hydrological soil group C [58,59]. On average, the

upper soil layer comprises 8% clay, 20% silt, 45% sand, and 27% gravel and the lower or subsoil layer contains, on average, 10% clay, 34% silt, 35% sand, and 21% gravel [55]. The upper soil layer exhibits moderate permeability, ranging from 10^{-8} to 10^{-6} m/s, while the subsoil layer demonstrates lower permeability, ranging between 5×10^{-8} and 5×10^{-6} m/s [55,60]. The natural moisture content of the top soil layer is 9% and 12% of the subsoil on average [55].

These results indicate soil conditions with poor drainage characteristics, low permeability, and low bearing ability [55].

The Agbogbloshie Scrapyard is at high risk of flooding due to its soil properties, as are the Odaw River and Korle Lagoon, which are prone to floods because of sediment and solid waste accumulation [57]. The Agbogbloshie area belongs to a natural floodable zone [61].

The pH value of soil and groundwater and the soil's total organic carbon (TOC) were assessed during the study.

2.2. Sampling

Analytical sampling involved the selection of seven (7) sites for collecting topsoil samples, six (6) sites for lower soil, and six (6) sites for water samples, resulting in a total of 19 samples. Among the samples, the topsoil layer is best suited for analyzing pollutants to draw direct conclusions about the environmental effects of informal e-waste treatment processes [40,62–64]. In our study, we selected and assessed the following processes: small household appliances dismantling (site 1); reference sample (site 2); compressor dismantling (site 3); printer dismantling (site 4); CRT dismantling (site 5); ICT dismantling (site 6); oil collection workshop (site 7). The processes, their brief description, and the neighboring influences, which need to be considered for the discussion of the results, are shown in Table 1.

Table 1. Main informal e-waste processes, activities, and surrounding influences.

Site	Assigned Main Process	Abbreviation	Main Activities	Influencing Activity		
				Burning	Landfill	Traffic
1	Small household appliance dismantling	SHA	SHA and microwave dismantling	weak	weak	strong
2	No direct process	No	No dismantling activity, football pitch, soil layer renewed 2 years ago	strong	strong	no
3	Compressor dismantling	Compressor	Fridge and AC compressor dismantling	weak	weak	strong
4	Printer dismantling	Printer	Printer, smaller quantities of phones, and ICT dismantling	strong	strong	no
5	CRT dismantling	CRT	CRT dismantling	weak	no	no
6	ICT dismantling	ICT	ICT dismantling, mainly phones, laptops, PCs	strong	no	no
7	Oil collection workshop	Oil	Oil collection originating from cars and filling stations, e-waste	no	no	no

The sampling locations and depths are outlined in Table 2 and Figure 1. The positions were chosen based on the occurrence of different informal recycling processes. Spatial relationships with the surrounding environment, encompassing nearby businesses, waste disposal practices, landfills, and seasonal rain-induced flooding, were considered as potential influencing sources of environmental pollutants. All samples were collected through the hand auguring method, using stainless steel scoops and sealed glass containers for storage of samples. All soil samples underwent sieving using a 95 mm mesh to remove stones and larger particles.

Table 2. Sampling locations for soil and groundwater samples.

Site	Topsoil Sample	North	West	Sample Depth (m)
1	1-b	5°33′11.9″ N	0°13′33.4″ W	0.3
2	2-b	5°33′14.0″ N	0°13′35.5″ W	0.3
3	3-b	5°33′10.1″ N	0°13′36.1″ W	0.2
4	4-b	5°33′11.0″ N	0°13′38.1″ W	0.1
5	5-b	5°33′09.8″ N	0°13′37.4″ W	0.1
6	6-b	5°33′06.4″ N	0°13′33.5″ W	0.05
7	7-b	5°33′08.1″ N	0°13′38.1″ W	0.05
Site	**Lower Soil Sample**	**North**	**West**	**Sample Depth (m)**
1	1-S	5°33′11.9″ N	0°13′33.4″ W	2.5
2	2-S	5°33′14.0″ N	0°13′35.5″ W	2.2
3	3-S	5°33′10.2″ N	0°13′36.8″ W	3.0
4	5-S	5°33′14.7″ N	0°13′38.0″ W	2.3
5	4-S	5°33′09.2″ N	0°13′30.7″ W	2.4
6	6-S	5°33′06.4″ N	0°13′33.5″ W	2.5
7	-	-	-	
Site	**Water Sample**	**North**	**West**	**Groundwater Level (m)**
1	6-W	5°33′12.2″ N	0°13′33.2″ W	1.3
2	5-W	5°33′13.9″ N	0°13′35.1″ W	1.3
3	3-W	5°33′07.9″ N	0°13′33.7″ W	1.6
4	1-W	5°33′11.1″ N	0°13′39.04″ W	0.8
5	2-W	5°33′09.8″ N	0°13′37.4″ W	0.4
6	4-W	5°33′03.9″ N	0°13′33.2″ W	0.7

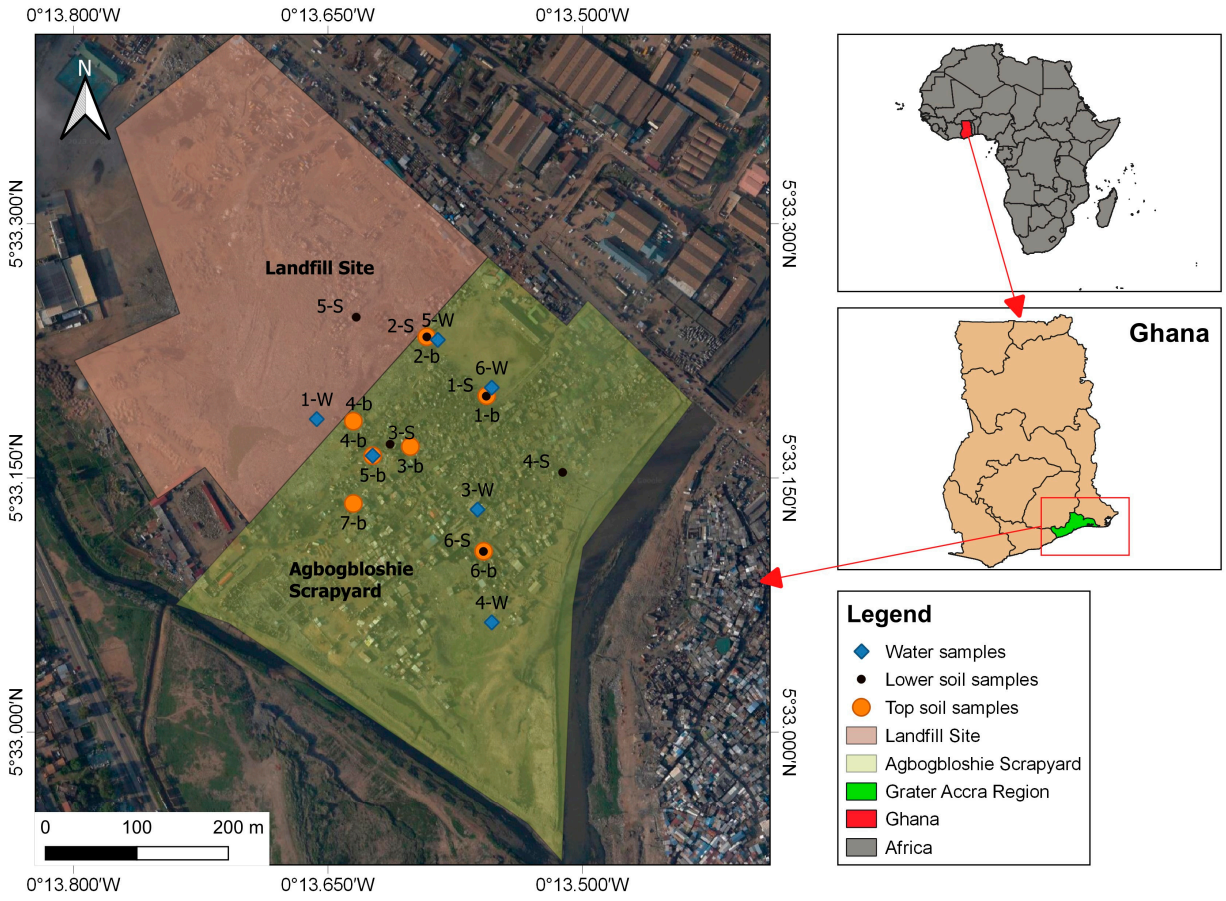


Figure 1. Study map of the sampling area at the Agbogbloshie Scrapyard.

The choice of the sampling locations and informal processes met specific criteria to justify their relevance and impact on the informal sector's operations and the environmental and health impacts, such as: (a) They were conducted frequently, resulting in a substantial volume of output; (b) they have significant economic importance within Ghana's informal sector; and (c) they are environmentally relevant or have the potential to pose health hazards. One sample (site 2) was taken at a location without a direct e-waste recycling process on the field as a reference sample. Given the dynamic nature of the informal structure, it was not always feasible to collect samples at initially planned positions. Sampling points 3-W, 5-S, 4-S, and 4-W had to be adjusted to navigate obstructions or facilitate the movement of vehicles and human traffic during fieldwork while maintaining the safety of our research team. However, we ensured that the same criteria were met for each sampling location. Given the dynamic nature of the informal structure, it was not always feasible to collect samples at initially planned positions. Sampling points 3-W, 5-S, 4-S, and 4-W had to be adjusted to navigate obstructions or facilitate the movement of vehicles and human traffic during fieldwork while maintaining the safety of our research team. However, we ensured that the same criteria were met for each sampling location. Given the dynamic nature of the informal structure, it was not always feasible to collect samples at initially planned positions. Sampling points 3-W, 5-S, 4-S, and 4-W had to be adjusted to navigate obstructions or facilitate the movement of vehicles and human traffic during fieldwork while maintaining the safety of our research team. However, we ensured that the same criteria were met for each sampling location.

2.3. Sample Analysis

The soil samples were analyzed for heavy metals, TOC, Polycyclic aromatic hydrocarbons (PAHs), Polychlorinated biphenyls (PCBs), Polybrominated diphenyl ethers (PBDEs), and Chlorobenzenes (CBs), the water samples were analyzed for heavy metals, PCBs and PAHs according to established methods. A comprehensive physicochemical analysis was conducted for all samples. Soil samples were dried, homogenized, and sieved to obtain a uniform sieve size of 1.25 mm. Analysis of pH, electrical conductivity (EC), and total dissolved solids (TDS) were carried out. Heavy metal analysis was performed using X-ray fluorescence (XRF) and Inductively Coupled Plasma Mass Spectrometry (ICP-MS), following the guidelines of DIN EN ISO 17294-2 [65]. Gas Chromatography-Mass Spectrometry (GC-MS) was employed for organic pollutants analysis. Total Organic Carbon (TOC) analysis was conducted according to DIN EN 15936 [66]. Water samples and subsoil samples were analyzed for heavy metals at the laboratory of CSIR Ghana, while analysis for organic pollutants was conducted at the Atomic Energy Commission Laboratory. This division was required due to restricted shipment possibilities and the unavailability of all necessary analyzers in a single laboratory. Upper soil samples underwent complete analysis at the teaching and research laboratory at ISWA, University of Stuttgart.

2.4. Contamination Indices and Data Processing

In order to ensure that our study could be compared internationally, we utilized legally defined permissible standards and limits for pollutants in soil and groundwater, as well as permissible concentration levels. However, it is important to note that these standards may not always be directly relevant or applicable to our specific study area. To address this, we turned to contamination indices as a valuable alternative for assessing soil contamination. These indices have several advantages, including the ability to provide a relative assessment by comparing pollution against natural background values, accounting for individual toxicity responses to consider ecological risks, and facilitating trend monitoring over time [67–69]. Among the various pollution indices available, Igeo stands out as one of the most accurate and widely used indices for evaluating contamination levels. Its long-standing use allows for the comparison of previous and present contamination levels, aiding in trend analysis and providing valuable insights into pollution dynamics over time [68,69].

Heavy metal contamination was evaluated using pollution indices introduced by Hakanson [70] and Muller [71]. We used the geo-accumulation index (I_{geo}), as in Equation (1), to assess the metal deposits in soil. The measured concentrations of C_n are compared to the background value B_n of unpolluted soil. We took the background values for B_n from Taylor and McLennan [49].

$$I_{(geo)n} = log_2\left(\frac{C_n}{1.5B_n}\right) \quad (1)$$

The Contamination Factor (C_f) and its sum, degree of Contamination (C_{deg}), and Equations (2) and (3) are also widely used indices to assess the extent of heavy metal contamination in soil. The measured concentration of the element in the sample (C^i_{0-1}) is divided by the background concentration in the continental crust average. For the topsoil samples, the eight relevant metals were selected to calculate the degree of contamination: Cr, Cu, Zn, As, Cd, Sb, Pb, and Hg. For the lower soil samples respectively Mn, Fe, Co, Cu, Zn, As, Sb, and Pb.

$$C^i_f = \frac{C^i_{0-1}}{C_n} \quad (2)$$

$$C_{deg} = \sum C^i_f \quad (3)$$

The ecological risk index is used to assess the potential ecological risk (R_i) as in Equations (4) and (5) posed by contaminants in the environment. It involves comparing the concentrations of contaminants with the soil quality guidelines values. and the potential ecological risk [69–71].

The contamination factor C^i_R for an element is multiplied by the toxic response factor T^i_r which is provided in the literature [68]. The sum of the ecological risk factors for the selected elements gives the potential ecological risk index R_i

$$E^r_R = T^i_r \cdot C^i_R \quad (4)$$

$$R_i = \sum_{i-1}^{n} E^r_R \quad (5)$$

For the evaluation of the status of the overall metal pollution of the groundwater, the Heavy Metal Pollution Index (HMI), and the CCME Water Quality were used [72,73]. As important heavy metals for the HMI Cu, Zn, Cr, Pb, Mn, Ni, As, and Se were considered. Regarding the CCME Water Quality Index, 25 variables were evaluated according to the WHO Standard, are Electrical conductivity (EC), Total Dissolved solids (TDS), pH, Na^+, K^+, Ca^{2+}, Mg^{2+}, HCO^{3-}, Cl^-, $SO_4{}^{2-}$, $NO_3{}^-$, F^-, the metals Al, Ba, Cd, Cu, Zn, Pb, Mn, Na, Ni, As, Se, and the organic pollutants Benzo(a)pyrene and PAH16.

The chemical distribution pattern of organic pollutants was used to determine their primary source, whether from oil, burning, other processes, or external influences. The results were analysed using the *t*-test in Microsoft Excel, with statistical significance set at $\alpha = 0.05$.

3. Results

The results for each assessed process can be reviewed for the soil and groundwater assessment in Table 3 and the raw analytical values can be examined in the Supplementary Material.

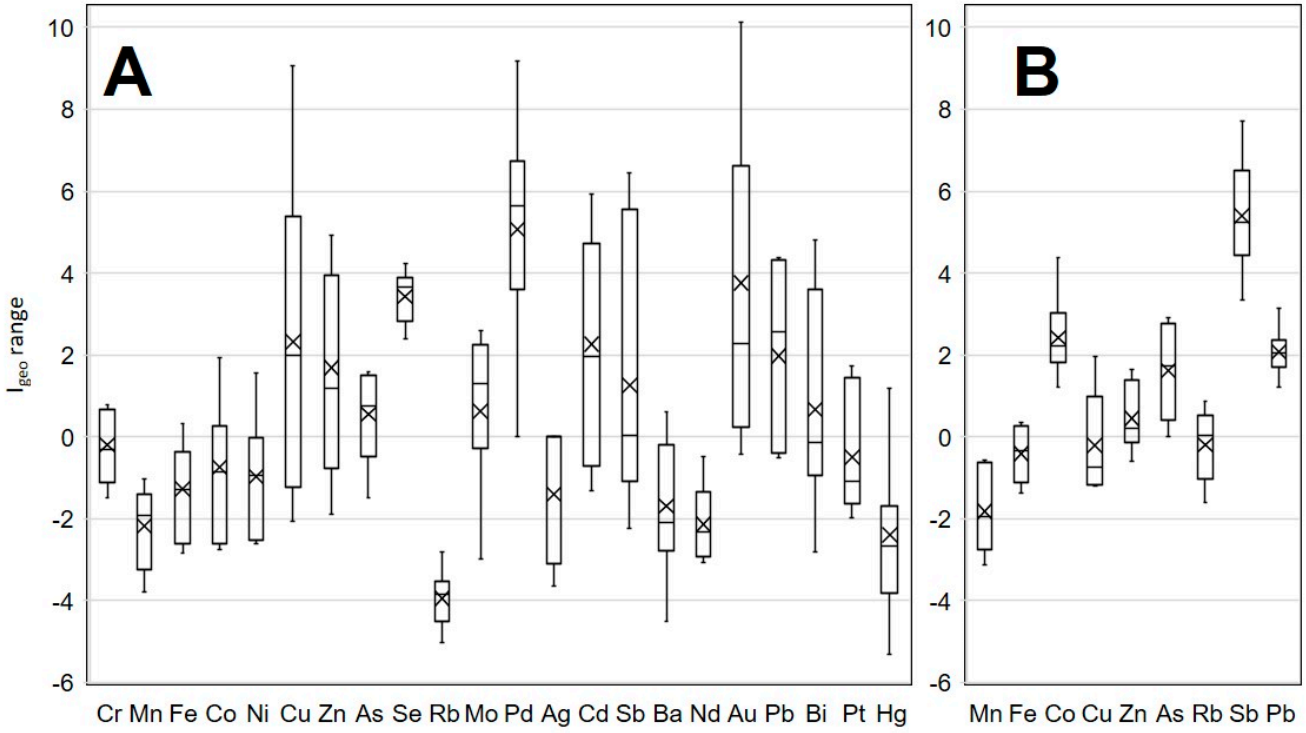
Table 3. Results of soil and groundwater analysis and calculated parameters for the top and lower soil layer.

Site No.	Soil Parameters									
Topsoil	**Contamination Factor C_f**								**Degree of Cont. C_{deg}**	**Classific.**
	Cr	**Cu**	**Zn**	**As**	**Cd**	**Sb**	**Pb**	**Hg**		
1	1.19	6	3.38	2.22	5.88	2.64	10.75	0.46	32.51	Very high
2	0.54	0.35	0.4	0.53	0.6	0.32	1.13	0.04	3.91	Low
3	0.69	0.63	0.88	1.07	0.92	0.71	1.05	0.11	6.04	Low
4	1.2	2.35	2.14	2.54	2.27	0.93	2.4	0.22	14.03	Moderate
5	2.4	802	23.1	4.53	39.69	130.5	31	0.45	1033.66	Very high
6	2.57	62.8	22.39	4.25	37.45	71	29.65	0.24	230.35	Very high
7	2.01	8.56	45.07	3.9	91.63	1.53	8.8	3.44	164.94	Very high
Lower Soil	**Contamination Factor C_f**								**Degree of Cont. C_{deg}**	**Classific.**
	Mn	**Cu**	**Zn**	**As**	**Co**	**Sb**	**Pb**	**Fe**		
1	0.94	0.67	1.79	9.97	6.01	103.15	6.4	1.05	129.98	Very high
2	0.6	0.69	3.67	2.2	7.57	61.85	5.49	0.58	82.66	Very high
3	0.17	0.64	1.67	9.13	3.47	41.4	13.2	1.36	71.05	Very high
4	0.25	2.34	0	11.27	30.84	51	6.02	1.92	103.63	Very high
5	1.01	5.85	4.64	0	6.32	314.6	6.45	1.76	340.63	Very high
6	0.24	1.16	0.99	2.75	8.91	15.3	3.44	0.73	33.53	Very high
Topsoil	**Potential Ecological Risk Coefficient E_r**							**Risk Index R_i**	**Classific.**	
	Cr	**Cu**	**Zn**	**As**	**Cd**	**Pb**	**Hg**			
1	2.38	30	3.38	22.2	176.33	53.75	18.48	306.51	high	
2	1.07	1.77	0.4	5.34	17.91	5.65	1.5	33.65	low	
3	1.39	3.16	0.88	10.67	27.49	5.23	4.22	53.02	low	
4	2.39	11.74	2.14	25.4	67.96	11.98	8.88	130.48	low	
5	4.79	4010	23.1	45.27	1190.82	155	17.84	5446.81	significantly high	
6	5.14	314	22.39	42.53	1123.47	148.25	9.44	1665.22	significantly high	
7	4.02	42.8	45.07	39	2748.98	44	137.6	3061.47	significantly high	
Lower Soil	**Potential Ecological Risk Coefficient E_r**							**Risk Index R_i**	**Classific.**	
	V	**Cu**	**Zn**	**As**	**Sb**	**Pb**	**Co**			
1	2.17	3.34	1.79	99.67	722.05	32	30.07	891.07	significantly high	
2	2	3.47	3.67	22	432.95	27.47	37.84	529.4	high	
3	3.68	3.22	1.67	91.27	289.8	66.01	17.36	473.02	high	
4	7.64	11.7	0	112.67	357	30.12	154.2	673.32	significantly high	
5	1.62	29.24	4.64	0	2202.2	32.24	31.61	2301.54	significantly high	
6	2.73	5.82	0.99	27.53	107.1	17.22	44.57	205.96	moderate	
Topsoil	**Organic Parameters**									
	Sum CBs $\mu g\ kg^{-1}$	**Sum PCB7** $\mu g\ kg^{-1}$	**Sum PBDEs** $\mu g\ kg^{-1}$	**Sum PAH16** $\mu g\ kg^{-1}$	**TOC** [%] d.w.					
1	44.67	26.35	29.25	407.06	1.34					
2	25.23	0.8	0.93	175.18	0.17					
3	48.84	1.49	6.84	3177.29	1.24					
4	12.78	1.49	40.59	5352.32	1.28					
5	56.78	6.5	123.72	802.01	3.97					
6	102.91	30.16	2451.48	4371.12	7.68					
7	238.25	202.07	22.49	6440.77	23.2					
Water	**Groundwater Parameters**									
	CCME WQI	**HPI**	**Sum PCB** $\mu g\ L^{-1}$	**Sum PAH17** $\mu g\ L^{-1}$						
1	33	149	0.09	0.81						
2	40	189	0.07	0.22						
3	26	394	0.08	0.75						
4	25	464	0.14	1.76						
5	28	65	0.09	1.45						
6	30	168	0.09	0.28						

3.1. Soil Contamination

Heavy metals and metals associated with the process of e-waste dismantling exhibit clear accumulation (I_{geo}) within the topsoil layer along the sampling sites, showing a severe to extreme contamination intensity as shown in Figure 2. Notably, Cu, Pd, Cd, Sb, and Au are found in significant accumulation. Moreover, Zn, Se, Pb, and Bi demonstrate a pronounced accumulation. Other relevant metals, including Cr, Ni, Co, As, Mo, and Pt,

display varying degrees of accumulation ranging from slight to moderate. Figure 2 visually represents the calculated geo-accumulation in a boxplot, illustrating the range across all samples assessed within the study area. Sb shows the highest accumulation in the lower soil layer, commonly used as a flame retardant for brominated compounds in e-waste plastics. Co, Cu, As, Zn, Pb, and V are accumulated slightly to moderately in the lower soil layer, confirming the existence of e-waste-related heavy metals.



Category	I_{geo} range	Contamination intensity
0	$I_{geo} \leq 0$	Uncontaminated
1	$0<I_{geo} \leq 1$	Slightly contaminated
2	$1<I_{geo} \leq 2$	Soderately contaminated
3	$2<I_{geo} \leq 3$	Moderately severly contaminated
4	$3<I_{geo} \leq 4$	Severely contaminated
5	$4<I_{geo} \leq 5$	Severely extremely contaminated
6	$I_{geo} >5$	Extremely contaminated

Figure 2. The geo-accumulation index is calculated as a box plot for metals in the top soil layer (**A**) and the lower soil layer (**B**) across the sampling area.

Table 3 shows the results of the calculated soil and groundwater parameters, including the contamination factors (C_f, C_{deg}) and ecological risk index (R_i) for the selected metals per location and the calculated degree of contamination for the locations at the top soil layer and the lower soil layer. Sites 2 and 3 show a low extent of contamination and site 4 shows moderate contamination in the upper soil layer. All other topsoil samples show a very high extent of contamination whereas site 5 has the highest C_{deg} of 1033 mainly due to the high Cu concentration. Sb, Cd, and Pb are responsible for the very high C_{deg} in sites 1, 5, and 6, and Cd and Zn in site 7. All lower soil samples show a very high C_{deg}. Among them, site 5 shows the highest C_{deg} and site 6 the lowest. Here, the high C_{deg} is mainly due to the concentration of Sb in all samples, Pb in site 3, and additionally As and Co in site 4.

Sites 2, 3, and 4 exhibit a low ecological risk index (R_i) in the topsoil, ranging from 33 to 130. Site 1 displays a high R_i of 306, while sites 5 and 6 demonstrate significantly

high values of 5446 and 1665 respectively. The high ecological risk coefficient (E_r) of site 1 which be attributed to Cd and Pb, E_r of site 5 can be attributed to Co, Cd, and Pb, and E_r of site 6 to Cd and Hg. Among the lower soils, site 6 shows the lowest R_i with a moderate ecological risk of 205. Sites 2 and 3 show high R_i (529 and 473) and sites 1, 4, and 5 have significantly high R_i ranging from 673 to 2301. The high risk can be attributed to the Sb and As concentrations found.

Findings for the sum of organic pollutants are outlined in Table 3 and their distribution pattern can be reviewed in the Supplementary Material. Site 7 exhibits a high PCB concentration, likely due to its proximity to an oil processing workshop. Elevated TOC levels in sites 5 and 7 were attributed to the significant oil content in these samples. For PBDEs, distinct technical mixtures like PentaBDE, OctaBDE, and DecaBDE used in EEE were identified in sites 1, 5, and 7. However, pollution in site 6 was linked to burning, as the chemical pattern does not align with the technical mixtures' constitution in this sample. PAHs analysis indicates a typical combustion-related distribution pattern in sites 1 to 6. Notably, site 7 shows a significantly high level of naphthalene, suggesting a potential association with oil and traffic influences in this area. The analysis of CB patterns shows, specifically, 1,2,4-dichlorobenzene dominated sites 2 to 4, while 1,4-dichlorobenzene is prevalent at site 7. Sites 5 and 6 exhibit a dominance of 1,2,3-trichlorobenzene, 1,2,3,4-tetrachlorobenzene, pentachlorobenzene, and hexachlorobenzene, suggesting a pollution source related to burning in these areas.

3.2. Water Cocontamination

All groundwater samples show poor water quality regarding the CCME water quality index and the HPI as shown in Table 3. The results for HPI show high heavy metal pollution for all samples except at site 5 with an index of 65, where moderate pollution was determined and poor CCME water quality index was determined for all samples. The highest organic pollution was found at site 4 with 1.76 µg/L PAH 17 and 0.14 µg/L PCB.

3.3. Relationship between Informal E-Waste Reycling and Soil and Groundwater Pollution

The analysis of the correlation of pollution indices and pollutants indicates that the sources of the pollution can be attributed to originate from the same activities, such as informal e-waste treatment processes. A strong correlation implies that contamination in both the topsoil, subsoil, and groundwater likely originates from the same source process. The Kolmogorov-Smirnov test shows that sample data are normally distributed. Table 4 shows Pearson Correlations between the parameters in different soil layers and groundwater. The groundwater's HPI shows a correlation with the R_i and C_{deg} of both soil layers and similar correlations are observed between the R_i and C_{deg} values of the soil layers. This indicates that the pollution can be attributed to originate from the same source, which is informal e-waste recycling. Furthermore, the results indicate a significant correlation ($r = 0.76$) between the accumulation of Cu in the top and lower soil samples, suggesting a strong association between the metal's presence in both layers. The accumulation of Sb, particularly in sites 2, 5, and 6, correlates with the cumulative presence of PBDEs in these samples. Given that these samples are significantly impacted by burning activities, the presence of Sb pollution can be associated with the burning of ICT devices, where Sb is used in plastics as a flame retardant agent. CBs can be used as an indicator for PCDD/Fs in incineration processes [74]. Strong relations between CBs and PBDEs were found which may be an indication that PCDD/Fs exist and are formed by the burning of e-waste plastics.

Table 4. Correlation between the parameters in different soil layers and groundwater.

	WQI	HPI	R_{il}	R_{it}	C_{degl}	C_{degt}	CBs	PCB7	PBDEs	PAH16	TOC
WQI	1.000										
HPI	−0.516	1.000									
R_{il}	−0.337	0.530	1.000								
R_{it}	−0.394	0.435	0.854	1.000							
C_{degl}	−0.337	0.542	1.000	0.856	1.000						
C_{degt}	−0.391	0.453	0.886	0.997	0.889	1.000					
CBs	−0.110	−0.379	−0.082	0.387	−0.087	0.320	1.000				
PCB7	0.080	−0.327	−0.193	0.062	−0.203	−0.005	0.724	1.000			
PBDEs	−0.064	−0.193	−0.379	0.132	−0.377	0.055	0.864	0.694	1.000		
PAH16	−0.636	0.252	−0.454	−0.233	−0.448	−0.265	0.139	0.011	0.434	1.000	
TOC	−0.318	0.012	0.018	0.508	0.019	0.439	0.912	0.651	0.910	0.349	1.000

3.4. Informal E-Waste Processes with Highest Pollutant Indices

Linking the analytical results to informal e-waste recycling processes follows this: Small household appliances (SHA) dismantling (site 1); reference sample (site 2); compressor dismantling (site 3); printer dismantling (site 4); Cathode-ray tube (CRT) dismantling (site 5); Information and communication technology (ICT) dismantling (site 6) and oil collection workshop (site 7). Figure 3 shows Pareto-Diagrams for C_{deg} (A), representing the heavy metal contamination, and for the cumulative sum of organic pollutants (B) in the topsoil. The dismantling processes of CRTs demonstrated the primary environmental impact associated with heavy metals, accounting for 70% of the total C_{deg} across all processes. ICT dismantling constitutes a portion of 15%, while oil collection accounts for 11% of the total C_{deg}. SHAs, printers, and compressor dismantling collectively represent a share ranging from 0.4% to 1%. Samples devoid of any dismantling activity contribute to 0.3%. The greatest proportion of the sum of organic pollutants is observed at the ICT dismantling site, accounting for 29% of the total, closely followed by the oil sample at 28.5%. Printer activities contribute with 22%, CRT with 4%, SHAs with 2%, and the site without a specific process contributes with 0.8%. ICT, oil, and printer processes collectively account for 80% of the release of organic pollutants. Notably, two of these processes generate significant amounts of e-waste plastics. A prioritizing of the need for action for the specific processes is shown in in Figure 4, based on the degree of contamination (C_{deg}) on the x-axis, the cumulative sum of organic pollutants on the y-axis, and the ecological risk factor (R_i) represented by the size of the circle. CRT, ICT, and oil collection processes were determined as priority areas for a significant reduction in major pollutants by the results. These results show a significant improvement in the situation can be achieved by adjusting relatively few processes.

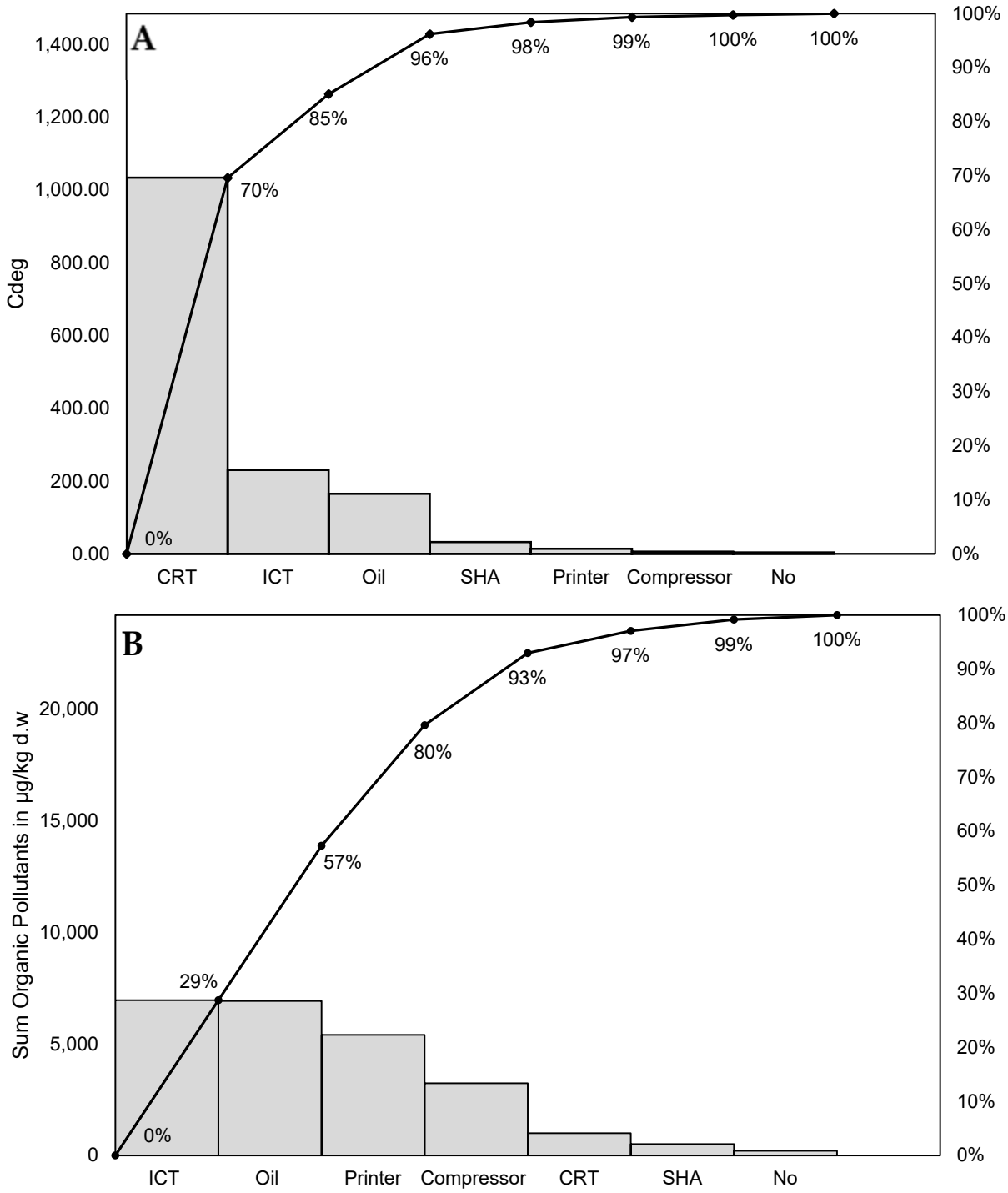


Figure 3. Pareto diagrams for the share of C_{deg} (**A**) and the sum of organic pollutants (**B**) in the topsoil layer per process.

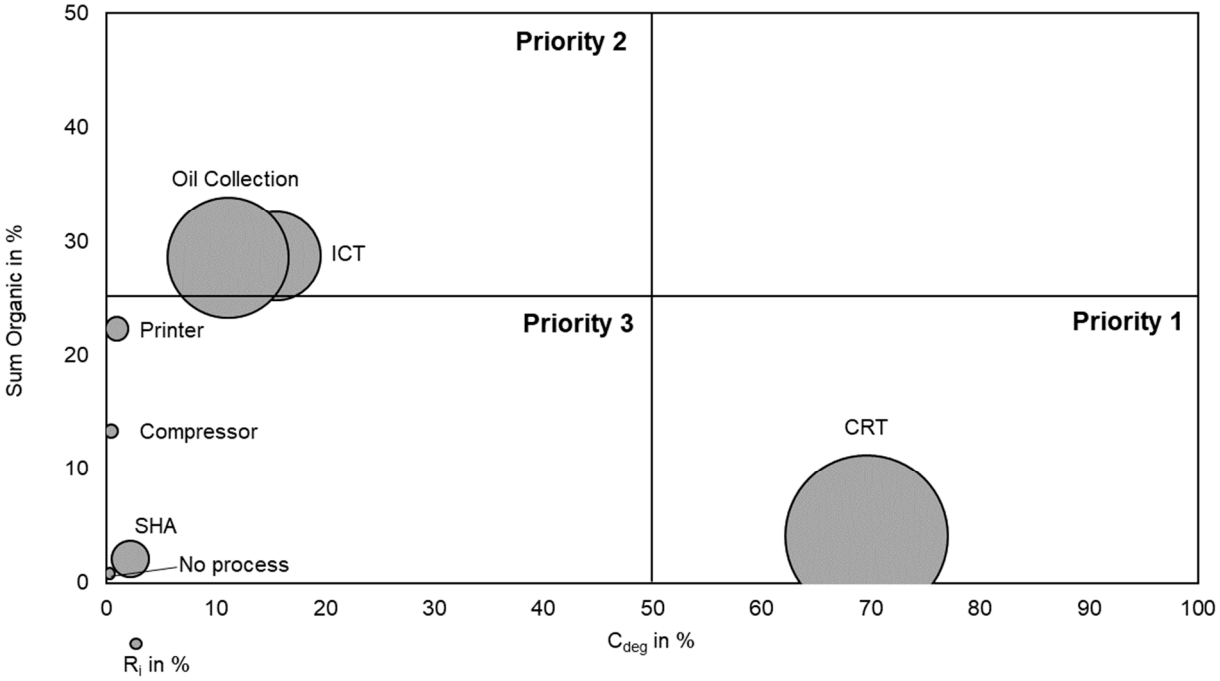


Figure 4. Priority for action for process-specific adjustments according to C_{deg}, R_i, and the sum of organic pollutants in the topsoil layer.

4. Discussion

4.1. General Findings

The results of this study indicate that informal CRT and ICT dismantling activities are the primary sources of heavy metal contamination in soil and groundwater. Additionally, organic pollutants, primarily originate from the burning of plastics and oil discharge. Groundwater quality assessment shows extensive pollution, rendering it unsuitable for drinking. Our findings underscore a relationship between soil pollution and groundwater quality parameters, suggesting the potential infiltration of heavy metals into groundwater systems. Comparatively, the reference sample exhibits the lowest pollution levels and contamination. Urgent measures are imperative to address the mitigation of pollution stemming from informal e-waste recycling practices in Ghana. Subsequent sections will delve into a detailed discussion of our findings.

4.1.1. Sources and Impact of Informal E-Waste Recycling to Soil Contamination

During the study, it was found that CRT dismantling and ICT dismantling are the main sources of soil and groundwater contamination from informal e-waste dismantling activities. These activities have the most significant environmental impact. Out of all the sites, site 5, associated with CRT dismantling, had the highest extent of heavy metal contamination C_{deg} and the highest ecological risk factor R_i in both the top and lower soil layers. The high concentration of Cu, Pb and Sb in the soil can be attributed to the release of Pb and Cu during CRT dismantling and the presence of plastics with flame retardants containing Sb. It is crucial to facilitate the collection of these materials to avoid further contamination.

At site 6 for both soil layers (ICT dismantling) and site 4 for the lower soil layer (printer dismantling) a very high extent of heavy metal contamination C_{deg} was determined. All subsoil samples present a very high C_{deg} and, except site 6, a high to significantly high Ri. The Cf for Sb, Cu, Cd and Pb at site 6 (ICT dismantling) is higher compared to the other processes, however only clearly recognizable in the upper soil layer. Similar to the CRT process, here the Sb is the decisive parameter for the high C_{deg}, indicating a strong relation to the e-waste plastics, where Sb is used as a flame retardant. At site 4 (printer) the high Cf

for Co among all sites in the lower soil layer stands out and might be referred to origin from toners. The lowest heavy metal contamination comes from compressor recycling, however to get a comprehensive picture, the other assessed pollutants need to be taken into account.

Organic soil pollutants found in the samples can be assigned 57% to the burning of plastics by their typical pattern distribution for the burning of PAH16, CBs, and the identified technical PBDE mixtures. About 29% of the organic pollutants can be assigned to originate from oil, justified through the found PCB levels and the TOC, used as an indicator for oil. About 14% of the organic pollutants were not assignable to where they exactly originated from. We assume they also originate from informal processes or from influencing sources such as traffic and landfill leakage of the close by landfill as described in Table 1.

It has been found that during the dismantling of SHA (site 1), the level of contamination is relatively lower as compared to other processes and contaminants evaluated. Although the Cf for Sb in the lower soil is high compared to the other values, the organic pollutants measured at this site relatively low. Here it needs to be further assessed if the high Sb in the lower soil stems from this process itself or has other sources due to previous land use, which seems more likely. The same applies for the R_i determined for this process. One argument to enhance this is, that also Sb for the reference sample is elevated, and due to the geographical proximity of both sampling sites, it stands to reason that an influence other than the processes is possible for Sb at both sites. Furthermore, it was observed that samples with elevated levels of Sb exhibit a corresponding increase in the total sum of PBDEs, notably at sites 5 and 6. Conversely, this correlation is not applicable to site 1 and 2, further reinforcing this assumption.

4.1.2. Relation between Groundwater Contamination and Informal E-Waste Recycling

The findings for the groundwater assessment suggests that the aquifer is unusable for drinking purposes according to the CCME WQI, as a score below 44 indicates that water quality is consistently at risk and deviating from desirable levels [72].

Furthermore, with the exception of sample 5, where it is 65, the HPI exceeding 100 indicates that the groundwater is unsuitable for use due to heavy metal pollution.

The Pearson Correlation indicates a significant correlation observed among the C_{deg} and the HPI between lower soil samples and groundwater samples exceeding 0.5 suggests that heavy metals can infiltrate groundwater and are likely to be dispersed within the groundwater system. A low positive correlation is observed for the PAH16 from the topsoil layer to the groundwater. PAHs, being slightly denser than water and only moderately soluble, tend to be adsorbed onto soil particles rather. Soils rich in organic substances have a higher capacity to adsorb hydrocarbons compared to mineral soils. The TOC content in soil at sites 5, 6, and 7 exceeds 3%, indicating that organic pollutants may bind more effectively in these soils. While correlation does not imply a causal relationship automatically, the similarity in pollutant patterns suggests that groundwater pollution may also be attributed to the informal e-waste treatment. However, the analyzed groundwater pollution data, as depicted in Table S2 of the Supplementary Material, were found to be below the researchers' expectations for such an environment. Several factors may contribute to this discrepancy, which will be further discussed in the following section.

The potential for pollutants to become available and mobile is influenced by the adsorption and desorption characteristics of soils, which are closely linked to their physicochemical properties, such as, pH, grain size distribution in soil and TOC [75].

The subsoil layer exhibits characteristics of low permeability and a higher bulk density than typical for its composition, indicating a limited infiltration rate. Similarly, the topsoil layer demonstrates low permeability. During heavy rainfall events, particularly in the rainy season, and associated flooding due to the geological conditions, pollutants may only infiltrate groundwater with a limited capacity and runoff into nearby water bodies such as the Odaw River and Korle Lagoon. Here, pollutants are likely to settle in the sludge, ultimately reaching the sea and accumulating in aquatic biomass such as fish [61].

Given the fine-grained nature of the soil and subsoil layers, with the subsoil being finer-grained, the soil is predisposed to adsorb pollutants rather than facilitating extensive groundwater infiltration. Soil pH emerges as a critical factor due to its significant influence on the solubility, sorption, and mobility of metals across various fractions. Lower pH levels typically enhance the mobility of metals. However, the neutral to alkaline pH range observed at the study site (pH: 7.17–7.87) does not promote increased mobility [75].

4.1.3. Environmental Impacts of Informal E-Waste Recycling Processes on Soil and Groundwater

The soil plays a crucial role in filtering pollutants in the environment. However, due to high pollution levels, its function is currently compromised. The primary sources of e-waste related pollution through heavy metals are identified as CRT and ICT recycling activities, while organic pollution stems from the burning of plastics and oil discharge into the soil. The soil's grain size distribution and adsorption capacity, combined with the consistent wind speed in the area, make contaminated soil particles prone to dispersal over long distances. This leads to widespread dissemination of pollutants, which poses environmental concerns and impacting nearby populations and food markets, attributable to informal e-waste recycling practices.

According to the results of a groundwater assessment, the soil is unable to guarantee the safety of the groundwater. The contamination of the groundwater is evident through various processes and it is not safe to drink. It is important to note that samples were collected and analyzed during the dry season. During the rainy season, the flooding of the area could potentially dilute the concentration levels and disperse pollutants.

It is important to carefully consider leachate, coarse and fine particles, and ash from other burning processes, which may be of another origin than e-waste treatment when interpreting the results. During the sampling, other potentially polluting sources such as burning of waste and cables, landfill leakage, and traffic were documented and considered when interpreting the results.

4.1.4. Possible Strategies in Mitigating Pollution from Informal E-Waste Recycling Practices in Ghana

The informal sector is an important part of urban waste management and e-waste management in Ghana. It increases material recovery, is efficient at low cost, and reduces poverty [76]. Studies indicated to target sustainability and the SDGs in urban waste management, the informal sector needs to be considered or included [52,76–78]. Therefore, the proposed measures from this study, should be carried out under the inclusion and consideration of the informal sector.

Our research findings indicate that, to reduce 85% of the heavy metal contamination expressed in C_{deg}, CRT and ICT dismantling processes need to be transformed, as they show the largest influence. We propose a binding, organized material flow model on informal scrapyards in Ghana, which includes the collection of e-waste plastics and foams to avoid burning and an oil collection system. According to our findings, this leads to an 86% decrease in organic pollution. However, the practical realization and actual achievability of this goal must be investigated further. On the other hand, some processes should not remain in the informal sector due to their health and environmental risks. As such a process we identified the CRT dismantling for the following reasons: It has the highest extent of heavy metal contamination among the assessed processes; there is a high risk of implosion during manual dismantling; it also contributes to plastic accumulation and burning and it is economically unsustainable as CRT devices are no longer produced. To address soil and groundwater pollution in the now-abandoned Agbogbloshie Scrapyard, a comprehensive remediation plan should be implemented. Additionally, measures such as the installation of impermeable barriers and the implementation of soil stabilization techniques can prevent further contamination spread. It is imperative to complete the remediation process before considering any new intended use for the land, as emphasized by recent research findings highlighting the urgency and necessity of this remedial action.

4.2. Categorisation of Results among Other Studies

Within the Ghanaian context, the transferability of the results on a process-specific level for other informal scrapyards can be confirmed as the chosen processes constitute the primary informal e-waste treatment methods in Ghana [12,23,24]. Our findings and the measured concentrations align with other studies and for some pollutants, such as the heavy metal concentrations on certain points slightly lower. We could confirm the literature review of Awere et al. [27], that the burning of e-waste plastics leads to major organic pollution at the Agbogbloshie Scrapyard, by our analytical findings. Moreover, we could identify other relevant sources for the organic and heavy metal pollution on a process level.

Fujimori et al. [36] indicated Cu as the most significant causative toxic metal within their samples which our results confirm. Our findings are in line with existing literature, such as: Ackah [43]; Brigden et al. [5]; Cao et al. [79]; Fujimori et al. [36]; Itai et al. [37]; Moeckel et al. [64] and Obiri et al. [29]. In the literature, median concentrations for PAHs ranged between 390 and 5555 μg kg^{-1} [33,48], PBDEs ranged between 8.6 and 930 μg kg^{-1} [33] and PCBs had a median concentration of 5.5 μg kg^{-1} [36,45]. Concentrations of Pb in the soil of the Agbogbloshie burning site range between 100 and 35,300 mg kg^{-1} [5,36]. Our findings for organic pollutants align with existing literature, also identifying waste burning as a major source of organic pollutants in the Agbogbloshie Scrapyard [32,49].

4.3. Limitations

Our results capture a certain point of time and may not reflect temporal changes. It is anticipated that pollution will accumulate over time, exacerbating the situation. Extreme weather events such as droughts and heavy rainfall can further exacerbate soil disturbances, leading to increased pollutant dispersion. However, our study lacks long-term monitoring capabilities to capture these dynamics. Optimizing the processes rather than relying on long-term monitoring can therefore serve as a viable alternative. Additionally, seasonal variations are not accounted for in our findings, preventing us from drawing conclusions regarding these weather events. Furthermore, it is essential to recognize that our sampling conditions were challenging, constrained by cost limitations, and resulted in a limited number of samples. Economic constraints and accessibility issues to sampling sites, as well as ensuring researchers' safety, contributed to the limited sample size. Nonetheless, despite these limitations, our approach provides valuable insights into improving processes. Notable, other studies show similar limitations in sampling and sample size, due to facing the same difficult framework conditions on site.

To gain a more comprehensive understanding of the interrelation between e-waste recycling processes and associated pollutants and their effects, additional data from diverse scrapyards and settings are recommended.

5. Conclusions

This study assessed the impact of informal e-waste recycling processes on soil and groundwater, focusing on heavy metal-, PBDEs, PCBs, CBs, and PAH concentrations. The analysis included 6 processes at the Agbogbloshie scrapyard in Ghana and a reference sample (site 2): SHA dismantling (site 1); compressor dismantling (site 3); printer dismantling (site 4); CRT dismantling (site 5); ICT dismantling (site 6) and oil collection workshop (site 7). The analytical assessment was conducted with XRF, IPC-MS, and GC-MS.

The most significant contributors to environmental pollution were identified as CRT and ICT dismantling processes. Notably, Cu, Pd, Cd, Sb, and Au are found in significant accumulation in the topsoil layer, and Sb, Cu, and As show the highest accumulation in the lower soil layer. Based on the pattern distribution of the organic pollutants, 57% of the found pollutants appear to originate from the burning of plastics and plastic-related products, such as cables and foams. 29% of the organic pollutants were related to originating from oil and the remaining 14% were not assignable to a specific origin. The reference sample displayed the lowest contamination levels. The calculated contamination indices all showed a high to

very high degree of pollution of the soil and groundwater, which poses a significant issue to the environment and public health, requiring urgent action. Groundwater sampling indicates an unsafe aquifer, and the correlation between pollutants in lower soil samples and groundwater implies infiltration of pollutants into the groundwater system. Nonetheless, the high probability of pollutant dispersion through runoff and soil erosion influenced by the soils specific characteristics, underscores the pressing necessity for comprehensive e-waste management strategies.

Our research indicated that by the adjustment of CRT and ICT dismantling, including the implementation of a binding plastic and oil collection system for all processes, 85% of the released heavy metals and 86% of organic pollutants analyzed in this study can be avoided. Processes handling e-waste with lower pollution potential, such as SHA, can potentially remain in the informal sector under its inclusion for a sustainable recycling system. Based on these findings, it is recommended to implement measures addressing the identified processes functioning as main pollutant sources and distribution pathways through groundwater and soil particles. Binding plastic and oil collection and their downstream management and the exclusion of CRT dismantling of the informal sector are evident. The researches further enhance the necessity of remediating the now-abandoned Agbogbloshie Scrapyard before repurposing the land for any new intended use.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su16114347/s1, Table S1: Chemical patterns of organic pollutants; Table S2: Groundwater parameters.

Author Contributions: Conceptualization, K.O.-S.; methodology, K.O.-S.; validation, K.O.-S., D.A.A., D.L. and M.O.-A.; formal analysis, K.O.-S.; investigation, K.O.-S.; resources, K.O.-S. and D.A.A.; data curation K.O.-S.; writing—original draft preparation, K.O.-S.; writing—review and editing, K.O.-S. and M.O.-A.; visualization, K.O.-S.; supervision, D.L., M.O.-A. and M.K.; All authors have read and agreed to the published version of the manuscript.

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