Thermal deconstruction, open burning and disposal of e-waste without pollution control: A systematic review of risks to occupational and public health

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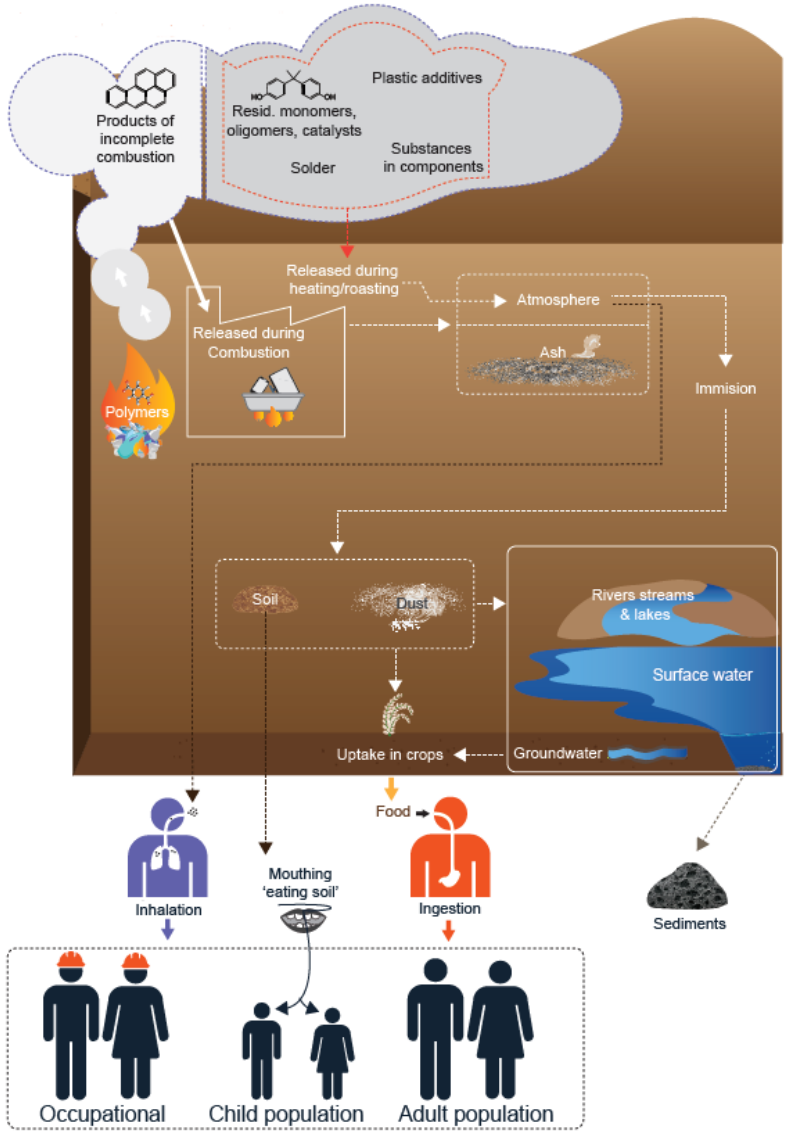
Abstract

The critical functionality provided by the informal e-waste recycling sector to the global circular economy is marred by the hazardous emissions from this practice when it is carried out under informal and unregulated conditions in the Global South. Here, we focus a systematic review (PRISMA) of evidence specifically on rudimentary thermal processing activities that are carried out to disassemble and recover metals bonded into the complex assemblies and composites of electrical and electronic products and items. We identified main combinations of hazard-pathway-receptor (H-P-R) associated with exposure to risk and ranked them to indicate severity and prioritise research needs and interventions. Two practices, open burning and heating/melting/roasting are highly efficient in comparison to mechanical disassembly of many components and materials, presenting a challenge for actors who want to discourage them. Yet, these activities result in significant and very serious potential health effects as evidenced by 48 references screened and critically assessed. Though a large body of research exists that report observations of potentially hazardous substances in environmental media and human bodies, there is an abject paucity of reliable or even indicative data to indicate the scale of the e-waste processing activity. Moreover, the concentrations measured in almost all studies suffer from a multiplicity of confounding activities, creating challenges regarding identifying the activity source. System level interventions should be designed to effectively mitigate the risk, whilst rapidly transitioning to low-risk processing with effective pollution abatement in place and safe systems of work.

Keywords: Health and safety; E-waste; WEEE; Waste; Informal recycling sector; Thermal processing; Open burning; Melting; Paint stripping; Recycling; Resource recovery; Circular economy; Global South; Risk; Hazardous waste; Hydrometallurgical processing; Potentially toxic elements; Low- and middle-income countries; Poverty alleviation; SDGs; Systematic review.

Graphical abstract



Abbreviations

8-OHdG	8-hydroxy-2′-deoxyguanosie
a-DP	*anti*-dechlorane plus
Al	aluminium
As	arsenic
Atm.	atmosphere
BaP_{eq}	benzo(a)pyrene equivalent
BDEs	brominated diphenyl ethers
Be	beryllium
BFRs	brominated flame retardants
Br	bromine
BTBPE	(); 1,2-bis(2,4,6-tribromophenoxy)ethane
Cd	cadmium
Co	cobalt
Cr	chromium
Cu	copper
DBDPE	decabromodiphenyl ethane
dl-PCB	dioxin-like polychlorinated biphenyls
DRCs	dioxins and related compounds
e-rec.	e-recycling
EU	European Union
Fe	iron
Fe	iron
Ga	gallium
Geog.	Geographical context
Haz.	hazard
HBB	(); hexabromobenzene
Hg	mercury
HSE	Health and Safety Executive
L	likelihood
LDPE	low density polyethylene
Li	lithium
LIC	low income countries
LIMIC	low income and middle income countries
MDA	serum malondialdehyde
Mn	manganese
Mo	molybdenum
MSW	municipal solid waste
n	number of samples
n/a	not available (n/a)
ND	Not detected
Ni	nickel
NS	not specified
OSHA	Occupational Safety and Health Administration
PAHs	polycyclic aromatic hydrocarbons
Pb	lead
PBDD/Fs	polybrominated dibenzo-p-dioxins and polybrominated dibenzofurans
PBDDs	polybrominated dibenzo-p-dioxins
PBDEs	polybrominated diphenyl ethers
PBDFs	polybrominated dibenzofurans
PBEB	pentabromoethylbenzene
PCBs	polychlorinated biphenyls
PCDD/Fs	polychlorinated dibenzo-p-dioxins and polychlorinated dibenzofurans
PCDDs	polychlorinated dibenzo-p-dioxins

PCDFs	polychlorinated dibenzofurans
PM	particulate matter
PM_{10}	particulate matter < 10 µm
$PM_{2.5}$	particulate matter < 2.5 µm
POP	persistent organic pollutants
PRISMA	preferred reporting items for systematic reviews and meta-analyses
PS	polystyrene
PTE	potentially toxic elements
PVC	polyvinyl chloride
R	risk
Ref.	reference
RQ	research question
S	severity
Sb	antimony
s-DP	*syn*-dechlorane plus
Se	selenium
Sr	strontium
TBBPA	tetrabromobisphenol A
temp.	temperature
TEQ	toxic equivalency
tonne	1,000 kg
TSP	total suspended particulate matter
US	United States
USEPA	United States Environmental Protection Agency
WEEE	waste electrical and electronic equipment
WHO	World Health Organisation
Zn	zinc

1. Introduction

Despite the critical function provided to the global circular economy, informal and often unregulated processing of waste electrical and electronic equipment (hereafter e-waste) in low income and middle income countries (LIMICs) represents a considerable threat to the health, safety and wellbeing of those engaged in the activity as well as those who live nearby [1, 2]. These activities are made possible by a continuing flow of obsolete electrical and electronic goods from high income countries, which are exported across international boundaries illegally [3], having been banned from doing so since 2002 [4, 5].

The constituent materials and components within e-waste have considerable value. For example, printed circuit boards contain copper (Cu) and gold; heat sinks are made from aluminium (Al) or Cu; and many product casings are Al or steel [6]. These metals retain that value following reclamation, however the complexity of electrical, and particularly electronic assemblies is such that they are often mechanically attached or physically bound with agents such as thermosetting plastics or solder, or are bonded together to the extent that they resemble composites in their own right [7]. Disassembling these materials and components to obtain a relatively pure and saleable product can be done manually, using basic hand-tools [8]. However, the ratio between effort required and material income make the use of rudimentary deconstruction unsustainable, therefore in LIMICs, it is common to see the use of hydrometallurgical (acid and alkali washing) or thermal processing to recover these valuable metals [9-11]. Here we focus on thermal processing of e-waste which can be divided into two basic categories:

(1) Smelting/roasting/heating to liquefy mainly solder for both recovery and to un-bond other components of value [12].
(2) Combustion of hydrocarbons, mainly plastics, to remove them from the assemblies and composites, and free-up metals and components for reclamation [13-15].

Perhaps the most common of these practices amongst e-waste processors is the combustion of electrical cabling to decompose the polyvinyl chloride (PVC) insulated sheath and reveal the valuable Cu within [16-18]. This is a highly efficient method of reclamation in comparison to mechanical stripping which has been shown to be a time-consuming and physically arduous process [19]. However in open, uncontrolled fires, the chlorine content in PVC contributes to the formation of polychlorinated dibenzo-p-dioxins and polychlorinated dibenzofurans (PCDD/Fs) which are believed to have a range of negative health consequences in humans

based on animal studies including: severe chloracne, neurological disturbances, hirsutism, nausea and headaches [20].

In addition to the use of heat and combustion to recover value from e-waste, combustion is also used to manage residues, mainly plastics, that have little of no value or for which the recyclers have no access to a market in which to resell them for recycling [21]. Combustion reduces the mass and volume of these materials and can also provide heat for cooking, warmth and the smoke has even been reported to be used to deter mosquitos and reduce transmission of malarial parasites [22]. Though the combustion and heating (hereafter thermal deconstruction and disposal) of e-waste has many benefits to those engaged in e-waste reclamation, the health implications from the many potentially hazardous substances emitted are potentially severe [23]. These implications have been well researched and several reviews exist that have summarised and arranged data on the topic including Tsydenova et al. [1], Townsend [2], Vaccari et al. [23] and Grant et al. [24]. Other reviews have focussed on specific geographical areas such as India [25, 26], Ghana [27-29], China [30], India and China [16], and developing countries [31]. Many of these reviews have included sections and information on open burning of e-waste and thermal deconstruction, however none focus on the topic specifically.

Given the potential for release of highly hazardous substances from these thermal reclamation activities, and the intrinsically vulnerable circumstances that exist for many of the workers who operate in this informal sector [23], we have built on previous reviews and findings with our own updated systematic review (PRISMA: preferred reporting items for systematic reviews and meta-analyses) targeted at this specific area of interest. The aim of this study is to go beyond the epidemiological data and provide a comprehensive overview of hazards and risks associated with processes used to reclaim e-waste using heat and combustion to deconstruct and disassemble e-waste items and products. The underlying purpose is to provide a basis for directing future research agenda and urgent actions to mitigate the harmful effects on this important topic.

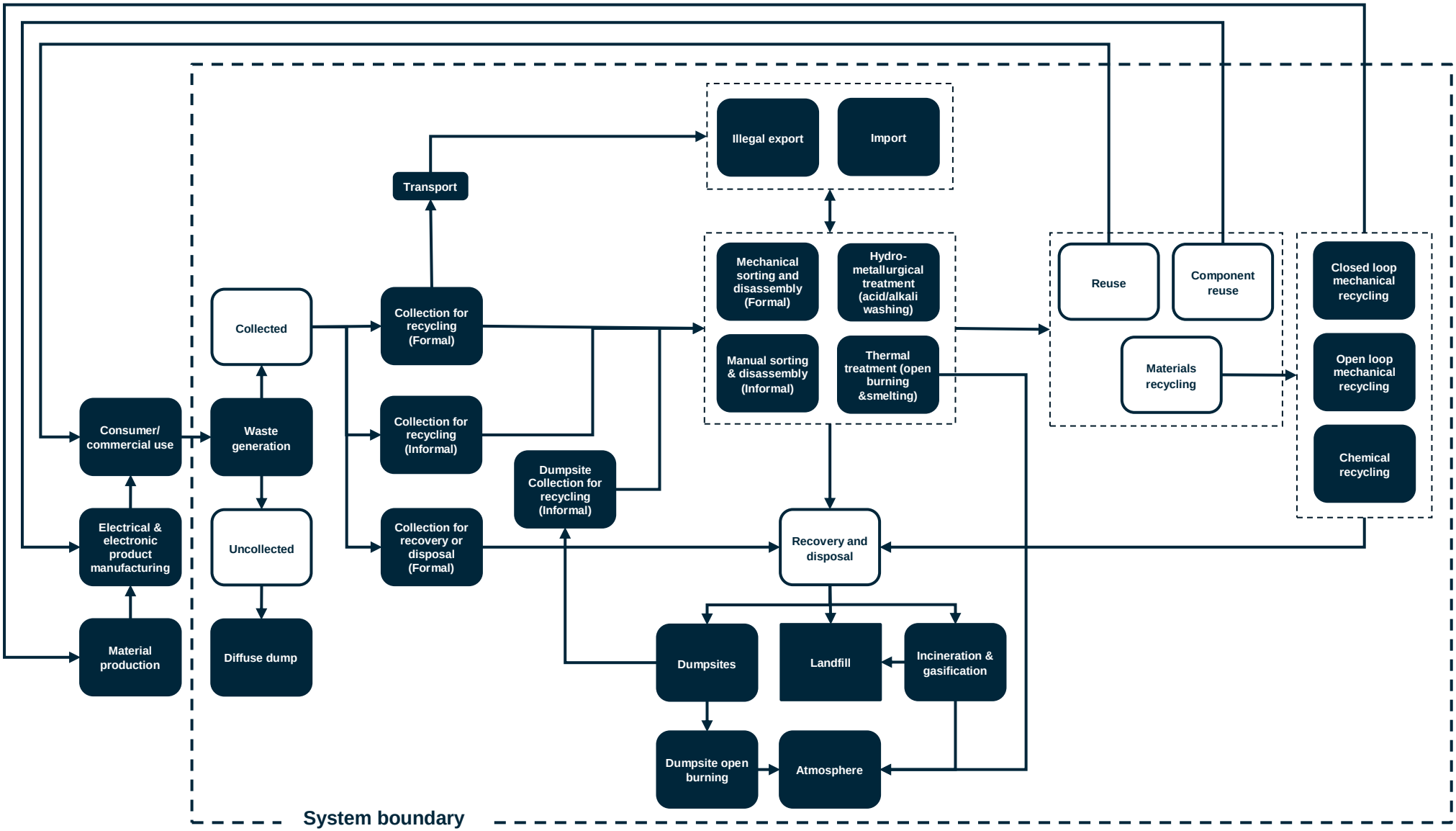


Figure 1: Material flow system for e-waste management through society; after Cook et al. [32].

2. Methods

2.1. Systematic review

Scopus, web of science and google scholar were systematically searched using PRISMA guidelines [33] adapted by Cook et al. [34] to address the following three research questions (RQ):

- **RQ1:** What evidence exists to indicate risk to public and occupational safety posed by the open burning of e-waste?
- **RQ2:** What are the comparative risks to public and occupational safety that arise from the open burning of e-waste?
- **RQ3:** What research could be carried out that would have the greatest impact on harm reduction in the open burning of e-waste?

Boolean search queries were streamlined using one-at-a-time sensitivity analysis to achieve the greatest number of relevant search results with the fewest non-relevant results (**Section S.1.1).** The pool of publications was screened using inclusion and exclusion criteria detailed in **Section S.1.2**; results shown in **Sections S.2** and **S.3**. Supplementary searches were carried out using snowball and citation searching [35] and through searching online data-sources from relevant national international organisations such as World Health Organization [36], Health and Safety Executive [37], International Labour Organization [38], The World Bank [39], Occupational Safety and Health Administration [40], and United States Environmental Protection Agency [41].

Hazards, pathways and receptors identified in the literature were grouped into combinations that were either inferred from the source, or that might be realistically experienced in scenarios discussed in sources. These were then grouped into three broad topics/ 'challenges': **Challenge 1**) Physical dismantling and reprocessing; **Challenge 2**) Hydrometallurgical treatment; and **Challenge 3**) Thermal processing. **Challenges 1** and **2** are discussed by Cook et al. [32], so the focus of the present review is on **Challenge 3**. The hazard-pathway-receptor combinations were illustrated in a conceptual diagram to describe the routs through which hazard exposure is enabled (**Figure 2**).

2.1. Risk based approach

Using a method reported by Cook et al. [34] adapted from Burns et al. [42], World Health Organization [43] and Kaya et al. [44] and Hunter et al. [45], the hazard-pathway-receptor combinations were assigned indicative risk scores according to a qualitative scoring of the likelihood of them occurring and the consequence/severity of the potential harm (**Table 1** and **Table 2**). This approach was not intended to quantitatively assess risk, but to provide a basis for indicative ranking of potential harm from each combination to assist with the prioritisation of future research agenda. The combined and sorted results of this process are shown in **Section S.4**

Table 1: Matrix used to calculate the relative risk of each hazard-pathway-receptor scenario; after Cook et al. [34].

			Consequence				
			Very slight	Slight	Moderate	Severe	Very severe
			1	2	3	4	5
Likelihood	Very unlikely	1	1	2	3	4	5
	Unlikely	2	2	4	6	8	10
	Likely	3	3	6	9	12	15
	Very likely	4	4	8	12	16	20
	Inevitable	5	5	10	15	20	25

Table 2: Colour coding used to rank hazard potential qualitatively in each category; after Cook et al. [34].

Red (R)	High harm potential
Amber (A)	Medium/high harm potential
Yellow (Y)	Medium/low harm potential
Green (G)	Low harm potential
Grey	Insufficient data

3. Thermal deconstruction and disposal of e-waste

The heating or combustion of e-waste results in the release of a range of potentially hazardous substances that exists within plastic casings, components and binding media such as solder or thermosets [13]. In addition, polymers, plastic additives, and substances within components and bonding agents produce a range of chemical substances as chemical bonds are broken and re-formed under low and heterogeneous temperature conditions that exist within open uncontrolled fires [46]. Once released or created, these substances are deposited

in ash or remain airborne in particulate, vapour or gaseous state, from where they may eventually be condensed, dissolved and deposited onto land or water [47]. Some of these substances, such as water and carbon dioxide are relatively harmless to human health, however there are many that result in a range of deleterious effects if receptors are exposed with sufficient dose [48]. Critically, if there is no pathway through which this exposure takes place, receptors will not be harmed, and therefore it is essential to assess potential risk to human health on the basis of hazard-pathway-receptor combinations that may be realistically experienced. For the thermal deconstruction and disposal of e-waste, we have simplified and illustrated these combinations in **Figure 2** and discussed the sources of information that evidence them in **Sections 3.1-3.6**

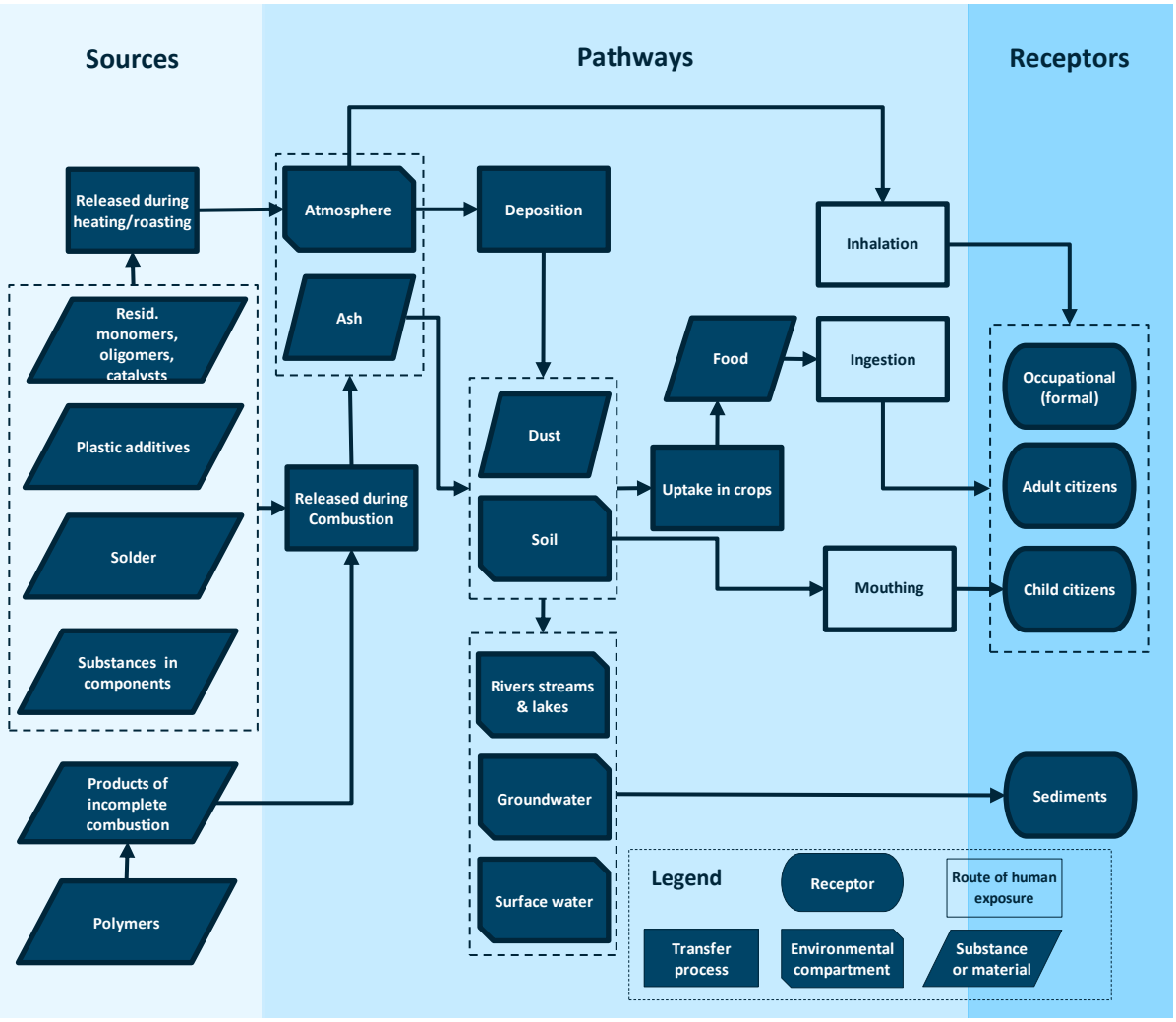


Figure 2: Hazard exposure conceptual model (source – pathway – receptor) associated with open (uncontrolled) burning or smelting e-waste (from substances contained and combustion products).

3.1. Potentially toxic elements (PTEs)

In e-waste, potentially toxic elements (PTEs) are found in plastics where they are used as catalysis; additives in components such as in transformers and capacitors; and in the materials that bind them together, such as thermosetting plastics and those that conduct electricity, for instance solder. When these products are heated to recover materials, these elements may become aerosolised and form a pathway to receptors, such as the workers or people nearby to heating and burning activities.

3.1.1. Air

Here we identified five studies [49-53] that analysed air samples in and around e-waste recycling facilities for elemental concentration alongside values from a review by Fang et al. [54] for comparison (**Table 3**).

Table 3: Selected elements detected in air samples (μg m^{-3}) close to e-waste open burning sites.

Ref.	Geog.	Sample context		n	Al	As	Cd	Cr	Cu	Fe	Mn	Ni	Pb	Sb	Zn
	IND	S1) Residential area	Reference	78				0.884	2.742			0.985	3.341		15.358
	IND	S2) Commercial & vehicular area	Close to open burning	78				2.124	23.312			2.586	9.278		42.515
Gangwar et al. [49]	IND	S3) Residential area	Closer than S2 to open burning	78				3.641	75.560			5.129	9.572		66.814
	THA			27					1	4					2
Arain [50]	CHI	E-rec. area	Proximity to workers	15						10					
Oguri et al. [51]	VNM	Village in e-rec. area	Bedroom or living room [a]	5			0.002		0.018		0.03		0.036	0.009	0.12
			Roof of a 3-story high building			0.010	0.007	1.161	0.483		0.061	0.010	0.444		1.038
Wong et al. [52]	CHN	E-rec. area		30		0.006	0.007	1.152	0.126		0.025	0.007	0.392		0.924
				1	5,500				1,200$^{\#\ddagger\dagger*¥}$	6,700$^{\#\dagger}$			980$^{\#\dagger*¥}$		
				1	6,200				ND	17,000$^{\#\ddagger\dagger}$			ND		
				1	6,500				ND	5,600$^{\#\dagger}$			ND		
				1	ND				ND	8,900$^{\#\dagger}$			ND		
			Personal air e-waste worker	1	ND				ND	5,000$^{\#\dagger}$			ND		
		E-rec. area	Fixed sampler	1					1,500$^{\#\ddagger\dagger*¥}$	7,800$^{\#\dagger}$			720$^{\#\dagger*¥}$		
Caravanos et al. [53]	GHA	Away from fires [b]	Control	1					ND	ND			ND		
	JAP, Sapporo	Urban city	n/a	n/a				0.003	0.021		0.017	0.004	0.044		0.149
	JAP, Tokyo	Urban city	n/a	n/a				0.006	0.030		0.040	0.006	0.125		0.299
	CHN, HK	Airborne	n/a	n/a					0.079		0.140		1.421		0.088
	CHN, Pontianak	Rural	n/a	n/a								0.018	0.039		0.105
	KOR, Taejon	Industrial	n/a	n/a				0.032	0.055		0.066	0.034	0.260		0.220
Fang et al. [54]	KOR, Seoul	Urban	n/a	n/a				0.014	0.028		0.039	0.020	0.096		0.163

Air concentrations benchmarked against UK and US occupational exposure limits (**Section S.5.1**) as follows: $^{\#}$ exceeds eight-hour TWA indoor air reference value set by the UK HSE; ‡ exceeds eight-hour TWA permissible exposure limit set by US OSHA; † exceeds eight-hour TWA permissible exposure limit set by Californian OSHA; * exceeds 10-hour TWA recommended exposure limit set by NIOSH (US); $^{¥}$ exceeds eight-hour TWA threshold limit value set by the ACGIH® 2019 TLV®; [a] H = 1 m; [b] ,method states that the sampler was placed 'away from the burning fires and away from the direction of the wind'; Cr as Chromium; Cd as Cadmium; Zn as total dust, Al as inhalable dust; Cu as Copper fume; Fe as iron oxide fume. Abbreviations: reference (Ref.); Geographical context (Geog.); number of samples (n); e-recycling (e-rec.); not detected (ND); not available (n/a).

The majority of the studies reviewed reported metal concentration below US and UK occupational exposure limits as detailed in **Section S.5.1.** One exception was the study by Caravanos et al. [53] who attached personal air samplers to e-waste recyclers engaged in open burning activities and stationed a fixed sampler at the notoriously polluted Agbogbloshie e-waste dismantling site in Ghana. Notably, levels of lead (Pb) on one of the personal air samplers showed a concentration of Pb nearly 20 times the Californian Occupational Safety and Health Administration (OSHA) [55], National Institute for Occupational Safety and Health (NIOSH) [56] and American Conference of Governmental Industrial Hygienists (ACGIH®) [57] and more than six times the Health and Safety Executive [58] indoor occupational exposure limits. The same two samplers also showed concentrations of Cu that exceeded the UK and US limits, however it is noteworthy that all the other samplers returned results below the rate of detection. While the study by Caravanos et al. [53] provides an indication of potentially serious exposure to informal e-waste recyclers, the sample size was too small to develop an understanding of the potential harm to the wider workforce.

The concentrations measured by Gangwar et al. [49] for Pb, zinc (Zn), and nickel (Ni) were approximately double or triple for the exposed samples than the reference and at least an order of magnitude or two in some cases greater than those measured by Oguri et al. [51] and Wong et al. [52], which were in turn similar to ambient air sample data reported by Fang et al. [54] for selected rural and urban locations in Asia. None of the studies made statistical comparisons between groups studied which means observations are speculative.

3.1.2. Soil and dust

Eight studies sampled soil and dust near e-waste open burning operations in five countries, providing an indication of emissions of 19 PTEs into the surrounding environmental media (**Table 4** and **Table 5**). Many of the concentrations exceeded United States Environmental Protection Agency [59] (USEPA) Soil Screening Levels for residential soil. Industrial values are possibly a more useful benchmark of high concentrations as befits the activity in these areas while acknowledging that workers on informal e-waste burning areas may also live in the same location. Notably, levels of arsenic (As) exceeded the USEPA carcinogenic screening level (TR=1E-06) for industrial soils in fourteen studies and the non-carcinogenic level in seven studies, by up to thirty-four and two times respectively. Concentrations of chromium (Cr) were also high, with all 26 samples exceeding the USEPA carcinogenic screening level for industrial soil.

Table 4: Element concentrations observed in soil and dust in and around e-waste burning activities (mg kg^{-1}).

Ref.	Activity context	Geog.	Sample	n	Ag	As	Be	Cd	Co	Cr	Cu	Fe	Ga [i]	Hg
	Burning area dry season		Soil [d]	21x3				26.39¥		35.45†¥‡	3,277¥			
	Burning area wet season		Soil [d]	21x3				12.69¥		23.04†¥‡	4,858¥♯			
	Burning area dry season		Soil [f]	21x3				26.09¥		33.23†¥‡	2,241¥			
	Burning area wet season		Soil [f]	21x3				15.72¥		26.4†¥‡	4,938¥♯			
	Burning area dry season		Soil [g]	21x3				21.7¥		33.59†¥‡	3,380¥			
	Burning area wet season		Soil [g]	21x3				13.48¥		26.65†¥‡	5,114¥♯			
	Control area dry season [i]		Soil	3				0.87		0.3	14.7			
Isimekhai et al. [60]	Control area wet season [i]	NGA	Soil	3				0.45		0.19	9.64			
	Burning area		Soil [a]	39	16	8†¥‡		14¥		139†¥‡	10,400¥♯	39,900¥		
	Burning area		Soil [b]	63	18	68†¥‡♯		16¥		95†¥‡	5,320¥♯	26,900¥		
	E-recycling site		Soil [a]	13	7	6†¥‡		11¥		59†¥‡	6,060¥♯	15,600¥		
Ackah [61]	Control	GHA	Soil	n/a	3	6†¥‡		<4		61†¥‡	14	36,500¥		
	Village [h]		Garden soil	5				1.7			771¥			
Oguri et al. [51]	Village [h] (bedroom, living room)	VNM	Floor dust	5				2.53			475¥			
	Burning area		Soil [a]	29	41¥	83†¥‡♯		10¥	1.5	69†¥‡	12,590¥♯	7,373¥	1.5	0.5
	Control area 100 to 500 m away		Soil [a]	29	2.5	0.7†		2.6	1.5	72†¥‡	18	12,336¥	7.9	0.5
	Burning area		Soil [a]	29	16	103†¥‡♯		7	1.5	123†¥‡	12,749¥♯	31,435¥	5.2	5¥♯
	Control area 100 to 500 m away		Soil [a]	29	14	4†¥‡		2.55	8.3¥	141.1†¥‡	70	35,835¥	9	1.1¥
	Burning area		Soil [a]	29	6.6	48.1†¥‡♯		1.2	1.5	125†¥‡	9,420¥♯	54,873¥	8.4	0.8
	Control area 100 to 500 m away		Soil [a]	29	1	2†		2.6	1.5	63†¥‡	21	21,710¥	10	18.5¥♯
Ohajinwa et al. [62]	Control area 100 to 500 m away	NGA	Dust	32	1	0.25		2.55	1.5	75.5†¥‡	126	38,440¥	4.8	0.5
	Informal e-recycling site		Soil	10		12.12†¥‡		10.07¥			5,720¥♯			
	Informal e-recycling site		Soil (> 250 µm)	5		85†¥‡♯		16.84¥			10,558¥♯			
Cao et al. [63]	Informal e-recycling site	GHA	Soil (< 250 µm)	5		22.6†¥‡		4.7			7,640¥♯			
	Burning area abandoned e-rec. site		Soil [e]	5	47.9¥		4,106†¥♯	6.82	50.3¥♯	318†¥‡	1,568¥			
	Paddy field ~50 m abandoned e-rec. site		Soil [e]	5	1.58		435¥♯	3.15	6.59¥	66.5†¥‡	154			
Wu et al. [64]	Stream ~50 m abandoned e-rec. site	CHN	Soil [e]	5	2.23		497¥♯	1.54	7.57¥	48.5†¥‡	167			
	Control area (informal)		Soil [e]		1	0.8†		2.55	1.5	70†¥‡	15		9	0.5
	Burning area (informal)		Soil [e]		41¥	83.2†¥‡♯		10.4¥	1.5	68.7†¥‡	12,590¥♯		1.45	0.5
	Control area (informal)		Soil [e]		14.2	4†¥‡		2.55	8.3¥	141†¥‡	70		8.6	1.1¥
	Burning area (informal)		Soil [e]		16	103†¥‡♯		7	1.5	123†¥‡	124,749¥♯		5.2	4.6¥♯
	Control area (informal)		Soil [e]		1	2†		2.55	1.5	63†¥‡	21		10	18.5¥♯
Ohajinwa et al. [65]	Burning area (informal)	NGA	Soil [e]	62	8	24†¥‡		0.5	1.5	102†¥‡	4,435¥		10	0.5

Samples taken from the following depths: [a] 0-30 cm; [b] 30-100 cm; [c] 2 cm; [d] 0-10 cm [e] 10 cm; [f] 10-20 cm; [g] 20-30 cm; [h] near e-recycling area; [i] Lagos state university campus. Soil screening levels for residential soil (**Section S.5.2**) as follows: † exceeds USEPA carcinogenic screening level (TR=1E-06) for residential soils; ¥ exceeds USEPA child non-carcinogenic screening level (THI=0.1) for residential soils; ‡ exceeds USEPA carcinogenic screening level (TR=1E-06) for industrial soils; ♯ exceeds USEPA non-carcinogenic screening level (THI=0.1) for industrial soils; specific screening levels elements were compared to: Cd to 'cadmium (Diet)'; Cr to 'chromium (VI)'; Hg to 'elemental mercury'. Abbreviations: reference (Ref.); Geographical context (Geog.); number of samples (n).

Table 5: Element concentrations observed in soil and dust in and around e-waste burning activities (mg kg^{-1}).

Ref.	Activity context	Geog.	Sample	n	Mn	Mo	Ni	Pb	Sb	Se	Tl	V	Zn
	Burning area dry season		Soil [d]	21x3	115.35		40.8	2,418¥♯	38.46¥				2,195
	Burning area wet season		Soil [d]	21x3	92		23.27	1,969¥♯	35.36¥				915
	Burning area dry season		Soil [f]	21x3	139.3		45.31	2,280¥♯	33.63¥				2,195
	Burning area wet season		Soil [f]	21x3	92.3		55.5	2,006¥♯	40.77¥				1,012
	Burning area dry season		Soil [g]	21x3	148.9		40.88	1,764¥♯	31.37¥				2,440¥
	Burning area wet season		Soil [g]	21x3	97.64		35.42	2,202¥♯	33.33¥				1,064
	Control area dry season [i]		Soil	3	1.88		0.7	20.62	0.22				24.53
Isimekhai et al. [60]	Control area wet season [i]	NGA	Soil	3	1.26		0.29	10.58	0.15				17.34
	Burning area		Soil [a]	39				5,080¥♯		11			7,010¥
	Burning area		Soil [b]	63				2,700¥♯		7			2,170
	E-recycling site		Soil [a]	13				1,690¥♯		5			2,010
Ackah [61]	Control	GHA	Soil	n/a				31		2			40
	Village [h]		Garden soil	5	550¥			580¥	16.9¥				860
Oguri et al. [51]	Village [h] (Bedroom, living room)	VNM	Floor dust	5	479¥			556¥	19.9¥				1,079
	Burning area		Soil [a]	29	160	8.5	194¥	6,358¥♯	1,544¥♯	6		24	3,152¥
	Control area 100-500 m away		Soil [a]	29	124	1.2	18	14	1.3	0.25		36.5¥	46.4
	Burning area		Soil [a]	29	740¥	8	93¥	21,423¥♯	592¥♯	26		54¥	3,327¥
	Control area 100-500 m away		Soil [a]	29	597¥	4	51.3	305	2	0.5		80¥	300
	Burning area		Soil [a]	29	430¥	16.3	90¥	3,810¥♯	500¥♯	5		31	4,533¥
	Control area 100-500 m away		Soil [a]	29	257¥	0.5	20	0.5	1.4	0.3		39¥	85
Ohajinwa et al. [62]	Control area 100-500 m away	NGA	Dust	32	502¥	0.5	28	353.4	5¥	0.7		67¥	446
	Informal e-recycling site		Soil	10				4,539¥♯	687¥♯				
	Informal e-recycling site		Soil (> 250 µm)	5				8,449¥♯	1,033¥♯				
Cao et al. [63]	Informal e-recycling site	GHA	Soil (< 250 µm)	5				6,385¥♯	6,385¥♯				
	Burning area abandoned e-rec. site		Soil [e]	5	410¥	18.9	362¥	1,423¥♯	5,003¥♯		0.82		2,978¥
	Paddy field ~50 m abandoned e-rec. site		Soil [e]	5	224¥	1.86	25.4	490¥	1,863¥♯		1.56		3,126¥
Wu et al. [64]	Stream ~50 m abandoned e-rec. site	CHN	Soil [e]	5	254¥	2.68	48.2	121	294¥♯		1.57		215
Pascale et al. [66]	Family residence (cable burning)	URY	Soil	40				7,103¥♯					
	Control area (informal)		Soil [e]		116.5	0.5	18	15.7	1.5	0.25			44
	Burning area (informal)		Soil [e]		160.1	8.5	194.5¥	6,358¥♯	1,544¥♯	6			3,152¥
	Control area (informal)		Soil [e]		597¥	4.2	51.3	305	2	0.5			300
	Burning area (informal)		Soil [e]		740¥	8	93¥	21,423¥♯	592¥♯	26			3,327¥
	Control area (informal)		Soil [e]		257¥	0.5	20	0.5	1.4	0.25			85
Ohajinwa et al. [65]	Burning area (informal)	NGA	Soil [e]	62	419¥	14	86¥	1,505¥♯	49¥♯	2.5			3,553¥

Samples taken from the following depths: [a] 0-30 cm; [b] 30-100 cm; [c] 2 cm; [d] 0-10 cm [e] 10 cm; [f] 10-20 cm; [g] 20-30 cm; [h] near e-recycling area. Soil screening levels for residential soil (**Section S.5.2**) as follows: † exceeds USEPA carcinogenic screening level (TR=1E-06) for residential soils; ¥ exceeds USEPA child non-carcinogenic screening level (THI=0.1) for residential soils; ‡ exceeds USEPA carcinogenic screening level (TR=1E-06) for industrial soils; ♯ exceeds USEPA non-carcinogenic screening level (THI=0.1) for industrial soils; specific screening levels elements were compared to: Cd to 'cadmium (Diet)'; Cr to 'chromium (VI)'; Hg to 'elemental mercury'; Ni to nickel refinery dust. Abbreviations: reference (Ref.); Geographical context (Geog.); number of samples (n).

Soil guideline values or soil screening levels provide a useful comparator to benchmark typical concentrations below which significant harm is unlikely to take place to people occupying that area. In isolation, soil guideline values do not necessarily indicate the risk to populations or workers. To do so, consideration should be given to the level of potential bioaccumulation, the likely exposure to individuals, and in relation to the background levels, which can be determined through published values for the exposure area where soil has been analysed from non-exposed areas, or alternatively by analysing control samples in the same study.

Four of the eight studies [60-62, 67] collected and analysed control samples, three [51, 63, 66] compared exposed samples with national guideline values and one [64], compared values between those identified within the study, but no control or reference was reported for comparison. Both Ohajinwa et al. [65] and Ohajinwa et al. [62] used analysis of variance to compare variability between samples, however the results were not reported specifically as comparisons between the control and exposed areas, so there is some ambiguity as to whether significance was achieved. Isimekhai et al. [60] and Ackah [61] compared the ratio of concentrations in exposed soils with control samples, which they reported as a ratio, but did not statistically compare samples to see if the differences were significant. Nonetheless, some stark differences can be observed between exposed and controlled samples.

For instance, Ackah [61] observed levels of Cu, Zn, and Pb to be an average of approximately 742, 175 and 164 times greater respectively in an e-waste burning area in Ghana compared to the control. In a similar study in Nigeria, Isimekhai et al. [60] observed levels of Pb, Cd and antimony (Sb) to be an average of approximately 85 to 208, 24 to 35, and 142 to 272 times higher in exposed sites compared to the control. Very large differences were observed between all elemental concentrations reported by Isimekhai et al. [60] and most of the concentrations of exposed soils reported by Ackah [61] were also high in comparison to controls.

In some cases, control samples did not appear considerably different to the exposed sites. For instance, Ackah [61] observed As levels to be approximately tenfold higher at one site compared to the control, but two of the exposed sites shows almost the same level as the control. Levels of Cd and selenium (Se) measured by Ackah [61] were also not hugely dissimilar, being just two to five times greater in the exposed samples compared to the controlled samples.

In few cases, levels of Cr, iron (Fe), and gallium (Ga), in the studies by Ohajinwa et al. [62] and Ohajinwa et al. [65] showed similar or higher concentrations in control samples compared to the exposed samples. In the case of mercury (Hg), the control samples were 18 to 37 times higher than the exposed samples, at levels exceeding non-carcinogenic residential and in one case, industrial US soil screening levels. Ohajinwa et al. [65] did not elaborate on the Hg concentrations being higher in the control site, but did mention that the levels were high in the burning site, seemingly without reference to the control. It is noteworthy that the control samples in the two studies were the same. Any further interpretation is conjecture, but it is possible that the control sites had been subject to historical contamination.

Another noteworthy finding was the concentrations of beryllium (Be) reported by Wu et al. [64] in samples from environmental media in and surrounding an abandoned e-waste recycling site in China. All three samples exceeded the non-carcinogenic screening level for industrial soil by two times in the case of the nearby paddy field and stream, and 20 times in samples taken directly from the site. Be is increasingly used in a wide range of electronic goods, and for non-smokers the main route of ingestion is through dermal contact, ingestion and contact with soil [68]. Be is also classified as a group 1 carcinogen and therefore its occurrence in environmental compartments near to e-waste recycling sites may be an indicator of a wider concern as its content was not determined by many authors in this study.

3.1.3. Water

Two studies sampled freshwater and leachate near to e-waste open burning sites (**Table 6**). The leachate samples analysed by Alabi et al. [69] from an e-waste dumpsite on which open burning takes place showed very high concentrations of metals, all of which exceeded at least one of the USEPA guideline levels for fresh-water. The Pb and Cd concentrations in the sample were approximately 1,500 and 3,400 times greater than the USEP threshold for acute harm to aquatic life and approximately 38,400 and 8,800 times greater than the chronic threshold for aquatic life respectively. Levels of As in the leachate exceeded all the guidelines, showing approximately 15 and 32 times the acute and chronic limits for aquatic life respectively.

Table 6: Element concentrations observed in water in and around e-waste open burning sites (µg L^{-1}).

	Alabi et al. [69]				Arain [50]		
	E-waste dumpsite (NGA)				< 1 km from refuse dump where e-waste burning occurs		Community >1 km away
Analyte	Tap water	Contaminated underground water (n=3)	Control underground water	Raw leachate	Surface water (n=14)		Surface water (n=7)
Ag	ND	ND	ND	820‡			
As	ND	ND	ND	4,820‡♯*ᵀ			
Cd	ND	1,100‡♯	ND	6,140‡♯	40‡♯		ND
Cr	ND	ND	ND	4,000‡♯			
Cu	40	120	ND	14,320*	900		20
Fe	5,050♯	5,650♯	5,500♯	6,410♯			
Mn	30	225*ᵀ	890*ᵀ	1,350*ᵀ			
Ni	ND	ND	ND	2,410‡♯*			
Pb	ND	190‡♯	ND	122,900‡♯	300	‡♯	10♯
Zn	‡♯	1,130‡♯	230‡♯	15,000‡♯*			

Water screening levels for drinking water (**Section S.5.3**) as follows:‡ Exceeds USEPA acute quality criteria for freshwater aquatic life; ♯ exceeds USEPA chronic quality criteria for freshwater aquatic life; * exceeds USEPA quality criteria for freshwater consumption of water and organisms; ᵀ exceeds USEPA quality criteria for freshwater consumption of organisms only. Abbreviation: not detected (ND).

In the groundwater nearby to the dumpsite where the leachate was collected by Alabi et al. [69], the Pb concentration was double and 60 times the USEPA acute and chronic aquatic life limit, and the Cd was approximately 600 and 1,600 times greater respectively. Though much lower levels were detected, Arain [50] also observed high levels of Cd and Pb which exceeded USEPA guidelines.

3.1.4. Food

Two studies measured concentrations of elements in food near to e-waste open burning activities (**Table 7**). The analysis by Arain [50] of rice grown near e-waste open burning areas in Thailand, reported that 20% of Cd and Pb samples exceeded reference levels of 0.2 mg kg^{-1}. No comparative thresholds were available for the rice plant parts analysed by Wu et al. [64], however the study did report significantly higher concentrations in plant parts in the order of root > leaf > stem > grain with the exception of manganese (Mn), molybdenum (Mo) and strontium (Sr) which showed that the concentrations in leaves were similar or higher than the roots. The study also reported a bioaccumulation factor greater than 1 for Cr, Ni, Mn and Mo which indicates that these metals are readily taken up by the rice plants according to the study.

Table 7: Element concentrations (µg g^{-1} foodstuff) in food and crops grown near to e-waste open burning activities.

	Arain [50]	Wu et al. [64]			
	THA	CHN			
Analyte	**Rice (n=17)**	**Root (n=5)**	**Stem (n=5)**	**Leaf (n=5)**	**Grain (n=5)**
Ag		1.04	0.108	0.209	0.047
Be		1.07	0.069	0.151	0.012
Cd	0.1	0.911†	0.141†	0.164	0.039
Co		4.09	0.63	0.702	0.142
Cr		85.7	39.6	40.3	29.7
Cu	4.34	122	9.85	15.1	4.97
Fe	36.9				
Mn	36.3	259	290	456	51.2
Mo		2.54	0.935	2.18	1.11
Ni	2	27.4	2.24	3.97	1.76
Pb	0.3	127	12.3	24.7†	3.34
Sb		177	12.5	17.1	1.8
Tl		0.274	0.026	0.036	0.007
Zn	29.8	499	101	91.3	31.8

[a] Parts of rice plants from paddy field ~50 m abandoned e-recycling site. † Exceeds maximum concentrations of selected elements in foodstuffs according to Commission Regulation 1881/2006 (**Section S.5.4).**

3.1.5. Human exposure

Five studies [49, 50, 70-72] reported concentrations of elements in the blood of adults living and working in the vicinity of e-waste open burning activities, showing levels which exceeded those found in the Canadian population [73] in many cases (**Table 8**). Arain [50] found similar, or slightly higher, levels of Cd, Mn and Pb compared to the Canadian population. Schecter found slightly lower levels of cadmium (Cd) and slightly higher levels of Pb in one case and Amankwaa et al. [70] found similar or slightly higher levels of Pb. Gangwar et al. [49] and Popoola et al. [72] identified higher concentrations of Pb in comparison to the other studies, with levels of lead more than double in two sample sets. Gangwar et al. [49] also found a significant correlation between elevated levels of Cr, Ni, Cu, and Pb and proximity to open burning activities.

In blood samples taken from children living and working in proximity to open burning activities, levels of Pb were significantly higher than the reference areas in two studies [74, 75], and approximately two to six times greater than Canadian children of a similar age-group (**Table 9**). Pascale et al. [66] compared pre-school children with occupationally exposed children involved in burning activities, finding concentrations of Pb three to six times those of Canadian children respectively for the relevant age-group.

Table 8: Blood concentrations of selected elements compared for adults working near and in e-waste open burning activities (μg L^{-1}).

Ref.	Geog.			n	Cd	Cr	Cu	Mn	Ni	Pb	Zn
		E-rec. site	E-rec workers	46	0.9†			13.8			
	THA	Resident. area nearby	Residents	105	1†			15.9†		38†	
Arain [50]	CHI	Resident. area nearby	Residents	86	1.1†			6.9		22	
		S1) Resident. area (Ref.)	Residents	50 [a]		2.12†	342.38		6.36♯	4.346	9,277†
		S2) Area near burning	E-rec workers	54 [a]		62.54†	637.06		18.02♯	9.54	12,204†
Gangwar et al. [49]	IND, Moradabad	S3) Area closer to burning	Residents	28 [a]		102.82†	791.82		125.08♯	89.04†	12,356†
		E-rec. site	E-rec workers	40	0.59					29.3	
Schecter et al. [71]	VNM, Hanoi	Residential area nearby	Residents	20	0.59					48.2†	
			E-rec workers	81						34.9†	
Amankwaa et al. [70]	GHA, Agbogbloshie	E- rec. site	E-rec burners	8						49.8†	
Popoola et al. [72]	NGA, Lagos	E-rec. site	E-rec workers	13			339	194†		110†	1,262
Christensen et al. [76]	DNK	Adult citizens	Male (non-occ.)	23		0.09-0.55					
		3–79 year old citizens	All (non-occ.)						1.1		
			All (non-occ.)		0.83					33	
			Female (non-occ.)				1,000	16			6,700
Saravanabhavan et al. [73]	CAN	20–79 year old citizens	Male (non-occ.)	[b]			1,300	14			7,900

Reference values for concentration of elements on whole blood (**Section S.5.5**) as follows: † Exceeds reference value for blood on non-occupationally exposed Canadian adult citizens (20 to 79 years of age) or Danish citizens in the case of Cr; ♯ exceeds reference value for blood on non-occupationally exposed Canadian citizens (3 to 79 years of age); [a] converted from ppm to μg L^{-1} using blood density of 1.060 kg m^{-3} reported by Cutnell et al. [77]; [b] samples varied according to each element, therefore not shown here. Abbreviations: reference (Ref.); Geographical context (Geog.); number of samples (n); e-recycling (e-rec.); non-occupational (non-occ.).

Table 9: Blood concentrations of selected elements compared for children living in e-waste recycling sites with reference groups (μg L^{-1}).

Ref.	Year	Geog.			n	As	Cd	Cr	Cu	Hg	Mn	Ni	Pb	Se	Zn
		CHN, Guiyu	Live e-rec. site	Children	157	55.3‡**	1.2¥‡†♯**	144†**	9,191†♯**	19.2¥‡†♯	163.1¥‡†*	44.1♯	94.3 ¥‡†**	1,358¥‡†*	47,464¥‡†*
Lin et al. [74]	2017	CHN, Haojiang	Live non-e-rec site	Children	127	65.6‡	2.7¥‡†♯	106†	8,425†♯	22.5¥‡†♯	150.8¥‡†	34.4♯	67.9¥‡†	1,491¥‡†	43,130¥‡†
		CHN, Guiyu	Live e-rec. site	Children	263								56.1¥‡†*		
		CHN, Haojiang	Live non-e-rec site	Children	115								35.7¥‡†		
				Children (boys)	144								58.5¥‡†		
		CHN, Guiyu	Live e-rec. site	Children (girls)	119								53.3¥‡†		
				Children (boys)	63								37.6¥‡†		
Lin et al. [75]	2016	CHN, Haojiang	Live e-rec. site	Children (girls)	52								33.6¥‡†		
		URY,		Children (burn)	69								91.9¥‡†		
Pascale et al. [66]	2016	Montevideo	Live e-rec. site	Pre-school	10								58.6¥‡†		
Christensen et al. [76]	1993	DNK	Adult citizens	Male	23			0.09-0.55							
				All			0.18			1.5	18		20	200	
				Female											5,800
			3 to 5-year-old citizens	Male											5,500
				All		1.4	0.27			1.2	16		15	220	
				Female											6,500
			6 to 19-year-old citizens	Male											6,800
			3 to 79-year-old citizens	All								1.1			
				All		2	0.83			2.3			33	240	
				Female					1,000		16				6,700
Saravanabhavan et al. [73]	2017	CAN	20 to 79-year-old citizens	Male	[b]				1,300		14				7,900

Reference values for concentration of elements on whole blood (**Section S.5.5**) as follows: ¥ Exceeds reference value for blood on non-occupationally exposed Canadian child citizens (three to five years of age); ‡ exceeds reference value for blood on non-occupationally exposed Canadian child citizens (6 to 19 years of age); † exceeds reference value for blood on non-occupationally exposed Canadian adult citizens (20 to 79 years of age) or Danish citizens in the case of Cr; ♯ exceeds reference value for blood on non-occupationally exposed Canadian citizens (3 to 79 years of age); [b] samples varied according to each element, therefore not shown here; * Significantly higher ($p < 0.05$) in e-waste recycling area compared to reference (Mann-Whitney U test); ** significantly higher ($p < 0.01$) in e-waste recycling area compared to reference (Mann-Whitney U test);

Lin et al. [74] found significantly different ($p < 0.05$) concentrations of all samples compared to the control for all elements except for Hg and Ni. Though it is noteworthy that the levels were not always higher in the exposed group, indicating that other factors may be influencing the high levels of elements detected in comparison to the Canadian children of the same age group for all elements. Lin et al. [74] suggest several reasons for the exposure to both groups including sources such as seafood, which may influence the levels of Hg, As, Cd and Se, and the nearby power station, which may result in elevated levels of As, Cd and Se.

3.1.6. Non-carcinogenic risk

Five studies carried out human health risk assessments for PTE exposure from e-waste open burning activities, calculating the non-carcinogenic hazard index through four pathways: inhalation, ingestion, dermal contact and dietary intake (**Table 10**). Most of the calculations were for children or adults in the population, while three calculations were made for occupational exposure. For instance, Cesaro et al. [13] determined the theoretical hazard index of 3.5 for inhalation exposure of PTEs emitted during the open burning of computer printed circuit boards; mobile printed circuit boards and cables. Ohajinwa et al. [65] calculated an extremely high hazard index (1,600 to 15,000) for dermal exposure to PTEs by workers engaged in open burning activities, attributing the high risk from the absence of protective equipment used by the subjects being studied.

Table 10: Non-carcinogenic hazard index for several pathway/receptor combinations induced by e-waste open burning activities.

Pathway	Media	Ref.	Geog.	Media description	Activity context	Receptor	n	Hazard index	PTEs of concern (HQ>1)	PTEs included
		Oguri et al. [51]	VNM	Household ambient air	Burning area *	Adults	5	<1[e]		Pb, Cd, Cu, Mn, Zn, Sb
				PC PCB burning			-	355.6[†]		Pb, Ni, Co
				Mobile PCB burning			-	531[†]		Pb, Ni
Inhalation	Air	Cesaro et al. [13]	Theoretical	Wire burning	Burning area	Workers	-	3.5[†]		Cu
						Adults	39	3.3[†]	Pb	
				Topsoil [a]	Established burning site	Children	39	24.7[†]	Pb, Cu	
						Adults	63	1.9[†]	Pb	
				Subsoil [b]	Established burning site	Children	63	14.1[†]	Pb, Cu	
						Adults	13	1.3[†]		
		Ackah [61]	GHA	Topsoil [a]	Emerging burning site	Children	13	3.4[†]	Cu	Pb, Cd, Cr, Cu, Fe, Zn, Ag, As, Se
				Topsoil [c]	E-recycling site	Adults	10	2.13[†e]		
				Coarse (>=200 µm) topsoil [c]	E-recycling site	Adults	5	3.5[†e]		
		Cao et al. [78]	GHA	Fine (<200 µm) soil [c]	E-recycling site	Adults	5	2.4[†e]		Pb, Cd, Cu, As, Sb
		Oguri et al. [51]	VNM	Topsoil	Burning area *	Adults	5	<1[e]		Pb, Cd, Cu, Mn, Zn, Sb
Ingestion	Soil	Ohajinwa et al. [65]	NGA	Topsoil [d]	Burning area **	Workers	n/a	1.8[†]		Pb, Cd, Cr, Cu, Fe, Mn, Ni, Zn, Ag, As, Sb, V, Co, Mo, Ga, Hg, Se
					Established burning site	Adults	39	<1		
				Topsoil [a]		Children	39	<1		
					Established burning site	Adults	63	<1		
				Subsoil area [b]		Children	63	<1		
						Adults	13	<1		
		Ackah [61]	GHA	Topsoil [a]	Emerging burning site	Children	13	<1		Pb, Cd, Cr, Cu, Fe, Zn, Ag, As, Se
Dermal exposure	Soil	Ohajinwa et al. [65]	NGA	Topsoil [d]	Burning area **	Workers	n/a	1,600-15,000[†]	Pb, Cd, Cr, Cu, Fe, Mn, Ni, Zn, Ag, As, Sb, Hg	Pb, Cd, Cr, Cu, Fe, Mn, Ni, Zn, Ag, As, Sb, V, Co, Mo, Ga, Hg, Se
Dietary intake	Food/ water***	Oguri et al. [51]	VNM	Topsoil	Burning area *	Adults	5	<1[e]		Pb, Cd, Cu, Mn, Zn, Sb

Samples taken from the following depths: [a] 0 to 30 cm; [b] 30 to 100 cm; [c] 2 cm; [d] 0 to 10 cm; [e] Based on bio-accessible PTE concentrations; *mainly burning of wires; ** From three different e-recycling sites; ***Diet sampling day at breakfast, lunch, dinner, and snack time; [†] exceeds target value of one, indicating significant non-cancer risk. Abbreviations: printed circuit board (PCB); reference (Ref.); Geographical context (Geog.); number of samples (n); potentially toxic elements (PTEs).

Ackah [61] calculated the hazard index for residents living on, or nearby, e-waste open burning activities; investigating an intensive, established open burning site and an emerging site, both in Accra, Ghana. Hazard indices were calculated for dermal exposure to PTEs and ingestion of soil containing PTEs, the latter of which exceeded the threshold value for adults and children living in both e-recycling areas, with a higher reported risk for receptors near the established, intensive e-waste burning site. In contrast, the potential non-cancer risk due to dermal exposure was calculated to be low for both children and adult receptors.

The comparison of the results from studies on non-cancer effects due to PTE exposure at e-waste open burning areas (**Table 10**) indicated that soil ingestion constitutes a considerable exposure pathway, especially for children, while dermal exposure appeared to be the pathway of greatest concern for workers; acknowledging that only one study reported results here.

It is noteworthy that the methods varied between the studies. In particular, Oguri et al. [51] and Cao et al. [78], took into account the bio-accessibility of the PTEs, a method which several authors argue prevents an overestimate of adverse health outcomes [51, 78, 79]. For a substance to be bio-accessible, it needs to be: soluble in the digestive environment and capable of being absorbed by the human body; capable of entering the blood through fluid in lungs; or capable of being absorbed through the skin. Bio-accessibility varies considerably depending on the source media (for example,. soil and dust), its properties (for example, chemical speciation, particle size and organic carbon content), and conditions inside the body (for example, temperature and pH) [51, 80]. The fraction of a substance that is bioaccessible has been estimated by several authors [51, 80, 81] who combine empirical observations of element concentrations in faeces and soil with simulations of the gastrointestinal environment as described by Luo et al. [80]. Some examples of bioaccessible fractions determined by different authors are shown in **Table 11** for information. It is beyond the scope of this study to review bio-accessibility factors, however the studies reviewed here applied the same slope factor used for the ingestion pathways to the dermal and inhalation pathways as a proxy.

Table 11: Fractions of elements determined to be bio-accessible when ingested as part of dust and soil.

	Luo et al. [80]	Oguri et al. [51]		Ibanez et al. [79]
Element	**Soil**	**Soil**	**Dust**	**Dust**
Ag				6090%
Al				10–80%
As				10–90%
Ca	88%			
Cd	92%		71%	50–90%
Co	27%			15–50%
Cr	10%			10–50%
Cu	54%	58%	51%	20–80%
Fe	2.9%			5–45%
Hg				10%
Mg	16%			
Mn	45%	34%	37%	40–60%
Ni	26%			20–80%
Pb	49%	56%	78%	
Sb		12%	10%	
Sn				5–10%
U				10–30%
Zn	39%	48%	57%	80–90%

The consideration of the bio-accessibility of PTEs may in part explain the stark differences in the hazard indices reported by Oguri et al. [51] in comparison to other authors who did not consider it. Oguri et al. [51] reported that exposure to PTEs via air inhalation was a negligible risk, and a small (< 1) risk via food consumption (detail not shown). Cao et al. [78], who also considered the bio-accessibility of elements, estimated higher non-cancer indices due to soil ingestion for non-occupationally exposed receptors, which were similar to those reported by Ackah [61] who did not consider bio-accessibility.

3.1.7. Carcinogenic risk

Assessments of carcinogenic risk from exposure to PTEs from e-waste open burning activities were provided in three studies (**Table 12**). In general, the carcinogenic risk to children was higher in the study of people living on e-waste sites in Ghana by Ackah [61], as a result of exposure to As. Carcinogenic risk from ingestion was generally lower for adults in the studies by Ackah [61], Cao et al. [78] and Ohajinwa et al. [65] except in some cases of occupational exposure in Ohajinwa et al. [65]. However, dermal exposure for workers seems again a considerable pathway as significantly high cancer risk values were reported by Ohajinwa et al. [65].

Table 12: Cancer risk for several pathway/receptor combinations induced by e-waste open burning activities.

Pathway	Media	Ref.	Geog.	Media description	Activity context	Receptor	n	Hazard index	
				Topsoil [a]	Established burning site	Adults	39	1.0E-06	As
						Children	39	7.6E-06	As
				Subsoil [b]	Established burning site	Adults	63	2.6E-05	As
						Children	63	2.0E-04[†]	As
		Ackah [61]	GHA	Topsoil [a]	Emerging burning site	Adults	13	1.6E-05	As
						Children	13	1.2E-04[†]	As
		Cao et al. [78]	GHA	Topsoil [c]	E-recycling site	Residents	10	2.3E-06[e]	As
Ingestion	Soil	Ohajinwa et al. [65]	NGA	Topsoil [d]	Burning area*	Workers	n/a	8.2E-05 - 1.5E-04[†]	Cr, Co, Ni, As, Cd, Hg, Pb
Dermal exposure	Soil	Ohajinwa et al. [65]	NGA	Topsoil [d]	Burning area*	Workers	n/a	1.3E-03 - 4.9E-02[†]	Cr, Co, Ni, As, Cd, Hg, Pb

Samples taken from the following depths: [a] 0-30 cm; [b] 30-100 cm; [c] 2 cm; [d] 0-10 cm; [e] based on bio-accessible PTE concentrations; * from three different e-recycling sites; [†] exceeds target value of 1.0E-04 indicating unacceptable risk. Abbreviations: reference (Ref.); Geographical context (Geog.); number of samples (n); potentially toxic elements (PTEs).

3.1.8. Summary of PTEs

The determination of both carcinogenic and non-carcinogenic risk by the authors presented here provides compelling insight into the potential risk of exposure to e-waste workers, many of whom are clearly working in conditions that damage their health. However the small number of studies, specifically in the open burning context, and the considerable variation in results reported, make it challenging to draw strong conclusions beyond saying that burning e-waste is unlikely to be beneficial to adult health. For children, the results appear more compelling, with clear differences between exposed and non-exposed groups and unacceptably high hazard indices calculated in almost all scenarios involving children.

Bioavailability is still not considered in many studies, which may overestimate the exposure, and as reported by several authors, there are other confounding sources of PTEs exposure such as power stations, food and other sources of contamination in the countries being studied. There is an abject lack of data on PTEs exposure from open burning of e-waste through the air Oguri et al. [51], despite many authors expressing serious concerns. It is therefore advised that more research is carried out as a matter of urgency to determine the significance of this source, which from the data studied in this research, does not appear to be a significant pathway for PTEs exposure to humans.

3.2. Dioxins and related compounds (DRCs)

3.2.1. Context

The term ‘dioxins’, describes a group of 419 aromatic compounds characterised by a polychlorinated (or brominated) structure. Dioxins and related compounds (DRCs) can be classified into roughly three groups as follows [82]:

- 75 polychlorinated dibenzo-p-dioxins (PCDDs)
- 135 polychlorinated dibenzofurans (PCDFs)
- 209 polychlorinated biphenyls (PCBs)

Approximately 30 DRCs are potentially hazardous to health and many more are persistent in the natural environment being almost ubiquitously distributed across the biosphere. In this section the evidence will be reviewed for DRCs that have arisen as a consequence of the open burning of e-waste.

3.2.2. Air

Concentrations of DRCs in the air have been investigated in e-recycling workshops [83-85] and at residential areas nearby e-recycling sites [84] (**Table S 3**). Specifically, Zhang et al. [84] determined the levels of PCDD/Fs emissions near two typical e-recycling sites and compared the results with previously reported data to understand the impact of stricter policies imposed in China since 2010 to control open burning and acid washing. Although results showed a significant reduction of the release of PCDD/Fs and average daily intake only through inhalation did not exceed the tolerable daily intake limit set by World Health Organisation (WHO) (1-4 pg TEQs kg^{-1} body weight day^{-1}), the total daily intake, including both inhalation and dust ingestion (10-32 pg TEQs kg^{-1} body weight day^{-1}), was eight to ten times higher than the tolerable intake, indicating considerable levels of PCDD/Fs pollution [84]. In addition, significant differences were found between the two areas, the first neighbours to circuit board baking activities and the second to informal dismantling family workshops, indicating nearly seven times higher TEQ concentrations of PCDD/Fs in areas nearby e-waste burning activities compared to dismantling, and three times higher compared to plastic recycling activities.

Table 13: Concentration of dioxin-related compounds detected in air samples (pg m^{-3}) close to e-waste burning activities.

					Polychlorinated				Polybrominated	
Ref.	**Geog.**	**Activity context**	**Media description**	**n**	**PCDDs**	**PCDFs**	**PCDD/Fs**	**I-TEQs**	**PBDD/Fs**	**I-TEQs**
		Neighbour to plastic recycling	PM2.5				7.6	0.131		
			TSP				19.18	45		
			Gas phase				3.35	0.58		
			TPS & gas phase	2			22.5	1.03		
		Neighbour to circuit board baking	PM2.5				22.5	0.604		
			TSP				26	0.845		
			Gas phase				5.09	0.855		
			TPS & gas phase	2			31.1	1.7		
		Neighbour to dismantling	PM2.5				2.24	0.083		
			TSP				4.18	0.156		
			Gas phase				0.818	0.116		
			TPS & gas phase	1			5	0.271		
		Neighbour to green recycling centre	PM2.5				10.77	0.148		
			TSP				31	0.270		
			Gas phase				2.94	0.310		
			TPS & gas phase	2			34	0.59		
		Reference area	PM2.5				1.92	0.019		
			TSP				1.47	0.041		
			Gas phase				0.277	0.029		
Zhang et al. [84]	CHN		TPS & gas phase	2			2.02	0.081		
Ren et al. [86]	CHN	E-recycling site [a]	PM	4	193	124	317	14.5	481	91.3

Air screening levels for residential soil (**Section S.5.9**). [a] printed circuit board recycling workshop. Abbreviations: reference (Ref.); Geographical context (Geog.); number of samples (n); total suspended particulate matter (TSP); particulate matter < 2.5 µm ($PM_{2.5}$); polychlorinated dibenzo-p-dioxins (PCDDs); polychlorinated dibenzofurans (PCDFs); polychlorinated dibenzo-p-dioxins and polychlorinated dibenzofurans (PCDD/Fs); polybrominated dibenzo-p-dioxins and polybrominated dibenzofurans (PBDD/Fs); international toxic equivalency factor (I-TEQ).

Even higher levels of DRCs were found in a typical recycling workshop of waste printed circuit boards in China by Ren et al. [86] who measured the levels of PCDD/Fs, polybrominated dibenzo-p-dioxins and polybrominated dibenzofurans (PBDD/Fs) and dioxin-like PCBs (dl-PCBs) in air particles emitted during recycling of printed circuit boards by heating over grills on the stoves. Emissions were higher than reference areas, with polybrominated diphenyl ethers (PBDEs) being the most prevalent compounds, which were two to three orders of magnitude higher compared to previously reported concentrations at reference areas [83]. Ren et al. [86] reported that primitive e-recycling methods may represent a considerable source of dioxin-related compounds to local environments, indicating the need for further inhalation risk assessment.

Insights into dioxin-related compounds production during e-recycling were also obtained by [83], who conducted a laboratory experiment to determine the formation of PCDD/Fs and

PBDD/Fs in all states of matter during low-temperature thermal processing of scrap printed circuit boards under inert and oxidative conditions (**Table 14**). PBDD/Fs and PCDD/Fs were formed under all experimental conditions, but a rapid increase was observed with a temperature increase of 25ºC (three to six times higher for PCDD/Fs and up to two times higher for PBDD/Fs) and under oxidative conditions (two to four times higher for PCDD/Fs and nearly 60% higher for PBDD/Fs) [83]. In addition, considerably high TEQ concentrations of PBDD/Fs were observed due to the presence of PBDE in printed circuit boards, indicting their high contribution emission at e-waste thermal processing areas [83].

Table 14: Concentrations of dioxin-related compounds (ng I-TEQ kg^{-1} dry weight) in all states of matter of sample outputs during thermal decomposition of printed circuit board under different operating conditions reported by Duan et al. [83].

Activity content	Atm.	Temp (ºC)	Output phase	PCDDs	PCDFs	PCDD/Fs	PBDDs	PBDFs	PBDD/Fs
Untreated waste	-	-	Solid	2.7	2	4.7	350	16,000	16,000
Thermal decomposition under inert conditions	N2	250	Solid	40	6.1	46	2,500	68,000	71,000
			Liquid	-	-	-	-	-	-
			Gas	0.18	0.25	0.43	8.5	74	82
		275	Solid	67	100	170	3,800	94,000	97,000
			Liquid	-	-	-	-	-	-
			Gas	0.19	0.09	0.28	6	66	72
Thermal decomposition under oxidative conditions	Air	250	Solid	66	22	88	840	59,000	60,000
			Liquid	24	11	35	20	59	79
			Gas	0.19	0.092	0.28	0.53	4.5	5
		275	Solid	130	500	630	2,900	150,000	160,000
			Liquid	21	120	140	390	5,800	6,200
			Gas	0.29	1.1	1.4	3.7	34	38

Abbreviations: atmosphere (atm.); temperature (temp.); polychlorinated dibenzo-p-dioxins (PCDDs); polychlorinated dibenzofurans (PCDFs); polychlorinated dibenzo-p-dioxins and polychlorinated dibenzofurans (PCDD/Fs); polybrominated dibenzo-p-dioxins (PBDDs); polybrominated dibenzofurans (PBDFs); polybrominated dibenzo-p-dioxins and polybrominated dibenzofurans (PBDD/Fs); international toxic equivalency factor (I-TEQ).

Despite the considerably higher concentrations of DRCs reported in e-waste burning activities compared to reference areas, their TEQ concentration in air did not exceed the limit value (0.1 ng TEQ m^{-3}) imposed by the European Waste Incineration Directive 2000/76/EC [87]. This is attributed to the fact that dioxin-related compounds tend to be gathered in particulate matter (PM), leading to high concentrations in dust due to particle deposition [84]; inferring a need to consider concentrations in other matrices, such as soil and dust.

3.2.3. Soil and dust

Research has also been conducted on the determination of dioxin-related compounds in soil and dust nearby e-recycling sites (**Table 15**). Chakraborty et al. [88] determined the concentration of PCDD/Fs and dl-PCBs in surface soils of e-recycling sites and nearby open municipal dumpsites at four Indian cities. The TEQ concentrations in soil were nearly ten times higher in e-recycling sites than in open dumpsites [88]. There were substantially higher levels in metal recovery workshops with equal contribution of PCDDs and PCDFs than other e-waste related activities, indicating a potential risk of adverse health effects [89]. However, the implementation of stricter legislative framework that began in India in 2016 may lead to reduced levels and therefore future research is needed to assess the current situation [90].

Table 15: Concentration of dioxin-related compounds detected in soil and dust samples (ng g^{-1} dry weight) close to e-waste burning activities.

Ref.	Geog.	Activity context	Media	Media description	n	PCDDs	PCDFs	PCDD/Fs	I-TEQs[1]	PBDDs	PBDFs	PBDD/Fs	I-TEQs[1]	dl-PCBs	I-TEQs[1]
		E-recycling site		Topsoil (d=0-20 cm)	14	3.8	1.8	5	0.31					46.1	0.039
Chakraborty et al. [88]	IND	Nearby open municipal dumpsites	Soil	Topsoil (d=0-20 cm)	10	2	0.6	2.5	0.025					1.8	0.0115
Fujimori et al. [89]	GHA	E-recycling area	Soil	Topsoil (d=0-2 cm)	10	0.52 - 120	0.51 - 400	1.03 - 520	0.01 - 6.6	0.001 - 4	2.6 - 3,800	2.600 - 3,801	0.012 - 17	1.9 - 83	0.002 - 0.64
Xiao et al. [90]	CHN	E-recycling area	Soil	Topsoil (d=0-10 cm)	24					0.0253	0.26	0.285	0.0684		
		Burning area			5	62	230	292	3.8[a]	1.4	930	931		42	7.1[b]
		Non-burning area			5	0.99	2.1	3.1	0.047[a]	0.032	6.6	6.63		1.9	0.12[b]
Tue et al. [91]	GHA	Reference area	Soil	Topsoil (0-2 cm)	4	0.02	0.0073	0.027	0.00015[a]	0.0005	0.015	0.02		0.011	0.00016[b]
Hu et al. [92]	CHN	E-recycling area	Soil	Topsoil (0-5 cm)	24	16.211	4.889	21.1	0.043						
		Open burning area			6									149	1.7
		Nearby vegetable field			14									2.409	0.016
		Nearby paddy field			10									8.42	0.032
		Nearby desert soil			4									1.92	0.017
Wang et al. [93]	CHN	Nearby sediment from pond area	Soil	Topsoil (d=0-15 cm)	6									55.7	0.53
		Metal recovery			5									58	1
		Dismantling			9									1.3	0.02
		Nearby highways			6									1.1	0.03
Chakraborty et al. [94]	IND	Nearby industrial region	Dust	Roadside dust	18									1.6	0.002
Xiao et al. [90]	CHN	E-recycling area	Dust	Floor dust	6					0.128	1.897	2.024	0.4		
		E-recycling area						2.662							
Zhang et al. [84]	CHN	Reference area	Dust	Surface indoor dust	6			0.0454							
		E-recycling area			5	0.72 - 3	1.1 - 1.4	1.4 - 2.4		0.062 -0.1	23 - 49	23 - 49		1 - 2.2	0.49 -0.52[b]
Tue et al. [95]	VNM	Reference area	Dust	Surface house dust	2	0.37	0.19	0.56		0.005	1.9	1.9		0.85	0.14[b]
Hu et al. [92]	CHN	E-recycling area	Dust	Floor dust	6	16.276	40.592	56.869	0.38						

Soil screening levels for residential soil (**Section S.5.8)**. [1]TEQ values established by WHO; [a]including PCDDs/Fs and dl-PCB; [b]including all: PCDD/Fs, PBDD/Fs and dl-PCBs. Abbreviations: reference (Ref.); Geographical context (Geog.); number of samples (n); polychlorinated dibenzo-p-dioxins (PCDDs); polychlorinated dibenzofurans (PCDFs); polychlorinated dibenzo-p-dioxins and polychlorinated dibenzofurans (PCDD/Fs); polybrominated dibenzo-p-dioxins (PBDDs); polybrominated dibenzofurans (PBDFs); polybrominated dibenzo-p-dioxins and polybrominated dibenzofurans (PBDD/Fs); dioxin-like polychlorinated biphenyls (dl-PCBs); international toxic equivalency factor (I-TEQ).

Similarly, Fujimori et al. [89] measured the soil concentration of dioxin-related compounds, including PCDD/Fs, PBDD/Fs and dl-PCBs, in an e-waste open burning site in Ghana. The most prevalent were PBDFs, followed by PCDFs and PCDDs, occupying nearly 94% of total TEQ concentrations of dioxin-related compounds, indicating the selective formation of PBDFs and PCDFs over PBDDs and PCDDs, respectively. In addition, Fujimori et al. [89] examined the role of PTEs (Cu, Pb, Zn, Fe, cobalt (Co), and Sr) and bromine (Br) in the formation of dioxin-related compounds, reporting a significant relation between Cu and Pb with dioxin-related compounds. Specifically, possible formation paths by catalytic behaviour of Cu and Pb chlorides via thermal decomposition of PVC were indicated. The presence of Cu, Pb, Zn and Br in various e-waste components seemed to influence the generation of dioxin-related compounds.

Similar results found by Tue et al. [91], who investigated soil contamination by various dioxin-related compounds in one of the largest e-recycling sites in Ghana. Considerably higher concentrations of PBDFs were identified on open burning sites compared to other dioxin-related compounds due to burning of PBDE-containing plastics. The total TEQ concentrations of dioxin-related compounds was nearly 60 times higher in open burning areas compared to non-burning areas of the same site. This indicates that e-waste open burning is a considerable source of dioxin related compounds and therefore related human health risk assessments need to be conducted.

The levels of dioxin-related compounds in dust were also investigated by Zhang et al. [84] and Tue et al. [95]. Zhang et al. [84] reported high correlation of PCDD/Fs for congener composition between air samples and dust samples. The fact that dust samples were collected from indoor e-recycling activities and had high levels of PCDD/Fs indicated the ambient air deposition in the surrounding area of e-recycling activities. Specifically, the high correlation between dust and air particles attributed to day-to-day particle deposition resulting in transfer of PCDD/Fs contained in fine particles to nearby indoor environments. Similar results were reported by Tue et al. [95], who determined the concentration of dioxin-related compounds, including PCDD/Fs, PBDD/Fs and dl-PCB, in house dust from two e-recycling sites in Vietnam. The levels of dioxin-related compounds were nearly three times higher compared to the reference area with PBDFs being the main contributor due to the presence of PBDE in e-waste. The average daily intake via dust ingestion exceeded the tolerable intake for local residents and especially for children.

Hu et al. [92] measured the levels of PCDD/Fs in both dust and soil and assessed the risk of dioxin exposure to local residents at an e-recycling site in China. Higher concentrations were reported in dust than in soil, indicating the behaviour and fate of PCDD/Fs during transportation from one matrix to other. In addition, the average daily intake through soil ingestion and dermal exposure exceeded the tolerable daily intake value suggested by WHO, indicating high risk of exposure to dioxins for residents.

Special attention to PBDD/Fs has been paid by Xiao et al. [90], who identified their concentrations in various matrices including soil, dust and sediment from one of the largest e-recycling sites in China. Significantly higher concentrations were reported in the site compared to reference areas, indicating that improper e-recycling can lead to high PBDD/F contamination. In addition, the toxic equivalent quality of PBDD/Fs increased from dust to sediments, implying further critical effect on the adjacent area. Furthermore, the daily intake of eight PBDD/Fs via ingestion and dermal exposure was estimated by Xiao et al. [90] for local residents, which were found to be higher than those induced by 17 PCDD/F congeners for the same set of samples, indicating increased health risk. Similar behaviour during transportation from one matrix (dust) to another (soil) was observed between PCDD/Fs and PBDD/Fs [92, 93].

Two studies focused on the formation of dl-PCBs in soil [93] and dust [94]. Wang et al. [93] reported that the substantially higher TEQ concentrations of dl-PCBs in soil and vegetation compared to reference areas indicated the contamination of surrounding fields by uncontrolled e-recycling activities, leading to their migration into food chain. Chakraborty et al. [94] measured the levels of dl-PCB in the dust of different e-recycling workshops and nearby areas finding that e-waste metal recovery was the workshop with the highest toxicity equivalent and potential cancer risk for both adults and children. Compared to industrial roadside dust, TEQ concentration of dl-PCB was more than ten folds higher.

3.2.4. Food

The levels of dioxin-related compounds in foodstuff near an e-recycling site in China has been investigated by Shen et al. [96]. Specifically, food products were collected from the vicinity of two polluted areas, an e-recycling site and an area of municipal solid waste (MSW) incineration, and analysed (**Table 16**). Results revealed higher levels in both sites compared to maximum limit values, whereas the estimated daily intake was almost identical for the two sites (244 pg TEQ kg body weight^{-1} month^{-1} for MSW incinerator and 240 pg

TEQ kg body weight^{-1} month^{-1} for e-recycling site) exceeding the tolerable intake nearly three and a half times. Future research is required to the quantification levels of dioxin-related compounds in foodstuff in the vicinity areas of e-waste burning activities since more than 90% of human exposure is carried out via food consumption, mainly meat, fish and dairy products [96, 97].

Table 16: Concentration of dioxin-related compounds detected in food products (ng I-TEQ g^{-1} wet weight) from the vicinity of MSW incinerator and e-waste dismantling site reported by Shen et al. [96].

		E-waste dismantling site		MSW incinerator	
Geog.	**Food product**	**n**	**PCDD/Fs + dl-PCBs**	**n**	**PCDD/Fs + dl-PCBs**
	Rice	14	0.07	5	0.11
	Chicken egg	20	0.81	5	5.80
	Cabbage	8	0.07		
	Chicken	3	4.92		
	Chicken liver	5	1.66		
CHN	Fish	18	4.65	18	4.99

Recommended environmental risk limits of POPs in air, soil and foodstuff detailed in (**Section S.5.10**). Abbreviations: Geographical context (Geog.); number of samples (n); polychlorinated dibenzo-p-dioxins and polychlorinated dibenzofurans (PCDD/Fs); dioxin-like polychlorinated biphenyls (dl-PCBs).

Despite the considerable levels of dioxin-related compounds in various environmental matrices nearby e-recycling sites, information on human health exposure is limited. Only one study measured the concentration of PCDD/Fs in human blood of workers from a popular e-recycling site in Ghana and compared them with a reference group [98]. The levels of PCDD/Fs were significantly higher in the blood of the exposed group compared to the reference (6.18 pg TEQ g lipd^{-1} vs. 4.6 pg TEQ g lipd^{-1}), indicating the impact of e-recycling activities on PCDD/Fs exposure of workers. In addition, Tue et al. [99] investigated the accumulation levels of PCDD/Fs, PBDD/Fs and dl-like PCB in breast milk of women living in two e-recycling sites in Vietnam. Tue et al. [99] reported that the exposure to these compounds via dust ingestion was a considerable contributor of TEQ in breast milk of workers, while the estimated TEQ intake for breastfed infants was one order of magnitude higher compared to the tolerable dose.

Clear evidence shows that open burning, acid washing and open dumping constitute considerable sources of dioxin-related compounds that may induce adverse health effects [90]. In addition, e-waste burning activities constitute one of the greatest contributors to the

emissions of PBDD/Fs in the environment [100]. TEQ concentration of PBDD/Fs seem to be considerably higher than these of PCDD/Fs in e-waste burning activities (**Table 13**, **Table 14** and **Table 15**), whereas they exhibit similar toxicity and health effects as PCDD/Fs [89]. However, PBBD/Fs are less regulated [100] and are not currently listed under the Stockholm Convention [101]. A legislative framework for the concentrations of PBDD/Fs in different environmental compartments is required.

3.3. Flame retardants

3.3.1. Context

Brominated flame retardants (BFRs) are found in many environmental compartments close to e-waste burning activities, having arisen from atmospheric emissions followed by deposition into land and water or as residual ash after combustion of plastics used in electronic and electrical equipment. Emissions factors for BFRs have been discussed extensively in laboratory emission studies carried out by Li et al. [102] and Hong-Gang et al. [103]. Using emissions factors and market data, Redfern et al. [104] have estimated global emissions of PBDEs from e-waste open burning at between 0.255–5.56 tonnes per year^{-1}.

3.3.2. Air

Relatively few articles published atmospheric concentrations of BFR in the context of e-waste open-burning, with only two, Tian et al. [105] and Wong et al. [52], identified in this review that specifically related the concentrations to open burning activities (**Table 17**). The concentrations in both studies were many times greater than outdoor air concentrations reported by Besis et al. [106] in **Table S 8** (**Section S.5.6**). For instance, the concentration reported by Tian et al. [105] was six and fifty-five times greater than concentrations recorded in Dongguan and Guangzhou, China, respectively, and significantly ($p < 0.001$) higher than the rural (control) site in the same study. The concentrations reported by Wong et al. [52] taken near to three e-waste open burning sites in Guiyu, China were very high in comparison to other industrial samples taken in China [106], measuring approximately 375 and 672 times greater than concentrations recorded in Dongguan and Guangzhou respectively.

Table 17: PBDE concentrations in air near to e-waste open burning (ng m^{-3}).

					ΣPBDE
Author	**Geog.**	**Activity context**		**n**	**Geo mean**
			E-waste site		2.49
Tian et al. [105]	CHN		Rural site	60	0.287
Wong et al. [52]	CHN, Guiyu	E-rec. area	Roof of a three-story high building	30	16.822

Recommended environmental risk limits of POPs in air, soil and foodstuff (**Section S.5.6)** Abbreviations: Geographical context (Geog.); number of samples (n); total polybrominated diphenyl ethers (ΣPBDE); e-recycling (e-rec.).

The lack of air sampling data related specifically to open burning is surprising, given that many papers reviewed here mention open burning of e-waste as a source of BFR transmission into the environments. While measurements in environmental media such as soil and water provide evidence for emissions, they do not differentiate other potential pathways such as acid leaching and mechanical processing from thermal release.

3.3.3. Soil and sediment

Evidence for the presence of BFRs in soils and sediments around e-waste open burning sites was reported by four authors (**Table 18**). Very high concentrations of BFRs were reported by all authors in comparison to USEPA soil screening levels. In particular, Wu et al. [64] reported concentrations that exceeded the carcinogenic screening level for BDE-209 by more than five times and the non-carcinogenic screening level by more than 30 times. Wong et al. [52] also found very high concentrations of BFRs in soils sampled in e-waste open burning sites up to 13 times the USEPA soil screening level for BDE-209.

Table 18: Flame retardant concentrations observed in soil and sediment in and around e-waste open burning (ng kg^{-1} dw soil).

Author	**Geog.**	**Activity context**	**Media**	**n**	**a-DP**	**s-DP**	**ΣPBDE**
				n/a			4.76
	NGA, Lagos			n/a			20,899[Ŧ♯]
				n/a			10.54
	NGA, Ibadan			n/a			6,974
				n/a			77.7
Ohajinwa et al. [65]	NGA, Aba	Open burning sites	Soil	n/a			205.55
		Burning site		5	246,000	236,000	1.79E+07[†‡Ŧ♯]
		Paddy field	Soil	5	25,200	26,600	4.74E+06[†‡Ŧ♯]
Wu et al. [64]	CHN, Guiyu	Stream	Sediment	5	171,6000	793,000	9.35E+07[†‡Ŧ♯]
		Open burning site		3			7,700
		Workshops		10			1.20E+06[‡Ŧ♯]
Someya et al. [107]	VNM	Paddy field	Soil	19			500

Author	Geog.	Activity context	Media	n	a-DP	s-DP	ΣPBDE
		River running through e-burning site	Sediment	8			38,000[Ŧ♯]
		Reservoir	Sediment	3			2,000-6,220
		Rice field		2			45,100[Ŧ♯]-102,000[Ŧ♯]
		Near open burning site		2			85,000[Ŧ♯]-201,000[Ŧ♯]
Wong et al. [52]	CHN	Open burning site	Soil	3			2.91E+06[†‡Ŧ♯] - 4.45E+07[†‡Ŧ♯]

Soil and dust concentrations benchmarked against USEPA screening levels (**Section S.5.7**) as follows: [†] exceeds USEPA carcinogenic screening level (TR=1E-06) for BDE-209 in industrial soils; [‡] exceeds USEPA non-carcinogenic screening level (TR=1E-06) for BDE-209 in industrial soils; [Ŧ] exceeds USEPA non-carcinogenic screening level (TR=1E-06) for BDE-153 in industrial soils; [♯] exceeds USEPA non-carcinogenic screening level (THI=0.1) for BDE-47 and BDE-99 in industrial soils. Abbreviations: Geographical context (Geog.); number of samples (n); total polybrominated diphenyl ethers (ΣPBDE); *anti*-dechlorane plus (*a*-DP); *syn*-dechlorane plus (*s*-DP); not available (n/a).

Someya et al. [107] found much lower levels of BFRs in the soils near open burning sites in comparison to the soils sampled near to e-waste recycling workshops. Of course, it is possible that some open burning takes place at the workshops too, but it may indicate that other pathways such as comminution and other physical processing constitute a significant source of BFR release. Someya also found high concentrations in the sediment of the stream which runs through the open burning site that were much higher than those from the soil within the site. This may also indicate that BFRs were being washed through the open burning site more readily, explaining the lower concentrations in the soils compared to the sediments.

3.3.4. Food

Analysis by Wu et al. [64] of rice plants grown close to an e-waste open burning site in Guiyu, China showed concentrations of PBDEs in the order root > leaf > stem > grain (**Table 19**). The bio-concentration factor (ratio of uptake) was < 0.05, indicating low uptake by rice plants. Comparisons with PBDE uptake in other flora were not carried out and this would be a useful consideration in future studies.

Table 19: Concentrations (μg kg^{-1}) of flame retardants reported by Wu et al. [64] in different parts of rice plants growing near an e-waste open burning site in Guiyu, China.

Part of plant	n	a-DP	s-DP	ΣPBDE	BTBPE	DBDPE	HBB	PBEB	ΣotherBFR
Root	5	1.68	1.63	105	2.25	8.74	28.4	3.57	46.3
Stem	5	0.176	0.132	15.1	0.308	3.81	2.08	0.510	7.02
Leaf	5	0.849	1.26	51.4	0.948	37.8	7.61	3.37	51.9
Grain	5	0.122	0.091	8.31	0.143	2	1.77	0.23	4.35

Abbreviations: number of samples (n); *anti*-dechlorane plus (*a*-DP); *syn*-dechlorane plus (*s*-DP); total polybrominated diphenyl ethers (ΣPBDE); decabromodiphenyl ethane (DBDPE); 1,2-bis(2,4,6-tribromophenoxy)ethane (BTBPE); hexabromobenzene (HBB); pentabromoethylbenzene (PBEB); brominated flame retardants (BFRs)

3.3.5. Non-cancer risks

One study [67] was found of the non-carcinogenic risk through dermal exposure and ingestion of BFRs encountered in soils around e-waste open burning activities that indicated low risk through soil ingestion in two contexts and an unacceptable risk in one (**Table 20**). Risk through dermal exposure was calculated to be extremely high in two cases due to the high concentrations identified in soils in those locations.

Table 20: Non-cancer hazard quotients and hazard indices reported for different PBDE exposure pathways at sites where open burning of e-waste takes place; after Ohajinwa et al. [65].

Pathway	Geographical location	BDE-47	BDE-99	BDE-153	BDE-209	Hazard index
	Lagos, Nigeria	<1	<1	<1	1.3	2.4
	Ibadan, Nigeria	440	570	160	<1	1,600
Dermal exposure	Aba, Nigeria	30	62	55	7.9	160
	Lagos, Nigeria	<1	<1	<1	<1	<1
	Ibadan, Nigeria	<1	<1	<1	<1	1.2
Ingestion	Aba, Nigeria	<1	<1	<1	<1	<1

Based on soil samples taken at depth of 0-10 cm. Abbreviations: brominated diphenyl ether (BDE).

3.3.6. Cancer risks

High carcinogenic risk reported from dermal exposure in one study of BFRs focusing on the BDE-209 congener (**Table 21**).

Table 21: Carcinogenic risk indices reported for BDE-209 exposure pathways at sites where open burning of e-waste takes place; after Ohajinwa et al. [65].

Pathway	Location	Cancer risk (CR)
Dermal exposure	Lagos, Nigeria	6.6E-06
Dermal exposure	Ibadan, Nigeria	2.2E-03[†]
Dermal exposure	Aba, Nigeria	3.9E-05
Ingestion	Lagos, Nigeria	4.7E-09
Ingestion	Ibadan, Nigeria	1.6E-06
Ingestion	Aba, Nigeria	2.8E-08

Based on soil samples taken at depth of 0-10 cm; [†]exceeds target value of 1.0E-04.

3.4. Polycyclic aromatic hydrocarbons (PAH)

3.4.1. Context

Polycyclic aromatic hydrocarbons (PAHs) are hydrocarbons characterised by two or more aromatic rings and are ubiquitous in nature and the anthroposphere. Most PAHs are

carcinogenic with sufficient dose, having a toxic potency indication of 1 ng m^{-3} benzo(a)pyrene equivalent (BaP_{eq}), resulting in a cancer rate of approximately 8.7 cases per million people. The majority of PAHs are persistent in the environment and are prevalent throughout the natural environment in soils, sediments, water and air [108, 109]. While there are many sources of PAH emission, open burning is estimated to contribute 39% (334 million kg) of global atmospheric emissions [110]. The proportion that can be attributed to e-waste isn't known, and there are limited data available to quantify emissions activity.

3.4.2. Air

Two studies [111, 112] measured concentrations or PAHs in air associated with e-waste open burning activities (**Table 22**). Specifically, Chen et al. [112] determined the levels of PAHs in the air at a typical e-recycling site and the surrounding area by measuring the concentration in gaseous and particulate phase over four seasons. Higher concentrations in $PM_{2.5}$ were reported, and the pollution levels were lower during summer and autumn. Nearly 82% of PAH emissions were attributed to e-recycling activities within the studied area, indicating that e-waste processing is a considerable source of PAHs. The carcinogenic risk via inhalation was also assessed by considering only bioaccessible PAHs in human lungs; exceeding the selected limit of 10^{-6} in the e-recycling site (1.82×10^{-6}) but not in the vicinity area. Similar results were found by Luo et al. [111], who examined the atmospheric particle size distribution and deposition fluxes of PAHs and estimated the cancer risk in an e-recycling area in China. The concentrations and respiratory deposition fractions for PAHs were mainly found in fine particles (<1.8 mm) revealing that they carry more PAHs deep into the respiratory tract [111]. Cancer risk assessment showed that particle-bound PAHs may pose cancer risk for residents within e-recycling areas [112].

Table 22: Concentration of PAHs detected in air samples (ng m^{-3}) close to e-waste burning activities.

Ref.	Geog.	Activity context	Media description	n	PAHs†
		E-recycling area			80.7
		Roadside area near e-recycling site			54.94
		Residential area near e-recycling site			35.61
		Village near e-recycling site			29.78
Chen et al. [112]	CHN	Reference area	TPS & gas phase	120	29.59
			Height at 1.5m	8	15.1
			Height at 5m	8	15.5
		E-recycling site	Height at 20m	8	17.7
			Height at 1.5m	7	6.7
Luo et al. [111]	CHN	Reference area	Height at 20m	4	5.8

†PAHs levels did not exceed air concentrations benchmarked against NIOSH recommended environmental risk limits (**Section S.5.10**). Abbreviations: reference (Ref.); Geographical context (Geog.); number of samples (n); total suspended particulate matter (TSP); polycyclic aromatic hydrocarbons (PAHs); National Institute for Occupational Safety and Health (NIOSH).

Both Chen et al. [112] and Luo et al. [111] indicated that PAHs are a considerable source of environmental concern, emitted from a range of e-waste processing activities, many of which have the potential to accumulate in fine atmospheric particles and their presence may pose a cancer risk for residents in e-recycling areas.

3.4.3. Soil

Soil concentrations of PAHs from land in or surrounding e-waste open burning activities were reported in eight studies (**Table 23**). Chakraborty et al. [113] measured PAHs concentration in soil of various e-recycling workshops and municipal open dumpsites in the vicinity area for four cities in India. The highest levels were found in acid washing and plastics burning workshops followed by open dumpsites reporting similar PAH congeners profiles for both sites. Hoa et al. [114] determined PAHs levels in soil of various e-recycling workshops, a nearby paddy field and river sediment from a nearby village in Vietnam. Similar soil contamination in open burning and dismantling workshops was observed and attributed to the fact that e-waste containing lubricants and engine oils (for example, electric generators and water pumps) release petrogenic PAHs during dismantling. However, fingerprint profiles of PAHs in both soil and sediment showed that the main source of contamination was pyrogenic rather than petrogenic, indicating that e-waste burning was likely to be the main contributor. The cancer risk assessment carried out by Hoa et al. [114] also indicated that the risk was significantly higher in e-recycling sites than in the nearby area, but still it did not exceed the threshold limit value, indicating acceptable levels.

However, the concentrations of specific PAH compounds (phenanthrene, anthracene, fluoranthene, benz[a]anthracene, and benzo[a]pyrene) exceeded the permissible concentrations, implying a risk of ecotoxicological effects[114].

Table 23: Concentration of PAHs detected in soil samples (ng g^{-1}) close to e-waste burning activities.

Ref.	Geog.	Activity context	Media description	n	PAHs
		Acid washing and plastics burning workshop		5	2,198†
		Dismantling workshops		5	866†
		Sorting workshops		4	576†
Chakraborty et al. [113]	IND	Nearby municipal dumpsites	Soil	11	1,029†
		Paddy fields		15	1,100†
		Open burning		7	2,100†
		Dismantling	Topsoil	10	2,200†
Hoa et al. [114]	VNM	Nearby village	River sediment	8	570†
		Nearby rice paddies in 2011		129	590.4†
He et al. [115]	CHN	Nearby rice paddies in 2016	Topsoil	150	407.3†
		E-recycling site		15	3,000†
Moeckel et al. [116]	GHA	Domestic dumpsite	Topsoil	9	1,500†
		Open burning		2	390-710†
	VNM	Reference area		1	30
	PHL	Open burning		2	2,900-4,000†
Nishimura et al. [117]	GHA	Open burning	Topsoil	2	6,500-7,200†
		Acid leaching area		7	1,950-5,210†
		E-dumping area		5	268†
		Nearby rice field area		9	457-171†
Leung et al. [118]	CHN	Reference area	Topsoil	5	89-152
		Open burning sites		9	2,339.9†
		Dismantling sites		13	678.4†
		Nearby paddy fields		27	180†
		Nearby vegetable fields	Topsoil	13	129†
Huang et al. [119]	CHN	Nearby pond	Sediment	5	77.1
		Burning sites		5	4,940†
		Nearby vegetable field		10	705†
		Nearby paddy fields		14	271†
		Nearby deserted field	Topsoil	4	152†
Wang et al. [120]	CHN	Nearby pond	Sediment	6	686†

†PAHs levels exceed air concentrations benchmarked against NIOSH recommended environmental risk limits (**Section S.5.10**). Abbreviations: reference (Ref.); Geographical context (Geog.); number of samples (n); total suspended particulate matter (TSP); polycyclic aromatic hydrocarbons (PAHs); National Institute for Occupational Safety and Health (NIOSH).

Four studies focused on China, a country with intensive e-recycling activity [115, 118-120]. Leung et al. [118] measured PAHs concentration in soil of different e-recycling workshops and surrounding agricultural areas reporting higher levels in the acid washing site, followed by a duck pond, rice field and printer roller dumpsite. However, the highest concentration was found in combusted residues of e-waste, including wires, cables and computer equipment

(10,800–18,600 ng g^{-1}), which was four to five times higher than PAH concentration in soil of open burning sites. Similar research was also conducted by Huang et al. [119] reporting that incomplete combustion of e-waste is the main source of soil contamination in the selected area. PAHs were detected, not only in topsoil (d=0-40 cm), but also in subsoil (d=40-80 cm), indicating a deep soil contamination by e-recycling activities. Similar levels were also reported by Wang et al. [120] who found higher PAH concentration in e-waste burning site than the adjacent agricultural area, reporting that PAH levels are different depending on land use type. For example, vegetable fields had higher soil contamination than paddy fields, indicating the selective PAH uptake by plants. The average daily intake of PAHs via vegetable consumption grown nearby the e-recycling site exceeded the threshold dose and should be avoided. In addition to this, He et al. [115] compared the levels of soil contamination in agricultural areas nearby e-recycling sites in China between 2011 and 2016, reporting lower levels of PAHs in soil and reduced health risks for farmers.

Nishimura et al. [117] collected soil samples from three different developing countries to determine PAHs concentration in e-recycling soils. It was reported that PAH generation was attributed mainly to pyrogenic sources, indicating e-waste open burning as one of the most important sources of PAH emission. This was also reported by Moeckel et al. [116].

Interestingly, similar levels of PAHs in soils emerged from e-recycling activities in several countries have been found by different studies reporting that open burning of e-waste is a considerable source of soil contamination by PAHs. However, less evidence exists on human exposure and PAH levels in the human body. Specifically, Xu et al. [121] measured the PAH concentration in children's blood, concluding that children living in e-recycling areas are exposed to higher levels compared to reference group, while milk consumption, child height and chest circumference had a negative correlation with PAH levels in blood. Insight on human exposure to PAH were also obtained by Lu et al. [122], who measured PAH levels in urine of occupationally and non-occupationally exposed receptors. Results showed significant difference between the exposed and reference group as well as between workers (occupationally exposed) and residents (non-occupationally exposed) in the e-recycling area. In addition, it was reported that exposure to PAH may be associated with oxidative stress since positive correlation was found between PAH levels in urine and urinary -hydroxy-2′-deoxyguanosie (8-OhdG) and serum malondialdehyde (MDA), critical biomarkers for oxidative DNA damage. Last but not least, biomonitoring of human exposure to PAHs was

conducted with hair analysis by Lin et al. [123] reporting similar exposure for both workers and residents.

3.5. PCDs

3.5.1. Soil, dust and air

Concentration of PCBs in samples obtained from different environmental matrices in and around e-recycling areas indicated that e-waste burning activities constitute a significant source of PCB pollution and therefore a potential health risk for exposed receptors **(Table 24)**. For example, Wang et al. [124] compared the health risk differences between workers and local residents in an e-recycling site by estimating the exposure risk to PCBs through air inhalation and dust ingestion, indoors and outdoors in both exposure pathways. Higher levels of PCBs were reported in outdoor air of e-recycling site than indoors due to traffic and adjacent industrial activities, whereas the levels PCBs in dust were 10-100 times higher in e-recycling workshops compared to reference areas. The significantly higher levels of PCB pollution in workers' houses compared to residents' houses due to e-waste burning in their houses revealed a considerably high risk of occupational exposure [124]. Human health risk assessment showed that the risk was 3.8 times higher for workers compared to local residents, with workers considerably exceeding both cancer ($<10^{-6}$) and non-cancer risk (HQ<1), while for local residents only cancer risk slightly exceeded the limit ($5.8x10^{-6}$) [124]. According to Wang et al. [124] these findings indicated that workers constitute an environmentally vulnerable group to PCBs exposure related not only to exposure during working but also to lifestyle and economic status usually ignored by researchers. The concentration of PCBs in dust from an e-recycling area in India was also determined by Chakraborty et al. [94]. Specifically, the analysis of dust samples obtained from e-recycling workshops, a nearby area and a suburban industrial area showed that PCBs concentrations in metal recovery workshops were more than ten folds higher compared to the industrial area.

Table 24: Concentration of PCBs detected in environmental compartments, including air, dust and soil, close to e-waste burning activities.

Ref.	Year	Geog.	Activity context	Media	Media description	n	PCBs	Unit
			Workers' houses		Indoor air	6	30.99	
			Residents' houses		Indoor air	6	21.55	
			E-recycling site		Indoor air from workshops	3	47.85	
			E-recycling site		Outdoor air from roads	1	51.79	
Wang et al. [124]	2016	CHN	Residential area	Air	Outdoor air from roads	1	13.38	ng m^{-3}
			Workers' houses		Indoor dust	3	3,799.3†	
			Residents' houses		Indoor dust	5	1,954.2†	
Wang et al. [124]	2016	CHN	E-recycling site	Dust	Indoor dust from workshops	5	14,765.8†	ng g^{-1}
			Metal recovery workshop			5	112	
			Dismantling workshop			9	4.5	
			Nearby highways			6	2.6	
Chakraborty et al. [94]	2016	IND	Suburban industrial region	Dust	Outdoor surface dust	18	2.5	ng g^{-1}
			Dismantling workshops			5	6.5	
			Shredding workshops			4	8.2	
			Metal recovery workshops			4	148	
Chakraborty et al. [88]	2018	IND	Nearby open municipal dumpsites	Soil	Top soil (d=0-20 cm)	10	3.4	ng g^{-1}
Moeckel et al. [116]	2020	GHA	E-recycling site			17	92	
			Domestic dumpsite	soil	Topsoil	1	4.7	ng g^{-1}
			Burning site			6	2,100†	
			Nearby paddy field			14	17	
			Nearby vegetable field			10	66	
			Nearby deserted field		Topsoil	4	11	
Wang et al. [93]	2011	CHN	Nearby pond	Soil	Sediment	6	470	ng g^{-1}

†PCBs levels exceed soil concentrations benchmarked against NIOSH recommended environmental risk limits (**Section S.5.10**). Abbreviations: reference (Ref.); Geographical context (Geog.); number of samples (n); polychlorinated biphenyls (PCBs); National Institute for Occupational Safety and Health (NIOSH)

The concentration of PCBs in soil of e-recycling sites has gained more research attention **(Table 24)**. Chakraborty et al. [88] determined PCB concentrations in soil of an e-recycling site and an open municipal dumpsite reporting one order of magnitude higher levels in metal recovery workshops than open dumpsites. Almost 70% of total PCBs concentrations consisted of dl-PCB congeners, while PCB-126 might have resulted from plastic burning that took place in both e-recycling and dumpsite areas.

Wang et al. [93] reported much higher levels compared to current studies, which were justified by the presence of intensive uncontrolled e-waste processing activities, for example, open burning and acid washing. This difference is related to the fact that the commercial production of PCB for their use as coolants and lubricants in electrical equipment (for example, capacitors and transformers) has been banned since 1979 in the US and other countries. Although PCBs are no longer commercially produced, they can still be detected in

electrical products [125]. For example, in 2007, it was estimated that 50,000 tonnes of e-waste with PCBs levels >500 ppm and 500,000 tonnes with levels between 50 to 500 ppm existed in China [126].

The levels of PCBs in animal products originated from one of the largest e-recycling areas in Eastern China were reported by Labunska et al. [126]. The enormous difference of PCB concentration in animal products between the reference and e-recycling area clearly (**Table S 4**) indicates a high exposure to PCBs for residents via dietary intake. Specifically, the average daily intake through animal products consumption (650-2,340 ng (kg body weight)$^{-1}$ day^{-1}) substantially exceeded the tolerable daily intake (20 ng (kg body weight)$^{-1}$ day^{-1}) [126].

Table 25: Concentration of PCBs detected in animal products (ng g^{-1} fat) collected from one of the largest e-recycling areas in Eastern China reported by Labunska et al. [126].

		E-recycling site		**Reference area**	
Geog.	**Animal product**	**n**	**PCBs**	**n**	**PCBs**
	Fish meat	8	75400	4	79
	Shrimp	3	1170	2	240
	Chicken meat	10	500	5	<1
	Duck meat	7	1320	5	33
	Pork meat	5	<1	5	<1
	Chicken liver	10	410	5	<1
	Duck liver	7	570	5	3
	Chicken egg	22	740-1180	10	<1
CHN	Duck egg	55	59-2860	11	<1

Abbreviations: Geographical context (Geog.); number of samples (n); polychlorinated biphenyls (PCBs).

Determination of human exposure to PCBs by measuring concentration in biomarkers is limited [127, 128]. Eguchi et al. [128] compared the serum concentrations of PCB in an occupationally exposed group from an e-recycling area in Vietnam (620 pg g^{-1}) with those from a reference area (410 pg g^{-1}), reporting a significant difference, which implies a risk of occupational exposure. Guan-Gen et al. [127] focused on non-occupational exposure by measuring the blood concentration of PCB for children, reporting two times higher blood concentration for the exposed group compared to the reference group.

3.6. Risk characterisation of substances emitted from open burning of e-waste

The qualitative risk assessment for substances emitted from open burning of e-waste provides indicative global risk levels for emissions of a range of substances emitted as a consequence of e-waste combustion at low temperatures (**Table 26**). The risk assessment relies on a combination of identification of substances in environmental media coupled with the available evidence from studies that have determined risk scores for each context.

The highest risk scores were calculated for informal e-waste workers who are engaged in open burning activities, through inhalation and dermal contact with PTEs. The informal sector were also at medium to high risk of harm through exposure to PTEs through ingestion of, primarily dusts, and also soils, as well as through inhalation, ingestion and dermal contact with media containing DRCs and PAHs.

Children in the population were at high risk of carcinogenic and non-carcinogenic effects from injection of soils and dusts containing PTEs, as a consequence of their predisposition to put soil in their mouths. Medium to high-risk scores were calculated for the general population for all exposure pathways from DRCs and PAHs.

Table 26: Risk characterisation summary for thermal recovery of value and thermal disposal of e-waste.

Haz.	Pathway	Receptor	Geog.	Evidence and justification for risk assessment	Uncertainty (aleatoric and epistemic)	Receptor vulnerability	L	S	R	Global receptor context
PTE	Atmosphere/ inhalation	E-waste workers (informal)	THA, CHI, CHN, GHA, IND NGA	• Several examples of PTE concentrations detected in proximity to workforce [50, 52] and very high Cu and Pb in few selected cases, but the number of samples was small [53]. • Blood sample data indicates very high levels of Cr in workers [49] and slightly elevated Pb, [71, 72] in comparison to Canadian citizens [73], particularly in burning specialists [70]. Levels of Cd also slightly elevated in once study [50]. • Non-carcinogenic risk calculated by one author [13] as extremely high for those involved directly with burning printed circuit boards. Carcinogenic risk not determined for this hazard, pathway receptor combination.	• Ambient air levels often below workplace exposure limits. • Risk assessment relies on three scenarios' determination of hazard index for workers directly involved with burning. • Results may be confounded with dismantling activities and hydrometallurgical treatment. • Difficult to disaggregate blood sample data from confounding sources of exposure for non-occupationally exposed receptors.	• Informal workers operate without respiratory protective equipment.	4	4	**16**	LIMIC
		Population		• Higher concentrations of some PTEs in the air in some residential areas evidenced [49, 51, 52]. • Blood sample data indicated PTE levels slightly higher than exposed workers in some cases [70, 129, 130]. • Significantly elevated levels of several PTEs detected in the blood of children living in e-waste recycling sites in comparison to reference samples [74] and many times higher than Canadian citizens [73] in some cases. Other studies also show high levels of Pb [75], particularly in occupationally exposed children involved in open burning activities in one context[66]. • Non-carcinogenic risk to residents determined to be low by a single study [51]. • Carcinogenic risk not determined for this hazard, pathway receptor combination.	• Results may be confounded with dismantling activities and hydrometallurgical treatment. • Difficult to disaggregate blood sample data from confounding sources of exposure for non-occupationally exposed receptors. • Relies on a single study for risk in combination with generally low ambient air concentrations	• Adults and children have no choice to avoid exposure if they live around e-waste open burning activities.	2	4	**8**	LIMIC
		Children		• Higher concentrations of some PTEs in the air in some residential areas evidenced [49, 51, 52]. • Significantly elevated levels of several PTEs detected in the blood of children living in e-waste recycling sites in comparison to reference samples [74] and many times higher than Canadian citizens [73] in some cases. Other studies also show high levels of Pb [75], particularly in occupationally exposed children involved in open burning activities in one context [66].	• Relies on a single study for risk in combination with generally low ambient air concentrations and no specific determination of risk for children so equal, to general population	• Children have no choice to avoid exposure if they live around e-waste open burning activities.	2	4	**8**	LIMIC

Haz.	Pathway	Receptor	Geog.	Evidence and justification for risk assessment	Uncertainty (aleatoric and epistemic)	Receptor vulnerability	L	S	R	Global receptor context
				• Carcinogenic risk not determined for this hazard, pathway receptor combination.						
		E-waste workers (informal)		• Elevated levels of PTEs identified in multiple dust and soil samples close to e-waste combustion activities [51, 60-64, 66, 67], but levels generally lower than in those reported for dismantling. Generally higher concentrations of Pb, Sb, Cu, Cr and As exceeding USEPA industrial soil screening levels in many cases. • Blood sample data indicate very high levels of Cr in workers [49] and slightly elevated Pb, [71, 72] in comparison to Canadian citizens [73], particularly in burning specialists [70]. Levels of Cd also slightly elevated in once study [50]. • Non-carcinogenic and carcinogenic risk calculated to be high for workers carrying out in one context [65].	• Results may be confounded with dismantling activities and hydrometallurgical treatment. • Limited to one determination of carcinogenic and non-carcinogenic risk to workers from soil	• Poor hygiene means informal workers at risk of ingesting, particularly dust that they come into contact with.	3	4	**12**	LIMIC
		Population		• Elevated levels of PTEs identified in multiple dust and soil samples close to e-waste combustion activities [51, 60-64, 66, 67], but levels generally lower than in those reported for dismantling. Generally higher concentrations of Pb, Sb, Cu, Cr and As exceeding USEPA industrial soil screening levels in many cases. • Blood sample data indicate PTE levels slightly higher than exposed workers in some cases [70, 129, 130]. • Significantly elevated levels of several PTEs detected in the blood of children living in e-waste recycling sites in comparison to reference samples [74] and many times higher than Canadian citizens [73] in some cases. Other studies also show high levels of Pb [75], particularly in occupationally exposed children involved in open burning activities in one context [66]. • Non-carcinogenic risk determined by several authors [51, 61, 78] to be high for adults and very high for children in some contexts. • Carcinogenic risk to adults calculated low by two studies [61, 78] and carcinogenic risk to children [61] higher than adults in two cases.		• Adults and children have no choice to avoid exposure if they live around e-waste open burning activities.	3	4	**12**	LIMIC
PTE	Ingestion of dust, soil and water	Children	NGA, CHN, VNM, GHA, URY	• Elevated levels of PTEs identified in multiple dust and soil samples close to e-waste combustion activities [51, 60-64, 66, 67], but levels generally lower than in those reported for dismantling. Generally higher concentrations of Pb, Sb, Cu, Cr and As exceeding USEPA industrial soil screening levels in many cases. • Significantly elevated levels of several PTEs detected in the blood of children living in e-waste recycling sites in comparison to reference samples [74] and many times higher than Canadian citizens [73] in some cases. Other studies also show high levels of Pb [75], particularly in	• Results may be confounded with dismantling activities and hydrometallurgical treatment.	• Children ingest soil and have no choice to avoid exposure if they live around e-waste open burning activities.	4	4	**16**	LIMIC

Haz.	Pathway	Receptor	Geog.	Evidence and justification for risk assessment	Uncertainty (aleatoric and epistemic)	Receptor vulnerability	L	S	R	Global receptor context
				occupationally exposed children involved in open burning activities in one context [66]. • Non-carcinogenic risk very high in one study and three contexts [61]. • Carcinogenic risk to children [61] higher than adults in two cases.						
		E-waste workers (informal)		• Elevated levels of PTEs identified in multiple dust and soil samples close to e-waste combustion activities [51, 60-64, 66, 67], but levels generally lower than in those reported for dismantling. Generally higher concentrations of Pb, Sb, Cu, Cr and As exceeding USEPA industrial soil screening levels in many cases. • Blood sample data indicate very high levels of Cr in workers [49] and slightly elevated Pb, [71, 72] in comparison to Canadian citizens [73] particularly in burning specialists [70]. Levels of Cd also slightly elevated in once study [50]. • Non carcinogenic risk extremely high and carcinogenic risk high in one study [65].	• Results may be confounded with dismantling activities and hydrometallurgical treatment. • Assessment strongly driven by a single source	• Informal workers operate without dermal protective equipment.	4	4	**16**	LIMIC
PTE	Dermal contact with soil and dust	Population	NGA, CHN, VNM, GHA, URY	• Elevated levels of PTEs identified in multiple dust and soil samples close to e-waste combustion activities [51, 60-64, 66, 67], but levels generally lower than in those reported for dismantling. Generally higher concentrations of Pb, Sb, Cu, Cr and As exceeding USEPA industrial soil screening levels in many cases. • Blood sample data indicate PTE levels slightly higher than exposed workers in some cases [70, 129, 130]. • Significantly elevated levels of several PTEs detected in the blood of children living in e-waste recycling sites in comparison to reference samples [74] and many times higher than Canadian citizens [73] in some cases. Other studies also show high levels of Pb [75], particularly in occupationally exposed children involved in open burning activities in one context [66]. • Non-carcinogenic risk low [61] and carcinogenic risk not quantified.	• Results may be confounded with dismantling activities and hydrometallurgical treatment.	• Adults and children have no choice to avoid exposure if they live around e-waste open burning activities.	2	4	**8**	LIMIC
PTE	Uptake in food	Population	CHN	• Some evidence [131, 132] provided for concentrations in food near e-waste physical processing, with three examples showing slightly higher Pb concentration than EU Regulatory limits [133, 134], however evidence is not strong enough to correlate with the e-waste processing activities. • Low non-carcinogenic risk through dietary intake highlighted in one study [51].	• Limited information indicates that many PTEs are not easily up-taken by rice plants [64], however further sources were not reviewed.	• Local population may have limited ability to choose whether to eat food from local area or not.	1	4	**4**	LIMIC

Haz.	Pathway	Receptor	Geog.	Evidence and justification for risk assessment	Uncertainty (aleatoric and epistemic)	Receptor vulnerability	L	S	R	Global receptor context
DRC	Atmosphere/ inhalation	E-waste workers (informal)	IND, GHAQ, CHN, VNM	• Air concentrations determined by several authors [83-85]. Though lack of field data exist, laboratory studies confirm emissions [87]. Emission data do not exceed incineration Directive thresholds [84]. • Evidence of DRCs in blood and breast milk [99] showed elevated levels for those living near e-waste open burning activities compared to the reference.	• Very limited atmospheric field data available. • Though the data are poor, the theoretical basis exists and therefore a tentative estimate is made in this assessment.	• Informal workers operate without respiratory protective equipment.	3	4	**12**	LIMIC
		Population				• Adults and children have no choice to avoid exposure if they live around e-waste open burning activities.	3	4	**12**	LIMIC
	Ingestion of soil and dusts; dermal contact; and ingestion through food	E-waste workers (informal)		• One study indicated high risk to workers in e-waste workshops [94].	• Though the data are poor, the theoretical basis exists and therefore a tentative estimate is made in this assessment.	• Poor hygiene means informal workers at risk of ingesting, particularly dust that they come into contact with.	3	4	**12**	LIMIC
		Population		• DRCs present in high concentrations in multiple examples [88-95]. • Carcinogenic risk determined by one author indicating high risk to residents [90]. • Evidence of DRCs in blood and breast milk [99] showed elevated levels for those living near e-waste open burning activities compared to the reference.	• Data on risk are scant but the theoretical basis exists and therefore a tentative estimate is made in this assessment.	• Adults and children have no choice to avoid exposure if they live around e-waste open burning activities.	3	4	**12**	LIMIC
PAH	Atmosphere/ inhalation/ dermal contact/ ingestion	E-waste workers (informal)		• Two studies reported high PAH concentrations in the atmosphere around e-waste open burning activities [111, 112]. • Evidence of PAHs in children's blood [122], adult urine[123], and hair [124] all correlating with proximity to e-waste open burning and increased oxidative stress, which indicates DNA damage.	• Data on risk are scant but the theoretical basis exists and therefore a tentative estimate is made in this assessment.	• Informal workers operate without respiratory protective equipment. • Low hygiene means informal workers at risk of ingesting, particularly dust that they come into contact with.	3	4	12	LIMIC
		Population	CHN	• Multiple source of evidence showing concentrations in soil [114, 118-120] and evidence of selective uptake in plants [115, 120].		• Adults and children have no choice to avoid exposure if they live around e-waste open burning activities.	3	4	12	LIMIC
BFR	Atmosphere/ inhalation	E-waste workers (informal)	CHN	• Evidence of very high concentrations in air from two studies [52, 105], however no assessment of carcinogenic or non-carcinogenic risk was carried out.	• Data on risk are scant but the theoretical basis exists and therefore a tentative estimate is made in this assessment.	• Informal workers operate without respiratory protective equipment.	3	4	12	LIMIC
		Population				• Adults and children have no choice to avoid exposure if they live around e-waste open burning activities.	3	4	12	LIMIC

Haz.	Pathway	Receptor	Geog.	Evidence and justification for risk assessment	Uncertainty (aleatoric and epistemic)	Receptor vulnerability	L	S	R	Global receptor context
		E-waste workers (informal)		• Evidence in soils and dusts provided by several authors, all of whom detected levels exceeding USEPA soil screening levels five to thirty times [52, 64, 67, 107] with one exception where levels were lower than the open burning sites elsewhere [107]. • Non-carcinogenic risk determined by one author [67] who scored it low in all but one example in this source pathway reception context. • Carcinogenic risk low in all cases [67].	• n/a	• Adults and children have no choice to avoid exposure if they live around e-waste open burning activities.	2	4	**8**	LIMIT
	Ingestion of soil and dusts; dermal contact; and ingestion through food	Population	NGA, CHN, VNM	• Evidence in soils and dusts provided by several authors, all of whom detected levels exceeding USEPA soil screening levels by five to thirty times [52, 64, 67, 107] with one exception where levels were lower than the open burning sites elsewhere [107]. • Uptake by rice plants shown to be limited, reducing risk potential to local population [64]. • No specific carcinogenic or non-carcinogenic risk calculated.	• Data on risk are scant but the theoretical basis exists and therefore a tentative estimate is made in this assessment.	• Children ingest soil and have no choice to avoid exposure if they live around e-waste open burning activities.	2	4	**8**	LIMIT
		E-waste workers (informal)	NGA, CHN, VNM	• Evidence in soils and dusts provided by several authors, all of whom detected levels exceeding USEPA soil screening levels by five to thirty times [52, 64, 67, 107] with one exception where levels were lower than the open burning sites elsewhere [107]. • Non-carcinogenic risk scored high and extremely high for informal recycling workers in one Nigerian study [67] and carcinogenic risk scored high in one example in the same study	• Data on risk are scant but the theoretical basis exists and therefore a tentative estimate is made in this assessment.	• Poor hygiene means informal workers at risk of ingesting, particularly dust that they come into contact with.	3	4	**12**	LIMIT
	Dermal contact	Population	NGA, CHN, VNM	• Evidence in soils and dusts provided by several authors all of whom detected levels exceeding USEPA soil screening levels by five to thirty times [52, 64, 67, 107] with one exception where levels were lower than the open burning sites elsewhere [107]. • No specific carcinogenic or non-carcinogenic risk calculated.	• Data on risk are scant but the theoretical basis exists and therefore a tentative estimate is made in this assessment.	• Adults and children have no choice to avoid exposure if they live around e-waste open burning activities.	3	4	**12**	LIMIT

Abbreviations: likelihood (L); severity (S); risk (R); hazard being assessed (Haz.); low income and middle income countries (LIMIC); high income countries (HICs); geographical context (Geog.); potentially toxic elements (PTE); Brominated flame retardants (BFR); personal protective equipment (PPE); Volatile organic compounds (VOC); Brominated flame retardants (BFR); dioxins and related compounds (DRC); polycyclic aromatic hydrocarbons (PAH); United States Environmental Protection Agency (USEPA).

4. Conclusion

The release of hazardous substances from the open burning and thermal deconstruction of e-waste is a substantial challenge in LIMICs where the practice is carried out by informal workers whose vulnerability to exposure puts them at considerable risk of ill health from an array of potentially hazardous emissions. A large body of research already exists to evidence emissions from these thermal processes, much of which has been reviewed here. However, determining the source of observed substance concentrations in environmental media is a substantial challenge because other activities such as hydrometallurgy and physical dismantling are often co-located with thermal processes. Whilst an obvious response to harm mitigation is to attempt to prohibit all these potentially harmful activities, such an interdiction would deprive some of the world's poorest people of their income, or simply drive the activities further underground. Therefore, understanding and linking specific activities to environmental substance emission pathways and sinks, is critical to designing and implementing targeted interventions to reduce hazard exposure.

The large body of emission based research is dwarfed by the paucity of evidence that indicates the scale of the activity. Fundamentally these practices are considered illicit and the illegality of the global transboundary trade means that the flow of this material is almost impossible to reliably quantify. Moreover, there are no obviously available estimates of the number of workers who might be engaged in the e-waste reclamation sector, less so those who are specifically engaged in thermal processing. The absence of reliable estimates represent a conspicuous omission that will continue to reduce the ability of actors and interveners to take steps to mitigate future harm and it is a recommendation of this study that a combination of modelling and primary data acquisition is carried out to fill this gap in understanding.

The data presented here, nearly half of which was produced by research groups in China, overwhelmingly focus on PTEs and their occurrence in environmental media close to e-waste processing activities or in the blood of those who work or live nearby. Although many of the sources indicate that open burning is a source, this assumption was not substantiated by the few studies of atmospheric concentrations of metals many of which were below workplace exposure levels and possibly indicating that another process was a contributory source. Tragically, several large studies of lead concentrations in the blood of children who live and or work on e-waste processing sites found levels that exceeded those in reference groups,

highlighting an urgent child protection need.

Despite the limited field data, the effect of DRC exposure on workers and populations surrounding e-waste reclamation sites represents a substantial cause for concern due to the very serious potential health effects of exposure to this group of substances, evidenced by several risk studies and also the detection of these substances in blood and human breast milk. As well as being a substance of concern, DRC concentrations offer a useful indicator that combustion of halogenated plastics or plastic additives such as BFRs has taken place in the same area. Something that future field researchers may wish to consider when carrying out studies of non-DRC substances in the future.

As a final remark, we note that despite some shortcomings in available data, that there is clearly a need for serious, immediate and concerted response to identify and implement affordable, effective and accessible alternative and methods of reprocessing that reduce or eliminate the harmful emissions from thermal deconstruction and open burning of e-waste. Offered alternative practices and activities must involve those who are engaged in e-waste dismantling; integrating their valuable circular economic function into local, national and international waste management planning.

CRediT author statement

Ed Cook: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Project administration; Resources; Validation; Visualization; Writing – original draft; Writing – review & editing. **Costas A. Velis:** Conceptualization; Data curation; Formal Analysis; Funding acquisition; Investigation; Methodology; Project administration; Resources; Software; Supervision; Validation; Visualization; Writing – original draft; Writing – review & editing. **Spyridoula Gerassimidou**: Data curation; Investigation; Writing – original draft; Writing – review & editing; **Aditi Ramola**: Formal analysis; Funding acquisition; Project administration; Resources; Supervision; Visualization; Writing – original draft. **Arne Ragossnig**: Writing – original draft; Funding acquisition; Supervision; Project administration.

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