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Mismanagement of plastic waste through open burning with emphasis on the Global South: A systematic review of risks to occupational and public health

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Abstract

Large quantities of mismanaged plastic waste threaten the health and wellbeing of billions worldwide, particularly in low- and middle-income countries where waste management capacity is being outstripped by increasing levels of consumption and plastic waste generation. One of the main self-management strategies adopted by 2 billion people who have no waste collection service, is to burn their discarded plastic in open, uncontrolled fires. While this strategy provides many benefits, including mass and volume reduction, it is a form of plastic pollution that results in the release of chemical substances and particles that may pose serious risks to public health and the environment. We followed PRISMA guidelines to select and review 20 publications that provide evidence on potential harm to human health from open burning plastic waste, arranging evidence into eight groups of substance emissions: brominated flame retardants; phthalates; potentially toxic elements; dioxins and related compounds; bisphenol A; particulate matter; and polycyclic aromatic hydrocarbons. We semi-quantitatively assessed 18 hazard-pathway-receptor combination scenarios to provide an indication of the relative harm of these emissions so that they could be ranked, compared and considered in future research agenda. This assessment overwhelmingly indicated high risk of harm to waste pickers, a large group of 11 million informal entrepreneurs who work closely with waste, delivering a circular economy but often without protective equipment or many structured, safe system of work. Though the risk to human health from open burning emissions is high, this remains a substantially under-researched topic.

31 Abbreviations

ABS	acrylonitrile butadiene styrene
Backg'd	background
BaP_{eq}	benzo(a)pyrene equivalent
BDEs	brominated diphenyl ethers
BFR	brominated flame retardants
BPA	bisphenol A
ca.	circa
CCME	Canadian Council of Ministers of the Environment
CI	confidence interval
Com.	commercial
Conc.	concentration
DEHP	di(ethylhexyl) phthalate
DEP	diethyl phthalate
DMP	dimethyl phthalate
DRC	dioxins and related compounds
EU	European Union
Geog.	geographical context
HBB	hexabromobiphenyl
HBCD	hexabromocyclododecane
HDPE	high density polyethylene
IPCC	Intergovernmental Panel on Climate Change
IRS	informal recycling sector
K-resin	styrene-butadiene copolymer
L	likelihood
LDPE	low density polyethylene
LIMIC	low income and middle income countries
MSW	municipal solid waste
Mt	million metric tons
Na	not available
NEERI	National Environmental Engineering Research institute (2010)
PAH	polycyclic aromatic hydrocarbons
PBDEs	polybrominated diphenyl ethers
PC	polycarbonate
PC-ABS	polycarbonate/acrylonitrile-butadiene-styrene
PCB	polychlorinated biphenyls
PCDD	polychlorinated dibenzo-p-dioxins
PCDD/Fs	polychlorinated dibenzo-p-dioxins and polychlorinated dibenzo-p-furans
PCDF	polychlorinated dibenzofurans
PE	polyethylene
PET	polyethylene terephthalate
phth.	phthalates
PM	particulate matter
$PM_{0.1}$	particulate matter < 0.1 µm
PM_{10}	particulate matter < 10 µm
$PM_{2.5}$	particulate matter < 2.5 µm

PP	polypropylene
PS	polystyrene
PTE	potentially toxic elements
PVC	polyvinyl chloride
pw	plastic waste
R	risk
Res.	residential
RQ	research question
S	severity
SBC	styrene-butadiene copolymer
SD	standard deviation
Sed.	sediment
TBBPA	tetrabromobisphenol A
TCDD	2, 3, 7, 8-tetrachlorodibenzodioxin
ton	1,000 kg
TPM	total particulate matter
USMR	uncertainty, strength of knowledge and methodological robustness
VOC	volatile organic compound
wt.	weight (i.e. a weight reporting basis)

1. Introduction

The topic of solid waste mismanagement has attracted considerable attention in recent years, not least because of the large quantities of plastic waste that are reported to enter the aquatic environment (11 million metric tons per annum Mt y^{-1}), mainly in the low- and middle-income countries (LIMICs) of South and Southeast Asia.[1] Our high dependence on plastics in almost every aspect of life has resulted in an exponential growth curve for plastic production since the 1950s, anticipated to continue unabated until 2050.[2] Underlying this growth in plastic production, is the rapidly rising population that is projected for several middle-income countries in the Global South,[3] where newly attained prosperity is allowing their citizens to benefit from the properties and characteristics that plastics bring to their lives such as freshness of food, fuel economy of transport systems, and insulating properties in constructions. Critically, increases in packaging production are anticipated, a stream that has an inherently short use phase, often becoming waste within a few months of production.[2]

This rapid projected increase in plastic waste generation in LIMICs, particularly for short-use items and objects will necessitate concurrent and concerted effort by municipalities to provide systems to collect, dispose and potentially reclaim, recycle and recover significant additional material. However, the present situation is that approximately 40% wt. of municipal waste plastics are already mismanaged and that this proportion is projected to increase to 55% wt. by 2040 unless considerable and concerted action is taken to either inject more resources into an already struggling waste management system or dramatically reduce the mass that enters it.[1] Controlling and reducing this mass of unmanaged plastic waste is fast becoming one of the dominant environmental topics of the 21st century.

As yet, the focus on emissions of plastic debris to the marine environment has dominated the plastic pollution research landscape, with many of the proposed solutions focusing on reduction of at-risk items through fractional (by weight) plastic bans and action to stimulate the circular economy for materials.[4-6] However, other forms of plastic pollution have received comparatively little attention in recent years and the focus on circular economic aspirations has detracted from the foundational imperative for waste management in the first place, to protect human health and reduce our interaction with harmful effects of solid waste.[7] Two environmental compartments, the land and the atmosphere, accumulate large amounts of plastics, the former as debris in dumpsites (12 Mt y^{-1}) and diffuse terrestrial deposits (18 Mt y^{-1}), and the latter in the form of gasses, vapors and particulates that are emitted when plastics are combusted in open, uncontrolled fires (49 Mt y^{-1}).[1]

For the 2 billion humans that receive no solid waste collection services,[8] open burning is an effective self-management approach that quickly reduces the mass and volume of waste (indicatively, up to 75% wt.[9] and 90% v/v.[10] under ideal conditions in energy from waste plants). In addition, the heat generated in open fires, compresses the bioactivity of the putrescible fractions and associated direct infection risk as well as providing reduction in odor[11] and a perceived deterrent against mosquitos that transmit malaria.[12] In this perverse sense, open burning may offer benefits to people: however, at a serious potential risk to their own health, and that of any other people who may be exposed, for example via downwind plumes and wider atmospheric dispersion. Importantly, many of the most affected individuals are also the world's poorest people, including approximately 11.4 million waste pickers (a conservative estimate), who, as strong anecdotal evidence suggests, work in close proximity to waste fires; and who have few choices about whether to sustain exposure to their emissions.[13]

Two prominent studies have investigated the open burning of waste with a global perspective. Lemieux et al.[14] provided a comprehensive review of emission factors associated with the open burning of different materials, many of which were waste. The study summarised research on potentially hazardous emissions of several substance groups including certain brominated flame retardants (BFRs), dioxins and related substances (DRCs), polycyclic aromatic hydrocarbons (PAHs), particulate matter (PM) and volatile organic compounds (VOCs). Wiedinmyer et al.[15] presented the only comprehensive global estimate of emissions from the open burning of waste specifically to date, the study used as a basis for further research since. For instance, Cogut[16] presented the Wiedinmyer et al.[15] model outputs in the context of the wider waste management system. Kodros et al.[17] also used the Wiedinmyer et al.[15] data and combined them with a global burden of disease study by Lim et al.[18] to estimate 270,000 premature deaths per year worldwide (5th to 95th percentiles: 213,000 to 328,000) from the open burning of waste. In a more recent study, Williams et al.[19] combined the findings of Kodros et al.[17] with World Health Organization[20] and Institute for Health Metrics and Evaluation[21] to estimate between 270,000 and 270,500 premature deaths from the open burning of waste. The estimate accounted for an additional 5,000 child deaths not included in the study by Kodros et al.[17]. Only one global NGO report by Gower et al.[22] has specifically focused on emissions from the open burning of plastic waste, targeting in particular items produced by four major international corporations (Coca-Cola, Nestlé, PepsiCo and Unilever). The study was not subject to blind peer review, but involved informal academic review, and concentrated on the contribution to global warming from black carbon and CO_2 emissions. Importantly, no study as yet has attempted to collate and summarize evidence that focuses on the human health impacts of the open burning of plastic waste as a distinct material group. Given, the large quantities of plastic waste that are reported to be open burned each year and the inferred prevalence of the activity across the Global South,[23] potentially hundreds of millions of the world's poorest people may be exposed to a cocktail of hazardous emissions. We have, for the first time, collected, arranged and synthesized available evidence on the issue. We use a systematic approach based on PRISMA guidelines[24]. Here, we focus on the mismanagement of plastic waste through uncontrolled, open burning. This work is complimented by Cook et al.[25], who reviewed the risks associated with melt extrusion and legacy substance contamination 'inherited' by secondary plastics from the previous use phase. Both the present review and the review by Cook et al.[25] followed the same methodological approach based on PRISMA guidelines and feature the same initial pool of literature.

We begin this paper with an appraisal of evidence to indicate the mass of waste material burned in the open in different contexts (**Section 3.2**); this section does not strictly form part of the systematic review, but is intended to provide context on the magnitude of the open burning phenomenon – also a prerequisite to any global risk assessment. This is followed by six sections that address the state of knowledge around the emissions from burning waste plastics. Finally, we provide an indicative score for a series of hazard-pathway-receptor combinations to assist with basic ranking and prioritization of future areas of research. We do not include appraisal of incineration or energy from waste plants, at least where they incorporate air pollution control technology and management, as these are clearly out of the scope of open uncontrolled burning.

2. Methods

2.1. Systematic review

The present review is part of a wider piece of research that investigated the risks to human health and safety from the mismanagement of plastic waste. Whilst this paper presents findings on the risks to human health from the open, uncontrolled burning, another paper by Cook et al.[25] presents on plastics extrusion and legacy substance contamination in secondary plastics. The same initial pool of literature was used in the preparation of the two reviews as detailed in **Section S.1.4**, obtained by the same PRISMA adapted method[24]; presented in Cook et al.[25].

We searched three databases: Scopus, Web of Science and Google Scholar to explore the following three research questions (**RQ**):

- **RQ1**: What evidence exists to indicate risk to public and occupational safety posed by the open burning of plastic waste?
- **RQ2**: What are the comparative risks to public and occupational safety that arise from the open burning of plastic waste?
- **RQ3:** Based on the most important risks identified in **RQ1** and **RQ2** from plastic waste open burning, what are the core evidence gaps and, therefore, further research needs?

Boolean search queries are listed in the **Supporting Information (SI)** (**Section S1.2**). They were streamlined using one-at-a-time sensitivity analysis to ensure the maximum number of relevant articles whilst reducing the number of non-relevant sources. Articles were included or excluded according to criteria detailed in (**S1.3**). Snowball and citation searching techniques[26] were used to identify further relevant literature. Several websites and datasets were also queried for further relevant information, including those of Health and Safety Executive[27], International Labour Organization[28], The World Bank[29] and World Health Organization[30].

The hazards posed by waste plastic items, and chemical substances arising from them, were identified in each information source. These were listed alongside receptors and the various pathways through which they may be exposed to each hazard. These hazard-pathway-receptor combinations were used to produce a theoretical conceptual diagram (**Figure 1**) that illustrates potential core pathways through which receptors may be potentially exposed to hazards emerging from specific sources.

Estimates to indicate the mass of waste open burned were included to add context and scale to the review, and were obtained separately to the main literature review via non-systematic snowball and citation searching.

2.2. Uncertainty, strength of knowledge and methodological robustness (USMR)

As required by PRISMA guidelines[24], the strength of information provided in each of the sources reviewed was assessed. In our review this was done qualitatively as described by Cook et al.[25] and coded according to USMR on a case-by-case basis; commentary is provided in footnotes below each table, unless no issues were identified. Specifically, data/information reported in the literature falling within the scope of inclusion criteria were assumed to be robust unless marked for: (i) inconsistent or ambiguous description of sampling and sample processing; (ii) issues of comparability with data reported by different authors; and, (iii) comparability affected by age of study.

2.3. Risk based approach

To assist with comparisons and ranking of the relative risk of each hazard-pathway-receptor combination, a risk-based approach reported by Cook et al.[25], adapted from Hunter et al.[31], Kaya et al.[32], World Health Organization[33] and Burns et al.[34]. This approach assigns likelihood and severity scores to each hazard-pathway-receptor combination, enabling an indicative scoring of risk to be calculated. The matrix for scoring is shown in **Section S.2**. This process was not an attempt to fully and comprehensively quantify risk (which is not possible given the paucity of data), but instead intended to support decision-making on directing future research agenda. The aggregated results of this process are shown, ranked in **Section S.3**.

3. Open burning of plastic waste

3.1. Context

The variable conditions in plastic waste open fires results in the emissions of a wide range of gasses, particles and vapors.[14] These substances have several origins, described here in four groups. First, there are substances that have been intentionally added to plastic materials, i.e., in addition to the basic polymer, to improve their properties. For instance, flame retardants, fillers, antioxidants, and impact modifiers.[35] Second, there are substances that have been added unintentionally as a result of the inclusion of recycled content, so called "legacy substances" that were either additives to a previous product or that were introduced during the reprocessing or sorting of the previous product. Third, there are substances and derivatives that were used or arose during the production of the primary polymer, including catalysts, monomers and partially formed polymers called dimers or oligomers. Fourth, there are the polymers themselves.

In open uncontrolled fires, these four groups of substances and materials result in emissions via two main mechanisms:

(1) Heat causes the substances in groups 1-3 to volatilize; and,
(2) Thermochemical reactions at low and variable temperatures and oxygen presence result in bond fission and formation between present (groups 1-4) or newly created molecules. These are produced during pyrolysis, gasification and combustion; phenomena that can also be grouped according to fire types as:[36] i) flaming combustion, well ventilated; ii) flaming combustion, ventilation-controlled iii) oxidative pyrolysis (smoldering); and iv) anaerobic pyrolysis.[36]

The action of these two main mechanisms on the four groups of materials and substances results in the formation of residues in ash form ("inert", incombustible part), or the release of gasses, particles and vapors into the atmosphere from where they may be suspended or deposited onto land or into water with a risk of entering the food chain. **Figure 1** provides a conceptual generalised summary of the various exposure pathways.

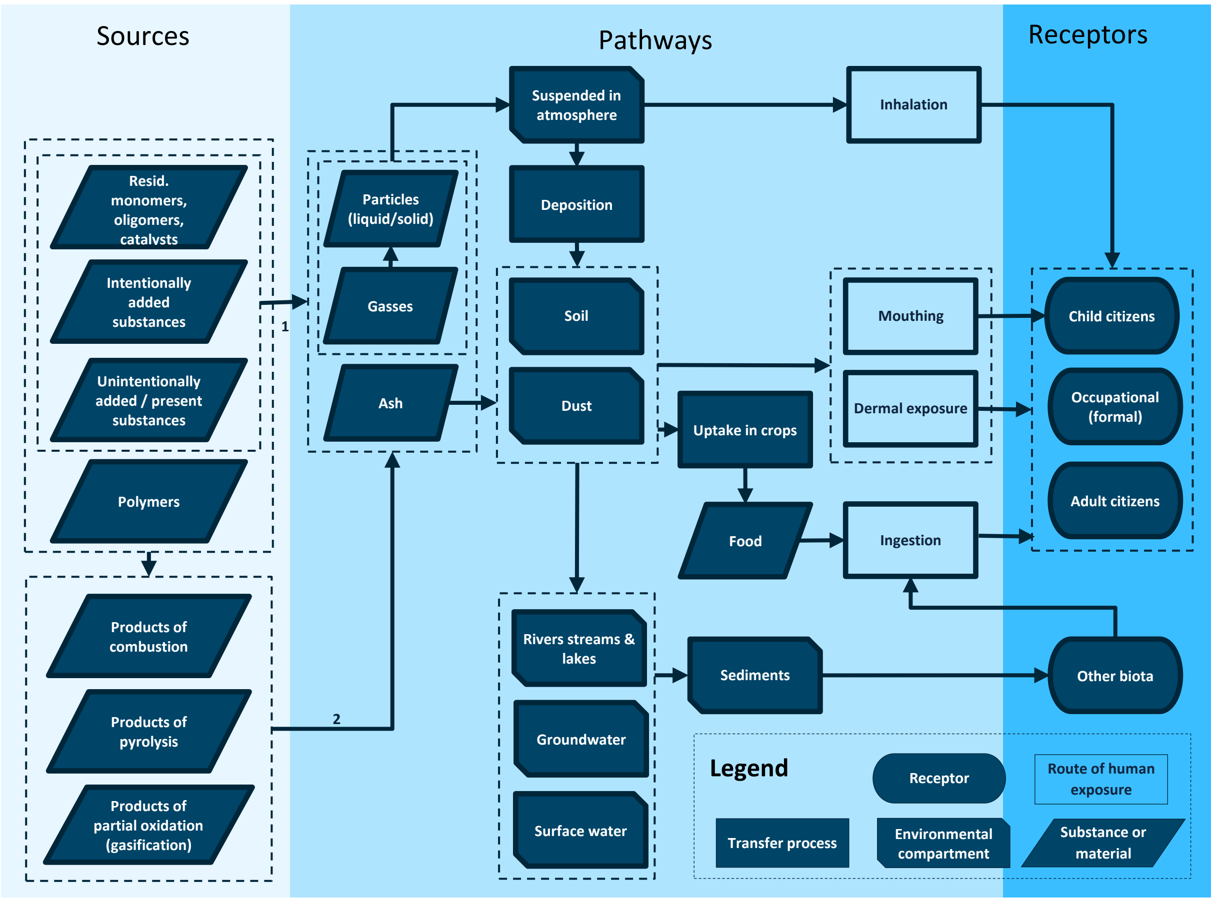

Figure 1: Theoretical hazard exposure conceptual (hazard-pathway-receptor) model associated with open uncontrolled burning of plastic waste (risks from substances contained and combustion/heating products). Notation: [1]volatilisation pathway; [2]thermochemical reaction pathway.

3.2. Mass of waste open burned

Understanding emissions from open burning of plastic waste and the resultant health implications, requires information about how much material is combusted in different contexts. In **Table 1**, 31 proportional estimates from 12 authors across six different waste stream denominators are shown for comparison. It is striking that most highly cited article by

Wiedinmyer et al.[15] uses an Intergovernmental Panel on Climate Change (IPCC)[37] estimate of 60% of municipal solid waste (MSW) deposited in dumpsites in LIMICs, which is based on an expert elicitation exercise. While expert elicitation is a useful last resort for estimating parameters in a sector where data is scarce, they do not purport to provide accurate data. Other estimates such as the National Environmental Engineering Research Institute[38] (NEERI) relate only to wards of Mumbai that have a dumpsites and uses an unclear denominator. As with the IPCC estimate, the NEERI study has its own risk of bias as the estimates were made on the basis of discussions with the Mumbai local authority who may have a vested interest to underestimate the mass. There was also no indication of how many officials were interviewed and what their position was. Notably, there is insufficient information regarding the exact location of the open burning, the urban vs. rural character and about the type of site or wider activity, despite the obvious utility of such contextual information.

Table 1: Selected estimates of the proportion of municipal solid waste (MSW) open burned in different geographical and socio-economic contexts.

Denominator	Ref.	Country	Locale	Geog.	Basis of estimate	Context	Rurality	Proportion of waste open burned
			Delhi	City				2-3%
	Nagpure et al.[39]		Agra	City	Transect sampling			24%
	Yedla et al.[40] as cited by Nagpure et al.[39]		Mumbai	City	Assumptions			2%
	Central Pollution Control Board[41] as cited by Nagpure et al.[39]		Delhi	City	Assumptions			1%
	Sharma[42] as cited by Nagpure et al.[39]	IND	Kanpur	City	Visual observation survey in few neighborhoods			8%
	Guttikunda[43] as cited by Nagpure et al.[39]	MNG	Ulaanbaatar	City	Assumptions		Urban	20%
	Pansuk et al.[44]	THA		National	Interviews (n=24)		Urban & rural	13%
	Chanchampee[45]	THA		National	Assumptions		Urban & rural	36%
	Premakumara et al.[46]	PHL		National	Assumptions		Urban & rural	17.5%
	Reyna-Bensusan et al.[47]	MEX	Huejutla de Reyes	Municipality	Survey		Urban & rural	23.4-24.7%
	National Environmental Engineering Research Institute[38] (NEERI)	IND	Mumbai	City	Interviews with officials		Urban	2%
	Getahun et al.[48] as cited by Bundhoo[49]	ETH	Jimma	City			Urban	22%
	Rodil et al.[50] as cited by Bundhoo[49]	SLB	Honiara	City			Urban	23%
	McCulloch et al.[51] as cited by Christian et al.[52]	Global		Global	Assumption	LIMIC	Urban & rural	50%
	Wiedinmyer et al.[15]	Global		Global	Assumption (IPCC)	Global	Urban & rural	41%
	United States Environmental Protection Agency[53]	USA		National	Survey	HIC	Rural	25-32%
All MSW	Das et al.[54]	NPL	Kathmandu Metropolitan City & surrounding municipalities	Municipality	Transect sampling & household survey	LIMIC	Urban	3% (0.9-5.6%)
							Urban	2-6%
Household solid waste	Reyna-Bensusan et al.[47]	MEX	Huejutla de Reyes	Municipality	Survey	LIMIC	Peri-urban	4.5-9.2%

Denominator	Ref.	Country	Locale	Geog.	Basis of estimate	Context	Rurality	Proportion of waste open burned
							Rural	66%
							Urban, peri-urban & rural	36%
	United States Environmental Protection Agency[55] as cited by Christian et al.[52]	USA		National		HIC	Rural	12–40%
	Ghana Statistical Service[56]	GHA		National	Survey (n=37,026)	LIMIC	Not stated	7.7%
	Kumari et al.[57]	IND	Ten cities & national	Cities & national	Assumption (IPCC)		Urban & rural	10 – 20%
	Pansuk et al.[44]	THA		National	Interviews (n=24)		Urban & rural	53.7%
	Premakumara et al.[46]	PHL		National	Assumptions	LIMIC	Urban & rural	50%
Uncollected waste							Urban & rural	60%
	Wiedinmyer et al.[15]	Global		Global	Assumption (IPCC)	Global	Urban & rural	13%
Dumpsite waste						LIMIC	Urban & rural	60%
	Wiedinmyer et al.[15]	Global		Global	Assumption (IPCC)	HIC	Urban & rural	13%
Landfilled waste[a]	National Environmental Engineering Research Institute[38] (NEERI)	IND	Mumbai	City	Interviews with officials	LIMIC	Urban	10%
Collected waste	Pansuk et al.[44]	THA		National	Interviews (n=24)	LIMIC	Urban & rural	2.5%

[a] NB the definition of landfill in this context is not specified and it is likely that the sites described would be classified as an open dumpsite. Abbreviations: municipal solid waste (MSW); Intergovernmental Panel on Climate Change (IPCC); low income and middle-income countries (LIMIC); high income countries (HIC); geographical context of the study (Geog.).

The largest sample and possibly most reliable estimate was provided by Pansuk et al.[44] who interviewed municipal officials (n=96) and householders (n=4,300) across Thailand. Based on the opinions of the officials, Pansuk et al.[44] estimated that 54% wt. of all MSW was burned residentially and a further 2.5% wt. was burned by local authorities post collection; presumably in open dumpsites. We speculate that local authority interviewees may have a vested interest in underestimating the mass that is open burned, and the data is specific to Thailand. Moreover, there is no information about how the officials were able to make such estimates or how they did so, indicting potentially high uncertainty in their reports. However, it suggests confirmation of the practice, albeit at a low rate. Several other studies provide evidence for open burning on land disposal sites, such as Oyegunle[58] who sampled soils on dumpsites in Canadian First Nation communities; Chanchampee[45] who reported that 66% of landfills (or dumpsites) in Thailand practice open burning as a form of waste mass/volume reduction; Cuadra[59] who reported the burning of MSW to retrieve metals; and Rim-Rukeh[60] who reported emissions characteristics at five landfill/dumpsites in Nigeria where fires were a frequent occurrence. Other forms of data exist to evidence open burning on land disposal sites such as: video footage from Lenkiewicz[61] in The Gambia, Human Rights Watch[62] in Lebanon, and TracingThought[63] in Bali; and from news articles such as Chandrashekar et al.[64] in Bengaluru and Doshi[65] in Kolkata.

Two studies[39, 54] used transect distance sampling to record incident of open burning along urban streets, selected for their representativeness of waste generation sector (for example households, commercial, institutional) within each urban environment. Nagpure et al.[39] determined the mass of material being burned by quenching fires at various stages of burning and comparing the level of completeness with the observations; scaling up the observed incidents on the basis of the number of buildings in the area being observed. Das et al.[54]

created coefficients by weighing and measuring the volume of waste samples, igniting them and then re-weighing and measuring the volume of residues. These were used to estimate mass combusted in the observed incidents during the transect analysis.

The studies by Nagpure et al.[39] and Das et al.[54] represent the only comprehensive efforts to determine the mass of material combusted in open uncontrolled fires through observations. Whilst the assumption, survey and interview data provide a useful contribution, it is recommended that they are compared with further observational studies to assess the variance between different methods.

3.3. Brominated flame retardants (BFR)

BFRs have been in use since the 1950s as additives in plastics used in applications where there is a risk of fire such as cars, airplanes, furniture and electrical and electronic equipment.[66] The groups of substances that can be classified as BFRs include bromophenols, hexabromocyclododecane (HBCD), polybrominated diphenyl ethers (PBDEs) and tetrabromobisphenol A (TBBPA), which is reported by The International Bromine Council[67] to be the most widely used BFR still on the market, used mainly (90%) in printed circuit boards, but also as a direct additive to engineered plastics (10%). Of the PBDEs, three broad formulations exist, Penta-BDE, Octa-BDE and Deca-BDE include 209 congeners. The Stockholm Convention lists and targets multiple BFRs for elimination due to their persistence in the environment and potential toxicity for humans and animals. Both the Octa- and Penta-BDE formulations were classified by the Stockholm Convention as persistent organic pollutants in May 2004 and the Deca-BDE formulations were added in 2019.[68] HBCD was added to Annex A of the Stockholm Convention in 2014, with certain products still permitted for use including some building insulation foams made from polystyrene (PS) as long as they are labelled as such.[69] According to Sharkey et al.[68], several groups of BFRs are almost completely prohibited in some countries and regions, for instance in the European Union (EU), hexabromobiphenyl (HBB), and HBCDD and PBDEs are entirely prohibited for use in production or content in products.

In plastics, BFRs are not generally chemically bonded to the polymers, but occupy the space in between.[70] They inhibit combustion and therefore when the host polymer is burned, they are released as gas, airborne particulates and in the residual ash. To date, most research into the open burning of MSW has concentrated on dioxins, with little attention paid to BFRs. In this study only a single research output by Hong-Gang et al.[71] was revealed that assessed BFR emission potential from combustion of plastic waste (**Table 2**). BFR concentrations were measured in five polymers collected from waste sites in China along with atmospheric emissions and residues in ash. All samples contained significant quantities of BFR congeners, albeit below the one million ng g^{-1} thresholds set by the European Restrictions on Hazardous Substances Directive[72] and Persistent Organic Pollutants Regulations.[73] Nonetheless, the presence of certain BFRs in all samples is an indication of a secondary plastics globalized market involving places where the source of feedstock is not controlled to reduce the risk of hazardous substances re-entering the product stream.

Table 2: BFR concentration in plastic wastes (Column A) and emission factors (Column B-D) when the plastic is combusted; after Hong-Gang et al.[71].

		A		**B**		**C**		**D**		
		Plastic waste[a] (ng g^{-1})		**Gas phase (ng g^{-1}-pw)**		**Airborne particle (ng g^{-1}-pw)**		**Residual ash (ng g^{-1}-pw)**		
BFR	**Polymer**	**Mean [c]**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Total**
	PVC	61,900	62,200	11.8	19.6	556	1,330	206	266	775
	PS	388,000	463,000	124	210	605	667	0.1	0.3	729
	ABS	26,700	22,600	93.6	245	650	1,310	1,050	2,340	1,790
	PP	67,000	88,400	8.6	24.2	37.1	83.8	556	1,040	602
	PE	228,000	246,000	96.2	208	20,700	40,400	13,900	31,600	34,700
ΣPBDE	Mean [b]	154,320		66.8		4,520		3,140		7,720

		A		B		C		D		
		Plastic waste[a] (ng g^{-1})		Gas phase (ng g^{-1}-pw)		Airborne particle (ng g^{-1}-pw)		Residual ash (ng g^{-1}-pw)		
BFR	**Polymer**	**Mean [c]**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Total**
	Median	67,000		93.6		605		556		775
	PVC	18,700	7,310	10.2	0.9	26.8	3.7	6.7	0.8	44
	PS	20,800	7,680	13.3	1.7	5,290	1,100	7.2	0.7	5,310
	ABS	18,700	8,640	13.0	1.1	43.7	9.7	4.9	0.6	62
	PP	25,000	7,980	15.6	1.3	48.1	11.4	60.0	15.8	124
	PE	20,300	7,360	17.1	1.6	61.0	9.5	77.1	22.1	155
	Mean	20,700		13.8		1,090		31.2		1,140
ΣHBCD	Median	20,300		13.3		48.1		7.2		124

[a] Plastic items used were as follows: PVC: cable sheath, wire jacket, tube; PS: foamed plastic, disposable plate, meat tray; ABS: cell-phone casing, air-conditioning wind deflector, computer housing; PP: soybean milk machine cover, lunch box, plastic bailer; PE: bottle, corrugated pipe, toys. [b] Arithmetic mean of means; [c] arithmetic mean. Abbreviations: polypropylene (PP); polystyrene (PS): polyethylene (PE); acrylonitrile-butadiene-styrene (ABS); polyvinyl chloride (PVC); hexabromocyclododecane (HBCD), polybrominated diphenyl ethers (PBDEs); plastic waste (pw); standard deviation (SD).

The highest concentration observed by Hong-Gang et al.[71] in the plastic itself was in the PS, and may originate from the foam board or corrugated pipe either of which may be expected to have some flame retardant properties. However, this is speculation; the authors did not test for any food contact material in this category separately, and it would have been useful to understand if these contained unregulated concentrations of BFRs. PE also showed a high BFR content, which may have originated from the corrugated pipe. Interestingly the PE showed a much higher ratio of airborne particle concentrations to plastic concentration compared to the PS that appeared to have fully combusted or transformed most of the BFRs.

Hong-Gang et al.[71] contextualized their findings by using the emission factors presented in **Table 2** to model emissions from incinerators at national level in China based on an emissions abatement efficiency of 99%; estimating 25.5 metric tons per annum emitted to the atmosphere and 71.7 metric tons per annum deposited in landfill or dumpsites. The study did not estimate emissions from open burning which are completely unabated, and we would recommend that such a calculation is carried out to estimate the magnitude of release of these potentially hazardous substances.

BFR concentrations in soils and sediments are also an indicator of plastic open burning activity. Both Tang et al.[74] and Tang et al.[75], investigated soil and sediment concentrations in an area of China where plastics recycling has been a major activity for more than 30 years. Whereas the studies were unable to determine whether the soil and sediment concentrations resulted from open burning, abrasion or extrusion, we speculate that the higher temperatures in open burning compared to extrusion could indicate that open burning is also a likely source. Tang et al.[74] took hair samples from the local population and compared them with the concentrations in sediments and soils to infer the level of exposure to human receptors. Young people (15−45 years old), who the authors state, are more likely to be involved in plastic recycling operations, featured much higher concentrations, 133 ng ΣPBDE g^{-1} hair (dry wt.), compared to children and older adults, indicating that BFRs may be transferring into their bodies through occupational exposure.

3.4. Phthalates

In plastics, phthalates are used primarily as plasticizers in polyvinyl chloride (PVC), where they modulate elasticity in products such as toys, building materials, clothing, and medial appliances,[76] with annual consumption reported to be as high as 8 Mt y^{-1}.[77] Their low molecular weight and tendency for non-covalent bonding to polymers means that some formulations are very sensitive to changes in temperature and pH and readily escape from their host products into the environment, where they have potential for long-range transport[78] and as a result are found in almost all environmental compartments.[79]

Phthalates bond readily with fats, which means they are easily absorbed into the human bloodstream.[80] Once inside the human body, they are transformed, and their metabolites can irreversibly disrupt the endocrine system,[81] metabolism[82] and interfere with thyroid hormones.[83]

Several studies have investigated phthalate transmission from waste incinerator plants, finding that they have the potential to be emitted intact from facilities without adequate air pollution control and management.[77, 78] However, studies of phthalate concentration in the atmosphere as a consequence of open burning plastic waste are limited. Simoneit et al.[81] combusted samples of several plastic products, some of which were "single polymer" items and some of which were mixtures (**Table S5**, **Section S.4**). The data indicate phthalate emissions from several sources, but the data are hard to contextualize, because they were presented as a proportion of "soot" generated from combustion of approximately 20 g of material.

Two papers have reported concentrations of phthalates in ambient outdoor air in Northern Indian cities[84, 85] and these are contextualized with concentrations observed in urban and remote environments by Teil et al.[86] and Thuren et al.[87] (**Table 3**).

Table 3: Total phthalate concentrations observed in ambient atmospheric samples and plastic extrusion facilities.

Ref.	Context	Sampling		Phase	Conc. (ng m^{-3}) Mean	SD / CI / range	USMR#
Shivani et al.[84]			Delhi		502.7	SD 136.4	
			Modinagar		387.7	SD 124.3	
			Mahendragarh		160.4	SD 43.8	
Gadi et al.[85]	National Capital region, IND		Delhi		210.8	± 79.7	
			Uttar Pradesh		158.9	± 72.2	
			Haryana	Particle phase	130.4	± 63.6	P
Teil et al.[86]	Paris, FRA		Paris	Particle phase	8.2	3.9-13	
				Vapor phase	55.3	20.6-109.3	
Thuren et al.[87]			Enewetak Atoll, N Pacific Ocean		2.27		
			Portland, Oregon		0.76		
			Great Lakes		4		
		Atmospheric field sampling	Sweden	Gas/particle phase	3.7		

[a] Comparison between exposed and reference concentrations significant ($p<0.05$); # uncertainty, strength of knowledge and methodological robustness (USMR) assessed qualitatively. It is assumed that there are no significant concerns unless marked as: P = results are indicative. While most phthalates are reported to originate from plastic waste burning, the study reports significant emissions from biomass burning. Gas phase not quantified. Results show species identified in $PM_{2.5}$ only. Abbreviations: dimethyl phthalate (DMP); diethyl phthalate (DEP); di-2-ethylhexyl phthalate (DEHP); styrene-butadiene copolymer (SBC); concentration (conc.); standard deviation (SD) confidence interval (CI).

The near ubiquity of phthalates, multitude of sources and ready migration from their host products and materials means that it is complex to determine if the emissions detected by Gadi et al.[85] and Shivani et al.[84] are a result of the open burning of plastic waste. Atmospheric emissions of phthalates may arise from manufacturing processes; vehicle exhausts; interior vehicle components; paints and coatings; plastic items; and agricultural fertilizers and insecticides.[85, 86] Therefore, measured atmospheric concentrations of phthalates are problematic to disaggregate from other emissions sources.

Both Gadi et al.[85] and Shivani et al.[84] used positive matrix factorization to apportion emissions sources to substances measured in $PM_{2.5}$ particles sampled at four locations in North India. The critical emissions factors used to apportion phthalate concentrations are from Simoneit et al.[81], also reported in the present study; indicating that 50-60% of phthalate emissions in the sampled areas originated from the open burning of plastic waste.

Concentrations of ambient atmospheric phthalates reported by Gadi et al.[85] and Shivani et al.[84] were in the order of two to ten times greater than maximum values reported in Paris[86] and comparable with concentrations identified inside ABS-PC and K-Resin extrusion plants that did not implement emissions control measures reported by Huang et al.[88]. Though they are relevant to indoor air in the workplace, the concentrations were very low in comparison to the mean long term Workplace Exposure Limits (WEL) over eight hours of 5,000,000 ng m^{-3} recommended by the United Kingdom's (UK's) Health and Safety Executive[89].

3.5. Potentially toxic elements (PTEs)

Many elements have the potential for toxicity in humans, particularly some metals such as cadmium, lead, chromium and nickel, all of which have the potential to cause cancer.[90] Other elements used in plastics are metalloids, for instance antimony, used as a synergist in BFRs, can irritate the lungs at low concentrations; and arsenic, used in small quantities as a biocide[35] and which can cause vomiting diarrhea and death in extreme circumstances.[91] Collectively, these substances are often discussed as "heavy metals"; however, here we use the term "potentially toxic elements" (PTEs) as suggested by Pourret et al.[92] as a less ambiguous term.

As well as being used as additives to enhance properties in plastics, PTEs are used as catalysts in polymer production[35]. One of the most common examples of a catalyst is Ziegler-Natta that can potentially leave titanium(IV) and aluminum oxide residues within the resulting material, for instance.[93] Several examples also exist to indicate that PTE content in plastic through unintentional contamination, such as during the reprocessing of e-waste or end-of-life vehicles.[90, 94]

Several PTEs are carcinogenic, and thus considered a priority for public health protection such as arsenic, cadmium, chromium, lead, and mercury.[95] The review by Cook et al.[25] revealed that migration to the surface of plastic material is very limited for PTEs in plastic items, even when mouthed by children or aerosolized during mechanical processing of plastic waste. Nonetheless, we have identified three laboratory studies (**Table 4**) which evidence the release of PTEs into the atmosphere in soot (defined as mostly carbonaceous particulate matter from incomplete combustion of hydrocarbons) during plastic waste combustion, from where they may be inhaled; deposited from the atmosphere into soils and water; or deposited in ash. Although all three studies[96-98] were intended to improve the evidence base around PTE emissions from open burning, they all neglected to include information such as: the source of plastics;[96] the composition of the plastics;[97] and the type of plastic, beyond the product description.[98] Concentrations of all PTEs were generally low in all studies, but despite the uncertainties, the presence of PTEs, particularly in soot, poses a health risk through inhalation, particularly to those who are in prolonged, close proximity to open burning activities such as participants in the informal recycling sector (IRS).[99]

Table 4: Potentially toxic elements (PTEs) observed in laboratory scale combustion of plastic materials.

Ref.	Context	Sampling		Substance	Key findings	USMR[#]
Valavanidis et al.[96]	GRC	PS, LDPE, HDPE, PP, PET combusted [a] at 600–750 °C	Soot	Pb, Cd, Cr, Cu, Ni, Zn	Detected low conc.	Q
			Ash	Pb, Cr, Cd, Cu, Ni, Zn	Detected low conc.	
		PVC combusted† at 600–750 °C	Soot	Pb, Ni, Cr, Al, Cu	Detected higher conc. compared to other plastics	
			Ash	Pb, Cr, Ni, Zn	Detected higher conc. compared to other plastics	
Park et al.[97]	KOR	Unspecified plastics combusted	Soot	Pb, Ní, Cu, Cd, Cr, Zn	Detected in PM from combustion of plastic samples	R
				Total PTE	27.09 µg g^{-1} combusted plastic, (compared to 9.7 µg g^{-1} for paper and 8.14 µg g^{-1} for wood)	
Wagner et al.[98]	USA, CHN, VEN	10 samples: rubber soles (n=3), rubber tires (n=2), rubber sole repair compound (n=1), insoles (n=2), printer cartridge (n=1) & PCV tube (n=1)	Soot/ ash	Pb	Detected in 80% of samples	S
				Sb and Cr	Trace or minor conc.	

[a] Samples (n=3 of each polymer) of PS, PVC, LDPE, HDPE, PP, PET (source not stated) combusted at 600-750 °C; ash and soot analyzed for 15 elements (Al, Ba, Mn, Pb, Cr, Cd, Cu, Zn, Ni, Na, Ca, Mg, Fe, Si, P). [#] Uncertainty, strength of knowledge and methodological robustness (USMR) assessed qualitatively. It is assumed that there are no significant concerns unless marked as: Q = source of plastics not stated; R = combustion was under controlled conditions and therefore likely to have underestimated emissions and plastic composition unknown, limiting the usefulness of this analysis; S= study is old and composition of these types of product may have changed since. Only very few results were shown, albeit with very high level of detail. Abbreviations: potentially toxic elements (PTE); Low density polyethylene (LDPE); high density polyethylene (HDPE); polypropylene (PP); polystyrene (PS); polyethylene terephthalate (PET); polyvinyl chloride (PVC).

Very little data is available on the quantity of PTEs emitted from open burning and less so from plastics specifically. The studies by Wiedinmyer et al.[15], Lemieux et al.[14] and Williams et al.[19] only include data on PTEs for mercury (Hg), however, Park et al.[97] combined their analysis with Korean Environment Ministry data of open burning behavior to estimate total “heavy metal” emissions in Korea. The study used three methods to estimate that between 0.03 and 1.16 metric tons per annum PTEs are emitted each year in Korea based on 24% of houses regularly combusting their waste. However, although direct inhalation of PTEs increases the likelihood of harmful health effects,[99] national PTE emission data does not directly indicate exposure to receptors and thus potential harm to public health.

The identification of PTEs in environmental media such as soils, sediments and water provide an indication of transport and accumulation. For instance, Oyegunle[58] sampled soils at open dumping grounds that showed visual evidence of open burning in Canadian First Nation Communities, finding very high concentrations of As, Cr, Pb, Zn and Cu in all samples (**Table 27**). The very high Zn content in these Canadian soils (1,000-10,000 μg g^{-1} soil) is consistent with Park et al.[97] who observed large amounts of Zn in soot from combustion of plastics (max. >65 μg g^{-1}) compared to paper (max. >18 μg g^{-1}); wood (max. >15 μg g^{-1}); and MSW (max. >14 μg g^{-1}). Whereas Zn is essential for human health and only toxic at very high levels, the concentration identified by Oyegunle[58] was more than 30 times the limit of the Canadian Council of Ministers of the Environment (CCME) commercial soil guideline.[100]

Table 5: Element concentrations detected in environmental media near historical plastics recycling area; potentially indicating open burning activities.

					Conc. µg g^{-1}			Soil guideline conc. µg g^{-1}	
Ref.	**Context**	**Sampling**		**Metal**	**Mean (± range)**	**CI**	**Backg'd**	**CAN res. / CHN I**	**CAN com. / CHN II**
				As	5-52[c]		4.3	12[d]	
				Cr	100-310[c]		84.8	64[d]	87[e]
				Pb	120-325[c]		25.5	140[d]	260[e]
				Zn	1,000-9,200[c]		151	200[d]	360[e]
			Garden Hill	Cu	160-800[c]		26.5	63[d]	91[e]
				As	21-56[c]		4.3	12[d]	
				Cr	320-630[c]		84.8	64[d]	87[e]
				Pb	130-230[c]		25.5	140[d]	260[e]
				Zn	4,500–10,000[c]		151	200[d]	360[e]
Oyegunle[58]	CAN[a]	Soil	Wasagamack	Cu	320-630[c]		26.5	63[d]	91[e]
				Cd	0.418	±0.547	0.094	0.2[f]	0.3[g]
				Hg	0.603	±2.224	0.036	0.15[f]	0.5[g]
				Pb	40.4	±35.5	21.5	35[f]	300[g]
			Zhaogezhuang	Sb	3.10	±3.80	1.22	- [f]	- [g]
				Cd	0.337	±0.398	0.094	0.2[f]	0.3[g]
				Hg	0.211	±0.435	0.036	0.15[f]	0.5[g]
				Pb	94.0	±134	21.5	35[f]	300[g]
		Soils	Daliu	Sb	3.6	±6.90	1.22	- [f]	-
				Cd	0.376	±0.428			
			Xiaobaihe River	Hg	0.320	±0.786			
				Cd	1.111	±1.740			
			Renwen Canal	Hg	0.204	±0.285			
				Cd	33.350	±3.551			
Tang et al.[75]	Hebei, CHN	Sed.	Yincun Ditch[h]	Hg	6.402	±6.951			
				As	10.1 (±1.96)		13.6		
				Cd	0.50 (±0.60)		0.094		
				Cr	112 (±22.1)		68.3		
				Cu	54.7 (±93.9)		21.8		
				Hg	0.15 (±0.19)		0.036		
				Pb	71.8 (±106)		21.5		
				Sb	10.6 (±34.9)		1.22		
Tang et al.[101]	Hebei, CHN	Dust	Road S334 (n=20) and residential areas (n=11)	Zn	186 (±346)		78.4		

[a] Garden Hill and Wasagamack First Nations, communities in northern Manitoba, Canada; [b] Wen'an County, northeast Hebei Province, China (main cottage industry plastics recycling area in northern China for >30 yrs); [c] data approximated from chart; [d] CCME soil guideline for residential land[100]; [e] CCME soil guideline for commercial land[100]; [f] Chinese soil guidelines Class I[102]; [g] Chinese soil guidelines Class II[102]; [h] Yuncun ditch is the main effluent outlet from a plastic recycling area; abbreviations: residential (res.); commercial (com.); sediments (Sed.); background (Backg'd); confidence interval (CI); concentration (conc.).

The analysis of soils and sediments in Hebei, China[75] is ambiguous about the specific sources of the PTEs detected, apart from an inference that the concentrations in the Yuncun Ditch may have originated from production catalysts and other additives rather than waste residues. Tang et al.[75] extrapolated the identified concentrations to calculate lifetime health risk from these metal concentrations finding a low non-carcinogenic hazard quotient to adults (reporting arithmetic mean: 0.255), but a considerable risk to children living in the area (1.67). Metal concentrations in dusts analyzed by Tang et al.[101] were also greater than background values, with similar average ratio of non-carcinogenic hazard quotient for adults (0.319) and children (2.06).

In general, elements are deposited in soils at low levels when plastics are open burned; however, over time these low concentrations may accumulate, posing a risk to children who are, in general, more likely to ingest soil compared to adults.[103] Our research has compared a handful of studies that indicate the magnitude of risk from soils contaminated with PTEs from open burning. However, given the prevalence of the activity worldwide, and the potential deleterious and cumulative effects of PTEs in humans, further research should be carried out to develop emission factors that will allow further modelling and extrapolation.

3.6. Dioxins and related compounds (DRC)

"Dioxins" is a term used to describe a group of 419 polychlorinated aromatic compounds, described hereafter as "dioxins and related compounds" (DRCs), which can broadly be classified into three groups:[104]

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

Only around 30 of these substances are considered significantly harmful to health,[105] however, they are persistent in the environment and have a half-life of between 7 and 11 years in the human body.[106] A range of adverse health impacts include short term conditions, such as chloracne (severe skin lesions) and longer-term conditions such as cancers; immunological, developmental, neurological, neurodevelopmental and hormonal disruptions; and reproductive issues.[16]

DRCs are found throughout the environment, but particularly in sediments, soils and non-vegetable foodstuffs.[107] More than 90% of dioxins exposure is thought to be through food, mainly meat, fish eggs and dairy products,[108] with only very small quantities being taken up by plants.[109] Dioxins are often formed through incomplete combustion of materials containing chlorine or other halogens,[110] but also, through non-combustion processes, such as chlorine bleaching of paper or production of some pesticides and herbicides.[107]

While biological material inevitably contains some chlorine that will lead to dioxin production following combustion, anthropogenic materials, such as plastics featuring highly chlorinated polymers (e.g. PVC) and those containing halogenated additives, such as BFRs, are likely to generate significantly more material per unit of mass combusted.[111, 112]

In 1995, controlled combustion of solid waste in incineration plants was reported to be responsible for 69% (wt.) of dioxin emissions worldwide.[105] However, this percentage contribution is likely to be considerably lower today, with many older incineration plants falling out of use, and newer technology being times more capable of emissions abatement. For instance, in the UK, MSW incinerators are estimated to be responsible for approximately only 1% (wt.) of total DRC emissions.[108]

With emissions from incineration largely abated in many countries, open burning has become the focus of increasing attention as a potential major source of DRCs. Fiedler[113] identified open burning of waste as one of the largest sources of DRCs; Zhang et al.[114] reported that open burning contributes to 28% (25th percentile) to 82% (75th percentile) of dioxins reported in 61 national inventories; and Lemieux et al.[14] reported that residential open burning in the US is likely to be one of the main atmospheric sources of DRCs in the country.

To put dioxin release from open burning into context, two authors[57, 115] have modelled emissions, exposure and health impacts from open burning MSW in India and domestic co-incineration of MSW with coal for heating in Poland (**Table 6**). The different types of feedstock modelled make the results hard to compare. However, they both indicate substantial numbers of excess cancer cases that could otherwise be avoided. Given that some estimates (**Table 1**) indicate that 13% wt. to 50% wt. of all MSW is open burned, the scenarios modelled by Kumari et al.[57] may be conservative if applied to other regions.

Table 6: Modelled risk from dioxin emissions from open burning of MSW.

Ref.	**Context**	**Scenarios**			**Substance**	**Excess cancer cases per 100,000 pop.**
Kumari et al.[57]	IND	Ten metropolitan cities	Open burning MSW	10% MSW open burned	PCDD/Fs	0.20
				20% MSW open burned		0.38
		Nationwide		10% MSW open burned		0.06
				20% MSW open burned		0.11
Dziubanek et al.[115]	POL	Upper Silesia	Domestic co-incineration of coal and waste	Winter	DRC	4.5 to 13.2
				Summer		0.9 to 2.1

Kumari et al.[57] findings normalized to 100,000 cases using population. Abbreviations: 2, 3, 7, 8-tetrachlorodibenzodioxin (TCDD); polychlorinated dibenzo-p-dioxins and polychlorinated dibenzo-p-furans (PCDD/Fs); dioxins and related compounds (DRC); municipal solid waste (MSW)

Another relevant study by Kunisue et al.[116] analyzed the human breast and cow's milk of subjects living near dumpsites in India, Cambodia, Vietnam, and the Philippines. The study showed that residents in all countries living near dumpsites were exposed to DRCs. In particular in India, where they were exposed to very high levels, most likely through ingestion of milk from cows that have grazed in exposed areas. The study did not infer open burning as the only potential source of DRCs, but also considered leaching of PCBs from legacy e-waste.

Another indicator of open burning or incineration without emissions abatement can be found by analyzing concentrations in soils and sediments as identified in two studies in Korea and China (**Table 7**). Both Im et al.[117] and Ding et al.[118] found a strong correlation between DRCs concentrations in soils and sediments and open burning or unabated incineration. All levels exceeded Canadian soil guideline values[119] (<4 pg toxic equivalency g^{-1} dry wt.), except for a single sample collected from the top of a mountain; showing that DRCs can travel considerable distances away from open burning activities.

Table 7: Dioxins and related compound (DRC) concentrations in soils in areas surrounding open burning/unabated incineration of solid waste.

				Conc. pg g^{-1} dry wt. soil				
Ref.	**Context**	**Samples**		**PCDFs**	**PCDDs**	**PCDD/Fs**	**I-TEQs**	
		Soil (n=24) samples collected from five locations	Group I: >5,000	15,922	5,786	21,708	2,140	*
			Group II: 1,000–5,000	2,078	1,101	3,179	228	*
			Group III: <1,000	127	94.9	222	8.75	*
Ding et al.[120]	Jiangsu, CHN	Sediment samples (n=6) collected from five rivers or ponds		254	424	677	15.3	*
			Industrial area (n=5)	1,317.2	1,939.8	3,257	46.14	*
			50 m from open burning (illegal) ind. waste incinerator (n=1)	87,249	34,158	121,400	3,720	*
			Top of 200 m mountain (n=1)	11	58	69	0.2	
Im et al.[117]	KOR	Soil	Residential, commercial, and rural areas (n=15)	267	295	561	7	*

* = concentration <4 pg TEQ g^{-1} dry wt. soil the Canadian soil guideline values [119]. Abbreviations: polychlorinated dibenzo-p-dioxins (PCDD); polychlorinated dibenzo-p-dioxins and polychlorinated dibenzo-p-furans (PCDD/Fs); polychlorinated dibenzofurans (PCDF).

3.7. Bisphenol A (BPA)

Bisphenol A (BPA) is a prolific chemical used in vast quantities (4.6 Mt in 2012)[121] as a principal reactant (monomer in PC and epoxy resin production).[122] It is also used as an antioxidant in some plasticizers; a polymerization inhibitor in PVC; and for synthesizing polysulfones and polyether ketones.[123] BPA is ubiquitous in the natural environment and the subject of monitoring studies across the world.[121] BPA is a known endocrine disruptor, as it has been reported cytotoxicity toward living tissue.[35] However, there is disagreement in the scientific community about how long BPA lasts in humans (half-life) and the impacts on human health.[124]

Despite considerable attention,[125] the specific risks of BPA to humans and the environment from plastic waste are not sufficiently quantified. Under complete combustion conditions, bisphenol A (BPA) is destroyed. However, Fu et al.[126] compared atmospheric aerosol samples (n=260) from 25 global locations and found significant quantities from between 2 and ~4,500 pg m^{-3} (**Table S5**, **Section S.8**). The study found a strong correlation between BPA levels and 1,3,5-triphenylbenzene; a marker that indicates the open burning of waste.[127] The inference is that if combustion of waste is incomplete, as is the case with domestic waste burning, then BPA is not always destroyed. Therefore, open burning could be a potential release mechanism for BPA into the atmosphere. Research to date does not quantify the impact of the concentrations reported by Fu et al.[126] on human health, and therefore further study is necessary to determine whether the impact of BPA release from open burning on public health is of concern.

3.8. Polycyclic aromatic hydrocarbons and particulate matter

When plastics are combusted (i.e., at sufficient air availability) at very high temperatures and time, for example, >1,000 °C,[128] they mostly form water and carbon dioxide (complete oxidation of carbon), along with other trace chemicals. However, combustion is rarely complete in open burning, and also other phenomena may occur (evaporation, thermal decomposition, gasification, pyrolysis), resulting in the formation of fine PM, which manifests as solid particles; liquid droplets of PAH; VOCs; tarry hydrocarbons; or a combination of the aforementioned.[36, 129]

3.8.1. Particulate matter (PM)

Solid PM is often expressed in three general categories based on diameter (**Table S7**, **Section S.6**). Whereas atmospheric PM can arise from a variety of sources, hydrocarbon combustion is the main one. Wiedinmyer et al.[15] estimated that approximately 24% wt. (12 billion kg) of all global emissions of PM_{10} and 29% wt. (10 billion kg) of all emissions of $PM_{2.5}$ are a consequence of open burned MSW. $PM_{2.5}$ is estimated to contribute to between 13 and 125 urban deaths per 100,000 people worldwide,[130] and as with other emissions reported, disaggregating the contribution made by plastics has not been attempted.

Black carbon, a subset category of PM, is noteworthy because several studies have suggested it is significantly worse for health than other types of PM.[131-133] Black carbon does not only pose a health risk. Inherently, burning plastic waste contributes to climate forcing, because the majority of plastic items are comprised of fossil carbon; but, this impact is compounded when plastic waste is combusted incompletely, because the black carbon aerosols that are generated have two distinct effects. Firstly, black carbon has its own direct radiative forcing effect; and secondly, black carbon reduces albedo on snow and ice, particularly in polar regions as it reduces the amount of heat being reflected from the earth's surface.[16, 134] Consequently, black carbon may have a global warming potential of 900 (120 to 1800 range) times the global that of carbon dioxide (100-year time horizon).[135]

Two studies[97, 98] identified in this review calculated emissions factors for plastic wastes (**Table 8**). However, both are of limited use for extrapolation, because the waste sources used are either unspecified in the case of Park et al.[97] or highly specific in the case of Wagner et al.[98]. Moreover, Wagner et al.[98] is more than 20 years old and it is possible that the compositions of the various rubber materials investigated have changed over the years. Park et al.[97] found that the mass of PM emissions from plastic waste items are much greater than for paper and wood, also quantified (data not shown), indicating that plastic waste is a key contributor to PM emissions from MSW.

Table 8: Particulate matter (PM) emission factors for plastic waste.

					Emission factors (µg g^{-1} plastic)	
Ref.	**Year**	**Context**	**Samples**	**Particle size (µm)**	**Mean**	**Range / SD**
Park et al.[97]	2013	KOR	Unspecified plastics	TPM	1,700	(+1,600 -1,200)
				PM_{10}	1,500	(+/- 900)
				$PM_{2.5}$	500	(+350 -400)
Wagner et al.[98]	1997	VEN	Rubber sole	TPM (smoke)	5,712	SD 2,485
		CHN	Rubber sole		8,961	SD 2,910
		USA	Rubber sole		6,638	SD 1,438
		USA	Rubber tire (body)		18,105	SD 1,756

Abbreviations: total particulate matter (TPM); standard deviation (SD); particulate matter <10 µm (PM_{10}); particulate matter <2.5 µm ($PM_{2.5}$).

Barabad et al.[136] investigated the effect of heating rate on PM emissions from combusted LDPE samples (**Table S 8**, **Section S.7**), finding that increasing the heat source increased the mass of PMs emitted from the samples in all particle size groups. While Barabad et al.[136], Park et al.[97], and Wagner et al.[98] all provide useful indications of PM emissions, their findings are not sufficient to construct a coherent global model of emissions from open burning of plastic waste to enable a more robust calculation of the overall impact of plastics on public health.

3.8.2. Polycyclic aromatic hydrocarbons (PAHs)

Organic compounds comprised of at least two aromatic rings, joined together, PAHs are generally carcinogenic, with a toxic potency indication of 1 ng m^{-3} benzo(a)pyrene equivalent (BaP_{eq}) concentration leading to 8.7 cases of cancer per one million people exposed.[84] Although only around 100 have been studied and characterized, it is thought that millions of PAH species may theoretically exist.[137]

PAHs have become prevalent throughout the natural environment, and open burning of waste is thought to be a significant source, being responsible for possibly 39% (334 million kg) of global atmospheric emissions.[15] Most PAHs persist in the environment after being deposited from atmospheric aerosol phase into soils and sediments, where they can accumulate.[138, 139]

The majority of open burning emissions studies characterize and quantify emissions from MSW rather than plastic waste specifically. As PAHs are produced through gasification and pyrolysis of biomass and other combustible materials, as well as fossil-engineered plastics, further research is needed to characterize and quantify emissions from plastics specifically. We identified two research outputs that compare PAH concentrations in aerosolized particulate matter and ash from combusted plastics (**Table 9**). The samples of PS and PVC both showed considerably higher PAH emissions compared to the other plastics, as did the mixed samples analyzed by Simoneit et al.[81]; possibly influenced by the high PVC content. The PE bag (likely LDPE) from the US showed the almost undetectable concentrations of PAHs in the PM when self-combusted.

Table 9: Total polycyclic aromatic hydrocarbon (PAH) emissions from plastic waste combustion.

Ref.	Context	Samples	Polymer	Conc. µg g^{-1} total particulate matter: Soot	Ash
Valavanidis et al.[96]	GRC	Spongy light insulating material	PS	1,023	427
		Plastic bottles	PVC	1,205	1,002
		Shopping bags and food wrap	LDPE	517	355
		Trash bags	HDPE	721	355
		Food containers	PP	592	250
		Beverage bottles	PET	363	319
Simoneit et al.[81]		New shopping bags	PE (likely LDPE)	548.8	
		"Roadside trash"	PE 17.3%, PET 29.7%, PVC 39.3%, PS 2.9%, unidentified 10.8%	910.7	
	CHL	"Landfill trash"		523.6	
	USA	New shopping bags	PE (likely LDPE)	4	

Abbreviations: low density polyethylene (LDPE); high density polyethylene (HDPE); polypropylene (PP); polystyrene (PS); polyethylene terephthalate (PET); polyvinyl chloride (PVC); concentrations (conc.).

Analysis of plastics purchased in Korea[97] provided PAH emission factors of 1.94 µg total particulate matter g^{-1} "plastic waste" and 14.35 µg $PM_{2.5}$ g^{-1} "plastic waste", which could enable extrapolation for future modelling efforts; however, the source and chemical composition of the plastic waste was not stated, limiting the usefulness of the results.

Combined with PM solids, PAHs may have a different or potentially greater deleterious effect on health compared to PM alone.[140] Particulates such as $PM_{2.5}$ PAH are carcinogenic and mutagenic;[141] can cause immunological and developmental impairments; and may lead to reproductive abnormalities.[142] Shivani et al.[84] estimated that "plastic and waste burning" (combined) contributes 13.5% of all $PM_{2.5}$ generated and 5.1% of lung cancer cases (5,000 per million population) or 255 cases per million in Indian cities.

Air pollution is thought to be responsible for as many as 3.7 million deaths per year[19] and speculatively, PAHs from open burning of plastic waste may make a contribution towards them. However, disaggregating PAH emissions produced when plastic waste is open burned from the multitude of other potential sources is problematic. Moreover, the paucity of reliable emission factors combined with poor knowledge of the amount of plastic waste being burned, means that accurate modelling of risk to human populations is almost impossible with the current state of knowledge. This lack of data, combined with the potential hazardousness of PAHs, emphasizes the need for specific characterization of emissions from the open burning of plastic waste, suitable for improving conceptual and quantified modelling of PAH emissions.

3.9. Risk characterization for open burning of plastic waste

The semi-quantitative risk assessment of plastic waste and open burning resulted in the identification of 18 hazard-pathway-receptor combinations involving seven substance groups detailed in **Table 10** and summarized and ranked in **Section S.3, Table S 4**. Members of the IRS were identified as being particularly vulnerable to emissions exposure from open burning as they often work on dumpsites that have been deliberately or accidentally ignited[143]. Moreover, waste pickers have been reported to burn residues of plastics and other wastes that are no longer required, either deliberately for fuel, warmth or insect repellence, or as a method of disposal. PM, PAHs, DRCs were all identified as posing a high risk to the IRS working in those contexts due to their sustained proximity. Both PAHs and PM were identified as posing a high risk to the population in areas where open burning takes place. These scores are evidenced through several studies that have quantified carcinogenic and non-carcinogenic risk.

DRCs were also assessed to pose a high carcinogenic risk to the population, not only through direct inhalation from the atmosphere, but also through deposition to soil and subsequent uptake in food or livestock. Children were assessed to by susceptible to high risk from DRCs, as they are likely to ingest larger quantities of soil that they enjoy placing in their mouths.[144]

Though there is evidence for BPAs near-ubiquity on earth, the evidence to link the concentrations observed to negative health outcomes is insufficient to carry out an indicative risk assessment, such as that presented here. Therefore, BPA hazards were not scored in this assessment.

Table 10: Risk characterization summary for open burning of secondary plastics.

Haz.	Pathway	Receptor	Geog.	Evidence & justification for risk assessment	Notable material/ polymer/ substance	Uncertainty (aleatoric & epistemic)	Receptor vulnerability	L	S	R	Global receptor context
	Atmosphere/ inhalation; uptake in food	Population		• Analysis of BFR conc. in plastic wastes and subsequent modelling of emissions in China indicate widespread release of BFRs into the environment from incineration.[71] Soil[74] and dust[75] concentrations indicate deposition from ambient atmosphere which may lead to uptake into crops.	PS, PVC, PE	• Limited direct evidence to assess occupational and public health risk from BFRs, so can only be inferred through qualitative adductive reasoning.	• Population living in proximity to open burning activities may be more exposed.	3	4	**12**	Population living without comprehensive waste collection in LIMICs
	Soil/ mouthing	Children			PS, PVC, PE	• No direct evidence of exposure to children, so inferred risk through qualitative adductive reasoning.	• Children are more vulnerable to exposure due to lower body weight and propensity for mouthing.	3	4	**12**	Children living in proximity to open burning in LIMICs
BFR	Atmosphere/ inhalation	Workers (informal)	CHN	• Analysis of BFR conc. in plastic waste and subsequent modelling of emissions in China indicate widespread release of BFRs into the environment from incineration plants in China.[71] • Informal workers likely to be disproportionately affected as participants operate in proximity to significant open burning.	PS, PVC, PE	• No direct evidence of exposure to informal workers, so inferred risk through qualitative adductive reasoning.	• IRS workers are acutely vulnerable to open burning at close range as they often work on dumpsites set on fire, and burn as a method of residue disposal or to recover other materials such as metals, and even to keep away mosquitos.	4	5	**20**	IRS workers on dumpsites and where residues are burned in LIMICs
Phth.	Atmosphere/ inhalation	Population	IND, CHN	• Ambient atmospheric concentrations in open burning areas comparable[84, 85] with concentrations inside extrusion	PVC, PC-ABS, K-resin	• Though atmospheric levels higher in exposed areas, not contextualized with air guidelines.	• Population living in proximity to open burning activities may be more exposed.	2	4	**8**	Population living without comprehensive waste collection in LIMICs

Haz.	Pathway	Receptor	Geog.	Evidence & justification for risk assessment	Notable material/ polymer/ substance	Uncertainty (aleatoric & epistemic)	Receptor vulnerability	L	S	R	Global receptor context
		Workers (informal)		plants[88] and 2–10 times greater than maximum values reported in Paris[86] where limited open burning takes place. • 50-60% of phthalate contributions in open burning areas modelled to originate from plastic waste burning.[84, 85]		• Though atmospheric levels higher in exposed areas, not contextualized with air guidelines. • Risk not quantified.	• IRS workers are acutely vulnerable to open burning at close range as they often work on dumpsites set on fire, and burn as a method of residue disposal or to recover other materials such as metals, and even to keep away mosquitos.	3	4	**12**	IRS workers on dumpsites and where residues are burned in LIMICs
	Soil/ mouthing	Children		• Deposition to soil and waterbodies[145] indicated in plastics recycling area could be a consequence of extrusion and/or open burning.		• No direct evidence of exposure to children, so inferred risk through qualitative adductive reasoning.	• Children are more vulnerable to exposure due to lower body weight and propensity for mouthing.	2	4	**8**	Children living in proximity to open burning in LIMICs
BPA	Atmosphere/ inhalation	Population	IND, CHN, JPN, NZL Indian, Atlantic and Pacific Oceans and Polar Regions	• Causal inference between open burning of plastics and high BPA concentrations in the atmosphere,[126] however then health implications of these concentrations are unknown.	Epoxy resin & PC	• Although link established between high atmospheric concentrations and open burning identified, the health impacts of these concentrations are unknown.	• Potentially entire global urban population vulnerable.	na	na	**na**	Population living without comprehensive waste collection in LIMICs
		Workers (informal)					• IRS workers are acutely vulnerable to open burning at close range as they often work on dumpsites set on fire, and burn as a method of residue disposal or to recover other materials such as metals, and even to keep away mosquitos.	na	na	**na**	IRS workers on dumpsites and where residues are burned in LIMICs

Haz.	Pathway	Receptor	Geog.	Evidence & justification for risk assessment	Notable material/ polymer/ substance	Uncertainty (aleatoric & epistemic)	Receptor vulnerability	L	S	R	Global receptor context
	Atmosphere /inhalation; soil/uptake in food	Population				• PTE emissions pose a risk to health and the environment, resulting in a variety of negative health impacts and potential to accumulate in biota. However exposure from open burning plastic waste not quantified and risk not calculated.	• Population living in proximity to open burning activities may be more exposed.	na	na	**na**	Population living without comprehensive waste collection in LIMICs
	Atmosphere/ inhalation	Workers (informal)		• Laboratory emissions observed[96-98] show metals are emitted when plastics are combusted, albeit in generally low concentrations. • Reasons to believe that PTEs are emitted through open burning by assessing evidence of concentrations in soil dust and sediment.[58, 75, 101]		• Although not quantified, the potential health risk through inhalation, in the case of prolonged, close proximity to open burning activities sufficient to score through qualitative adductive reasoning.	• IRS workers are acutely vulnerable to open burning at close range as they often work on dumpsites set on fire, and burn as a method of residue disposal or to recover other materials such as metals, and even to keep away mosquitos.	3	4	**12**	IRS workers on dumpsites and where residues are burned in LIMICs
PTE	Soil/ mouthing	Children	GRC, KOR, USA, CHN, VEN, CAN	• Soil concentrations of PTEs linked directly to open burning[58] and inferred circumstantially.[75, 101] • Non-carcinogenic hazard quotient for children at mean 1.67[75] and 2.06[101] for soil and dusts respectively.	Higher conc. detected in PVC waste compared to polyolefins and PET sampled[96]	• Though based on specific conditions in one area of China, it is reasonable to assume similar conditions throughout other areas of LIMICs where similar industry exists.	• Children are more vulnerable to exposure due to lower body weight and propensity for mouthing.	3	4	**12**	Children living in proximity to open burning in LIMICs

Haz.	Pathway	Receptor	Geog.	Evidence & justification for risk assessment	Notable material/ polymer/ substance	Uncertainty (aleatoric & epistemic)	Receptor vulnerability	L	S	R	Global receptor context
DRC	Atmosphere /inhalation; soil/uptake in food	Population	IND, POL, CHN, KOR	• Open burning is considered the largest source of dioxin release.[14, 113, 114] The contribution made by plastic waste is from mainly PVC and brominated flame retardants[110] which contain the relevant halogens but the proportion of emissions from plastic waste is not well reported. • Emissions are linked to open burning activities in cow's milk, human breast milk[116] and soil.[117, 120] • Estimated population cancer rates reported from MSW Kumari et al.[57] and domestic co-combustion with coal[115] - ca. 0.2 - 13 cases of cancer per 100,000 people - not allocated for plastic.	Halogenated plastics such as PVC, PVB, BFRs	• Not possible to disaggregate the contribution of plastic waste to these emissions.	• Population living in proximity to open burning activities may be more exposed.	3	4	**12**	Population living without comprehensive waste collection in LIMICs
	Atmosphere /inhalation	Workers (informal)		•			• IRS workers are acutely vulnerable to open burning at close range as they often work on dumpsites set on fire, and burn as a method of residue disposal or to recover other materials such as metals, and even to keep away mosquitos.	4	4	**16**	IRS workers on dumpsites and where residues are burned in LIMICs
	Soil/ mouthing	Children		• Soil concentrations[117, 120] in open burning areas exceeded Canadian soil guidelines by several thousand times in many cases posing significant risk to children living near open burning activities.		•	• Children are more vulnerable to exposure due to lower body weight and propensity for mouthing.	4	4	**16**	Children living in proximity to open burning in LIMICs

Haz.	Pathway	Receptor	Geog.	Evidence & justification for risk assessment	Notable material/ polymer/ substance	Uncertainty (aleatoric & epistemic)	Receptor vulnerability	L	S	R	Global receptor context
	Atmosphere /inhalation; soil/uptake in food	Population	KOR, VEN, USA, CHN	• Though the contribution of plastic waste is not known, open burning of all MSW is estimated[15] to contribute 24% of PM_{10} and 29% of $PM_{2.5}$ emissions. • Deaths from $PM_{2.5}$ are estimated at between 13 and 125 per 100,000 people in urban areas, therefore uncontrolled plastic waste combustion is likely to be a significant contributor.	All plastics at risk of open burning	• Not possible to disaggregate the contribution of plastic waste to these emissions.	• Population living in proximity to open burning activities may be more exposed.	4	4	**16**	Population living without comprehensive waste collection in LIMICs
PM	Atmosphere/ inhalation	Workers (informal)	KOR, VEN, USA, CHN				• IRS workers are acutely vulnerable to open burning at close range as they often work on dumpsites set on fire, and burn as a method of residue disposal or to recover other materials such as metals, and even to keep away mosquitos.	4	4	**16**	IRS workers on dumpsites and where residues are burned in LIMICs
		Population					• Population living in proximity to open burning activities may be more exposed.	4	4	**16**	Population living without comprehensive waste collection in LIMICs
PAH	Atmosphere/ inhalation	Workers (informal)	GRC, CHL, USA, KOR	• Most PAHs are carcinogenic with a toxic potency indication of 1 ng m^{-3} BaPeq concentration leading to 8.7 cases of cancer per million people exposed.[84]	PVC, PS	• Not possible to disaggregate the contribution of plastic waste to these emissions	• IRS workers are acutely vulnerable to open burning at close range as they often work on dumpsites set on fire, and burn as a method of residue disposal or to recover other materials such as metals, and even to keep away mosquitos.	4	4	**16**	IRS workers on dumpsites and where residues are burned in LIMICs

Abbreviations: likelihood (L); severity (S); risk (R); hazard being assessed (Haz.); phthalates (Phth.); geographical research context (Geo.); not available (na); polystyrene (PS); polycarbonate (PC); polyethylene terephthalate (PET); polyethylene (PE); polycarbonate/acrylonitrile-butadiene-styrene (PC-ABS); styrene-butadiene copolymer (K-resin); polyvinyl chloride (PVC); polyvinyl butyral (PVB); brominated flame retardants (BFR); low income and middle income countries (LIMIC); informal recycling sector (IRS); phthalates (Phth.); bisphenol A (BPA); potentially toxic elements (PTE); dioxins and related compounds (DRC); circa (ca.); brominated flame retardants (BFR); particulate matter (PM); particulate matter < 10 µm (PM_{10}); particulate matter < 2.5 µm ($PM_{2.5}$);polycyclic aromatic hydrocarbons (PAH); benzo(a)pyrene equivalent (BaPeq).

4. Outlook and prospects

Increasing quantities of uncollected solid waste will result in a continuation of the need to self-manage discarded material that is generated by billions of households and business across LIMICs in the coming decades. The choices are stark: burn, bury, deposit on land or into water. If the most pessimistic estimates are to be believed, nearly a billion tons of solid waste is burned every year in open, uncontrolled fires, much of which is plastic waste. When plastic waste is combusted, a range of unbound substances of concern (BFRs, PTEs, BPA, and phthalates), added either intentionally or unintentionally, may escape destruction and be released into nearby media such as the atmosphere and surrounding land. In addition, there are substances and particles that are produced as a result of chemical transformations that take place in variable, low temperature conditions that are inevitable within open, uncontrolled fires (PM, PAHs and DRCs). Here, we have systematically collected and arranged key sources that evidence these emissions (**RQ1**), the risks they pose to human health and the pathways through which the harm is realized, creating a generalised conceptual description (**Figure 2**) – but only 20 publications made it to our inclusion list; and this despite not including upfront rejection based on research quality criteria.

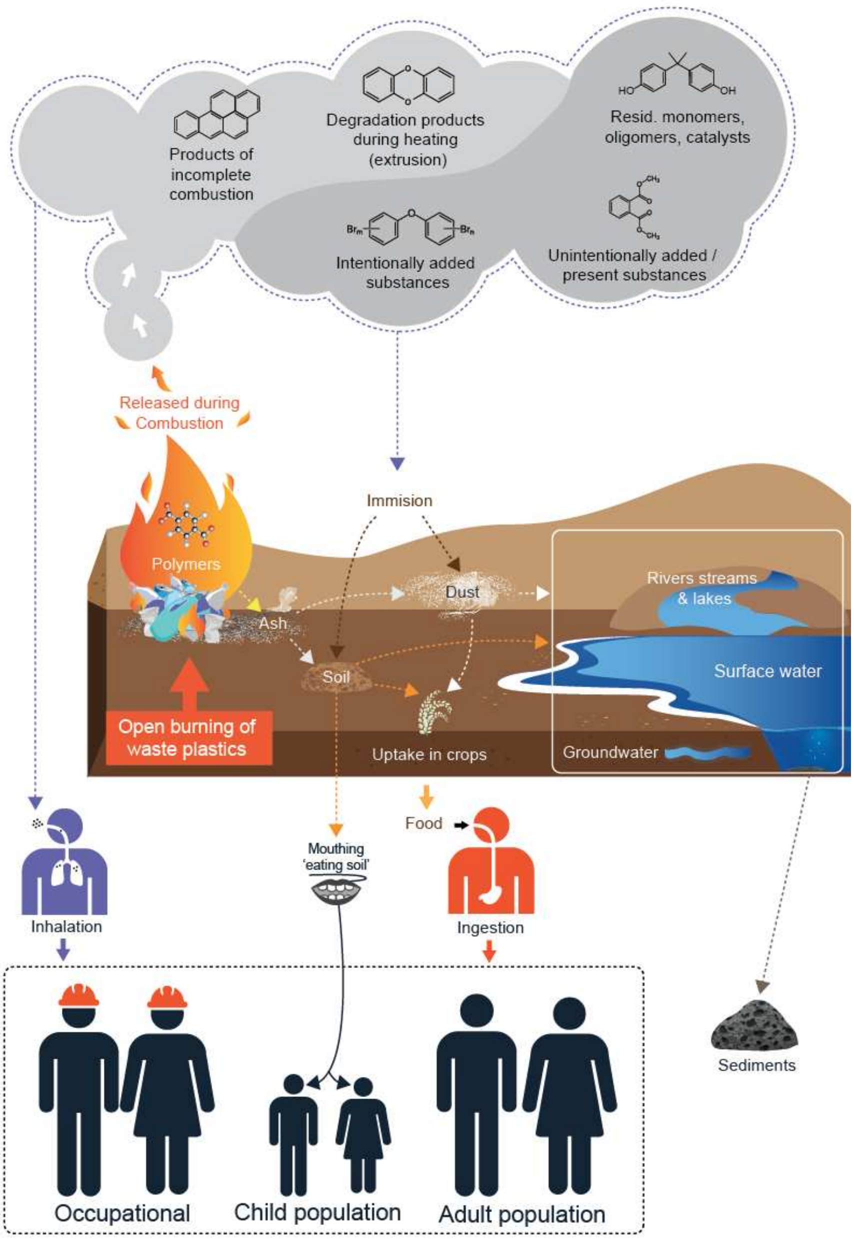

Figure 2: Graphical overview of the hazard exposure conceptual model (hazard – pathway – receptor) associated with open (uncontrolled) burning of plastic waste (from substances contained and combustion products), as indicated by the review of 20 literature sources eligible for the inclusion criteria in this systematic review.

Our risk-based approach highlighted 18 main hazard-pathway-receptor combinations, seven of which were scored as having high harm potential and six which were scored as having medium/high harm potential (**RQ2**). However, though we are confident with these indicative conclusions, the underlying research-base is extremely limited in several key areas, as directly implied by the paucity of relevant research (**RQ3**). Not least, we found little strong evidence to confidently estimate the mass of plastic waste or/and mixed waste that is open burned, beyond simple calculations that rely on bold assumptions. Only one city-scale study into open burning based its findings on observed behavior, whilst the majority were reliant on surveys, but more commonly, expert judgement or industrial opinion that was subject to potential bias.

Overwhelmingly, the scores indicated a higher risk of harm to human health in LIMICs compared to HICs. Within these the most sensitive receptor was waste pickers (informal waste reclaimers, IRS), a large global workforce of proud day-to-day survivors and entrepreneurs who operate without safe systems of work and who may carry out approximately half of all the world's recycling collections.[146] Despite this tremendous contribution to the global circular economy, waste pickers work in conditions that directly threaten their health along with the health of their families, who have few choices about where they live and work.

The quality of information we reviewed was assessed via an uncertainty, strength of knowledge and methodological robustness matrix and was found to be mixed, with only a subset of clearly presented studies - for example, identifying substance concentrations occurring in environmental media and humans. Overall, many of the studies fell short of identifying or attempting to identify causal linkages between the occurrence of a substance and receptor response, inferring exposure pathways rather than demonstrating a clear and verifiable connection between system components. In many studies, the source of substances identified in environmental media or humans was not determined, leaving some doubt over whether the source was waste plastics processing, open burning, or some other confounding source.

Resultant risks to human health may be comparatively small, yet not sufficiently quantified to be dismissed. Most worryingly, without substantial action, the health of those exposed to open burning of plastics, mainly waste pickers and wider communities in geographic proximity, could suffer substantial negative health effects; yet, it remains largely ignored and substantially under-researched.

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.

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Supporting Information

In the Supporting Information, we present on: (i) Choices on the application of the systematic review, including Boolean search queries, inclusion and exclusion criteria, and overview of results and stages (Error! Reference source not found.); (ii) Matrices used for the risk based approach (Error! Reference source not found.); (iii) Aggregated risk characterization (Error! Reference source not found.); (iv) Reference concentration and definition tables (Error! Reference source not found.-Error! Reference source not found.).

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