From dumpsites to engineered landfills: A systematic review of risks to occupational and public health

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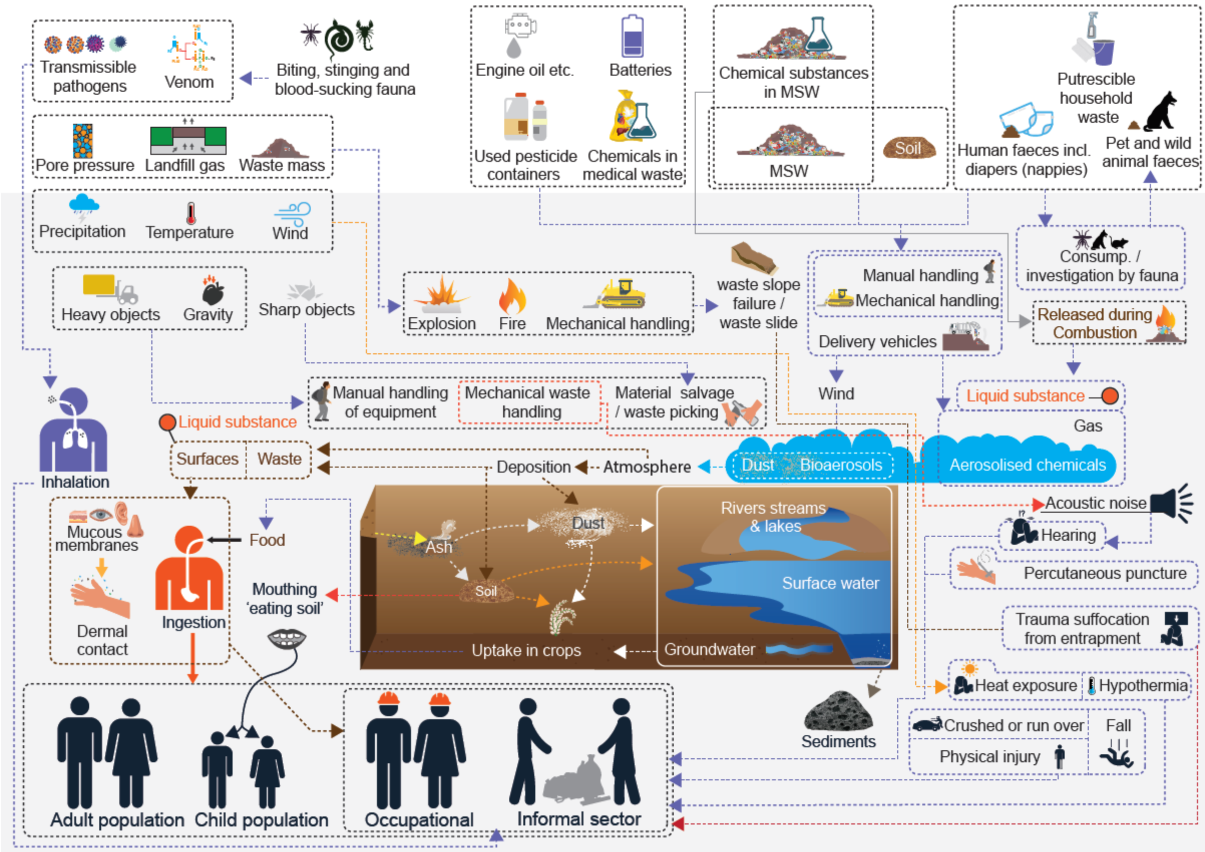
Abstract

Disposal on land has persisted as the most predominant form of waste disposal for millennia and despite advances in modern engineered landfills, large quantities (405 Mt y^{-1}) of collected municipal solid waste (MSW) are still deposited and concentrated in open, uncontrolled dumpsites throughout low- and middle-income countries (LIMICs) worldwide – a key form of waste mismanagement. These pose major threats to the health and safety of surrounding populations and mainly waste pickers who across the Global South target dumpsites to salvage and recycle under minimal protection measures. Here, we conducted an adapted PRISMA systematic review, distilling over 3,000 papers into 40 core sources from 22 countries, to critically assess the evidence on the associated risks. We identified prevalent hazard-pathway-receptor combinations and subsequently scored, compared and ranked the relative risk of exposure to harm experienced by various actors in land disposal sites. Our assessment indicates high risk levels experienced through interaction with medical waste, emissions from waste combustion, and critically through the fatal risk of waste slope failure, claiming the lives of at least (on average) of 34 people per year since 1992. Despite the strong anecdotal signals on the generic nature of the health and safety challenges at hand, many of the sources lack critical information with which to determine and link causality of health effects with the existence, or even exposure to emissions or other hazards. Yet, our critical analysis clearly demonstrates an unacceptable potential for damage to human health and safety; alerting us on the need to close, and immediately manage risks at dumpsites, preventing harm to some of the worlds' poorest inhabitants. Our aspiration is that quantification and mitigation of risks from dumpsites attracts substantial and scientifically robust efforts.

Keywords: Disposal, Human health, Public health, Waste, Waste Pickers

Graphical abstract



Abbreviations

AIDS	acquired immunodeficiency syndrome
BDEs	brominated diphenyl ethers
BFR	brominated flame retardants
Cd	cadmium
CDC	Centers for Disease Control and Prevention
CFU	colony forming units
dBA	A-weighted decibels
DRC	dioxins and related compounds
EU	endotoxin units
f	frequency
Fe	iron
fw	fresh weight
Geog.	geographical location of study
GNB	Gram negative bacteria
Hg	mercury
HIC	high income countries
HIV	human immunodeficiency virus
H-P-R	hazard-pathway-receptor
IgG1	Immunoglobulin G1
L	likelihood
LIC	low income countries
LIMIC	low income and middle income countries
LMC	lower middle income countries
lw	lipid weight
MSW	municipal solid waste
n	number of samples
NO_2	nitrogen dioxide
OCPs	organochlorine pesticides
PAHs	polycyclic aromatic hydrocarbons
Pb	lead
PBDE	polybrominated diphenyl ethers
PCP	pentachlorophenol
PCBs	polychlorinated biphenyls
PM_{10}	particulate matter > 10µg
R	risk
S	severity
Se	selenium
SO_2	sulphur dioxide
TSM	total suspended matter
TVB	total viable bacteria
TWA	time weighted average
UK	United Kingdom
UMC	upper middle income countries
US	United States
USMR	uncertainty, strength of knowledge and methodological robustness
γ-HCH	gamma-hexachlorocyclohexane
4,4’-DDE	dichlorodiphenyldichloroethylene
4,4′-DDT	dichlorodiphenyltrichloroethane

1. Introduction

For millennia, items, objects, materials and substances have been placed on, or in a depression or fissure in land when they are no longer required (Rodríguez, 2012), a method that is still one of the most short-term cost-effective (in the short-term) and accessible forms of waste disposal practiced worldwide. Lacking any form of further protection, beyond existing topographical features, a facility that harbours waste in this way is known simply as a dumpsite (or open dump), an unsophisticated and occasionally inevitable response to the increasing burden of waste generation, still implemented in countries where the resources to provide more advanced facilities are lacking (Yin et al., 2020).

Historically, small scale accumulations of mainly biological and mineral waste have presented only basic public health challenges. However, the comparative impacts of the large concentrations of waste in some modern facilities are profound (Mavropoulos, 2015). The anoxic environment typical of land disposal sites, together with the high putrescible content and complex, heterogeneous mixture of other materials and substances results in the generation of gasses, and leachate that can pollute our land, water and air if left unmanaged (Christensen et al., 2011c; Tchobanoglous et al., 1993). Alongside these biological and chemical challenges, materials that are light or buoyant enough to be affected by wind and water, may be carried away from the place where they were originally deposited and into the environment (Yadav et al., 2020).

The engineering response to mitigate these challenges is the controlled, engineered landfill, a concept and reality that has evolved over recent decades to offer maximum environmental and public health protection. Engineered landfills, sometimes described as 'sanitary landfills' implement barriers and processes to protect and manage the interaction between waste and the surrounding environment. These approaches include: multi-layer liners; leachate capture, treatment and / or recirculation systems (Christensen et al., 2011a; Christensen et al., 2011b); pipes to capture the methane, carbon dioxide and other trace landfill gasses that are in turn, used to power spark diesel engines and convert the combustible fraction into electricity (Qin et al., 2001); cells to prevent interaction between wastes that might react (Pichtel, 2014); daily cover with nets, soil or aggregate to deter vectors and prevent material escaping (Carson, 1992; Querio and Lundell, 1992); intermediate cover to enhance the daily cover properties and reduce infiltration and gas escape (Nolan and Campbell, 2014); and sealed with a semi-impermeable cap to reduce infiltration, prevent gas escape and provide longlasting encasement for the materials stored within (Scheutz and Kjeldsen, 2011).

Although basic sanitary (engineered) landfill technology has existed for some decades, contemporary fully engineered, controlled landfills require substantial additional resources to implement in comparison to a dumpsite, and in many parts of the world, the money, know-how or will is lacking (Rushbrook, 2000; Wilson et al., 2015). Of the 2 billion tonnes of municipal solid waste (MSW) generated globally, annually, approximately half is collected and deposited on land, of which 60% is reported to be deposited in landfill sites and 40% in 'open dumps' or 'dumpsites' (Kaza et al., 2018). However, the origin of these waste management data is varied, and there is no harmonised definition of what constitutes a dumpsite and an engineered landfill. Here we use the term 'dumpsite' and 'open dump' interchangeably to describe a facility on land where collected waste is deposited and concentrated, and where engineering controls to contain it are largely absent according to a definition for 'open dump' suggested by International Solid Waste Association (2007).

In practice, there are hundreds of permutations of land disposal types that range from the completely negligent scattering of waste through to the most advanced and controlled engineered landfill. Therefore, it is near impossible to estimate the amount of waste that is deposited in different types of facility, as the data are reported by a variety of actors, including governments, scientists and consultants, all of whom may have a different definition in mind. Countries such as Japan (Amemiya, 2018; Tabata and Tsai, 2015), Korea (Bourtsalas et al., 2019) and many in Europe (Blasenbauer et al., 2020) have begun to move away from land disposal in favour of energy recovery and recycling. Nonetheless, land disposal, including dumpsites are likely to continue as the predominant form of waste management for many years to come, due to their low costs and relative ease of implementation (Lau et al., 2020).

As with the different levels of engineering and management practices implemented to control waste emissions, there is also high global variability in the way that occupational safety is managed for the 4.3 million people who work, and sometimes live, on land disposal sites (**Section S.3**). The overwhelming majority of these workers (98%) are informal workers (waste pickers – informal recycling/waste reclamation sector, IR: also known locally as Portuguese: Catadores; Spanish: Cartoneros), independent and sometimes organised entrepreneurs, who make a living or supplement income through the reclamation and sale of materials recovered from the piles of waste (Navarrete-Hernandez and Navarrete-Hernandez, 2018). Inherently, these workers interact closely with the waste, walking and climbing through highly heterogeneous mixtures of materials and objects, risking encounter with unknown articles that may lie beneath the surface or which may be revealed as they forage for value (Schenck et al., 2019). It is common to see waste pickers on disposal sites, working extremely close to manoeuvring machinery and waste delivery vehicles (AP Archive, 2019), who's drivers may not see or care to see those working in close proximity, risking serious accident (Al-Khatib et al., 2020; Cointreau, 2006).

On mass, piles of waste can also have catastrophic consequences if they become unstable (Lavigne et al., 2014). There have been multiple incidents over recent decades that have resulted in the deaths of many hundreds of people who work on dumpsites or live nearby (Blight, 2008; Lavigne et al., 2014; Yoshida, 2018). It is worth noting that many dumpsite workers also live in their place of work, along with their families, including children, and that those who live closest to dumpsites may also be the poorest and least able to recover or mitigate the negative impacts of their proximity to these facilities (Raviteja and Basha, 2017).

'Waste management' and safety is a topic that has been systematically reviewed by several authors. Both Porta et al. (2009) and Ncube et al. (2017b) reviewed epidemiological studies of occupational and public health concerns relating to the full waste management system, including collection, transport, treatment, disposal and recycling of waste. In another systematic review, Mattiello et al. (2013) summarised the evidence for health effects to populations living in areas surrounding landfill and incineration sites. The study qualitatively assessed the validity of the reviewed studies, but was unable to 'define the relationship' between the processes being studies and the health effects reported. Of these three systematic reviews, only Porta et al. (2009) quantitatively evaluated the relative level of risk for each health effect in relation to landfill and incineration, based on just three of the studies and only in relation to the nearby population. All three of the reviews have highlighted the difficulty of determining a causative relationship between the waste management operations and the observed health effects due to lack of control by the authors for confounding factors such as smoking, alcohol consumption, age, gender, education and the length of time they had worked in or around the waste management operation.

More detailed summations of evidence for health and safety on land disposal sites are included as part of generic waste management reviews such as Cointreau (2006), Giusti (2009), Ferronato et al. (2019), Wilson et al. (2015) and Searl and Crawford (2012); but, whereas data and narrative are very detailed in each of these, data were not systematically obtained.

Surprisingly few reviews exist that focus on health and land disposal sites specifically. Possibly the most comprehensive assessment of potential exposure was carried out by Broomfield et al. (2010), who analysed multiple atmospheric and liquid emissions data from landfill sites in the UK, providing detailed indications of potential exposure to residents living in proximity as well as workers in a high income country (HIC) context. In the low-income and middle-income country (LIMIC) context, Levis et al. (2017) also comprehensively investigated water and airborne emissions, this time from uncontrolled land disposal sites (dumpsites). The review provided some valuable emissions data but very little on the wider phenomenon such as open burning, accidents and the occupational health effects of the various emissions, some of which are briefly summarised in a short conference paper from Yadav et al. (2019).

Several non-academic studies have also reviewed evidence, specifically on dumpsites, such as Mavropoulos (2015) and International Solid Waste Association (2016) in an effort to raise the public profile of the considerable risks that these facilities posed to human health. However, as yet, there appears to be no systematic attempt to review and evaluate the evidence for health effects from land disposal as a distinct category. This surprising paucity of systematically arranged evidence presents a considerable challenge for actors who want to design actions to protect the health and wellbeing of nearby populations and the large and vulnerable workforce (mainly waste pickers) who work on land disposal sites, often without personal protective equipment (PPE) or safe systems of work in place (Schenck et al., 2019) .

Here, we aim to address this gap in the scientific record, following adapted PRISMA guidelines to collect and organise data relevant to the on-land solid waste disposal topic. We arrange this review by summarising the key sources, hazards, risks and pathways identified in the literature into a series of prevalent combinations experienced ‘on-the-ground’, and grouped intuitively into six challenges so as to make them accessible and digestible. Namely: Challenge 1) biological hazards (**Section 3**); Challenge 2) potentially hazardous chemical substances (**Section 4**); Challenge 3) combustion (**Section 5**); Challenge 4) physical injury and hearing loss (**Section 6**); Challenge 5) meteorological and geophysical hazards (**Section 7**); and Challenge 6) psychosocial hazards (**Section 8**). These six groups are chosen, not because they represent a comprehensive list of risks and hazards associated landfill, but because they represent what has been reported. Where possible, gaps in understanding have been highlighted, however this review does not purport to provide an exhaustive and comprehensive assessment of what is experienced in reality.

The review encompasses all aspects of the land disposal system as shown in **Figure 1**, with a strong emphasis on LIMICs where the majority of the (mostly informal) workforce exists, focussing mainly on the occupational safety, whilst including public health as a secondary concern. Although leachate and groundwater contamination is included within the system boundary, we have chosen to touch on it only briefly, as there are already several reviews, such as Vaccari et al. (2019) and Madon et al. (2019), and for which we suggest a specialist review is more appropriate. We also, deliberately, exclude uncollected waste that has been deposited on land because by definition, it does not arrive on dumpsites, and has a range of health implications that deserve a separate specialist review.

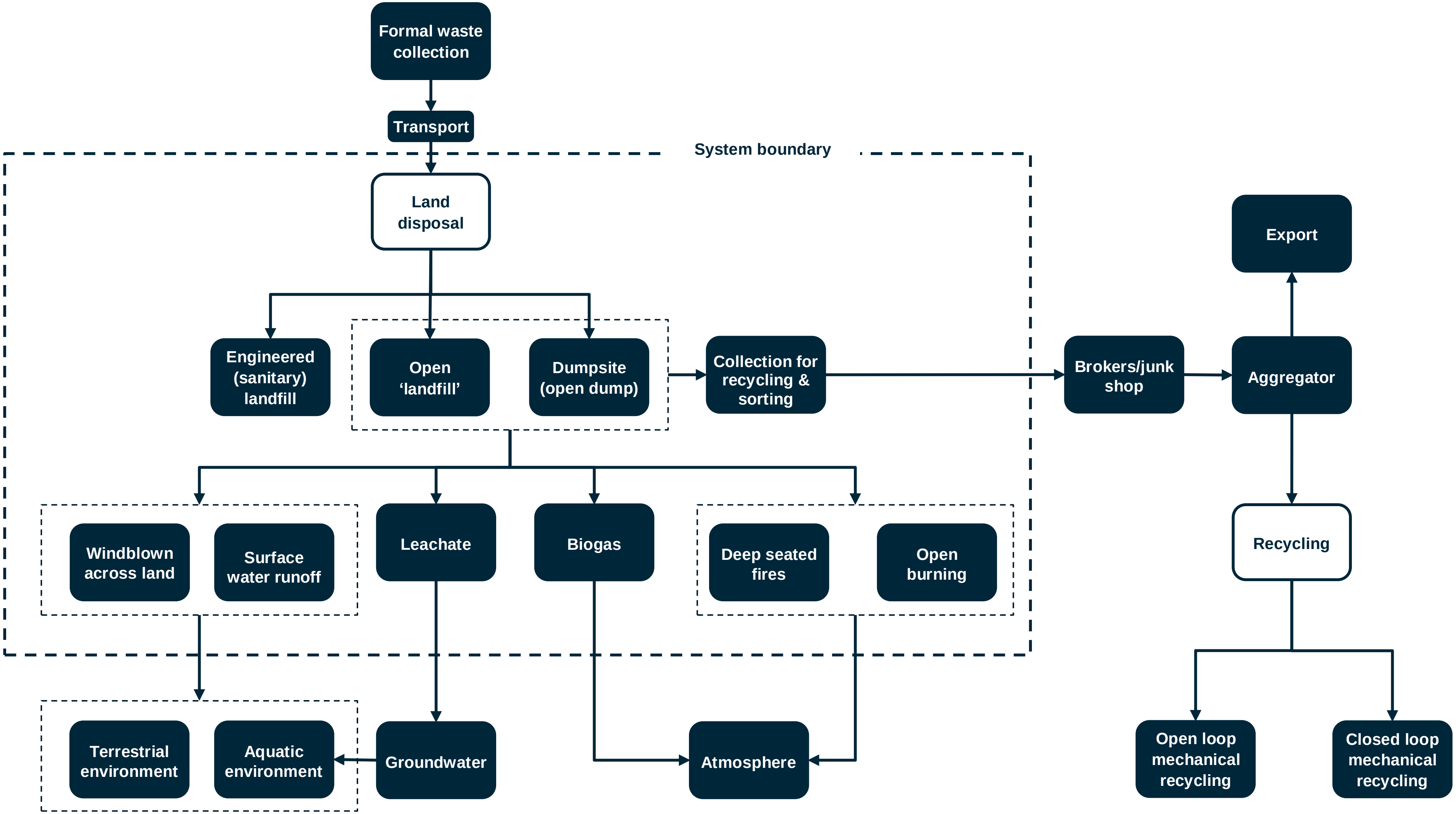


Figure 1: Land disposal system for mixed municipal solid waste (MSW).

2. Methods

2.1. Systematic review

The systematic review followed methods reported by Cook et al. (2020) adapted from PRISMA guidelines (Moher et al., 2009). The following three research questions (RQ) were used as a guide to the study:

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

Three databases were searched, Scopus, Web of Science and Google Scholar, using Boolean queries shown in Supporting Information (SI) **Section S.1.1**. Exclusion criteria are detailed in **Section S.1.2** and the basic statistical results are in **Sections S.1.3** and **S.1.4.** One at a time sensitivity analysis was used to obtain the optimum result pool using the fewest terms. Further sources were identified through snowball and citation searching (Cooper et al., 2018) and through searching websites such as International Labour Organization (2020), The World Bank (2020), World Health Organization (2020), and Health and Safety Executive (2020) (HSE).

Risks, hazards, pathways and receptor combinations were arranged according to realistic scenarios reported in the literature, as described by Cook et al. (2020), grouped into 6 ‘challenges’ and then mapped onto source-pathway-receptor diagrams illustrating hazard flow to receptors, as demonstrated by the unified diagram in Figure 2.

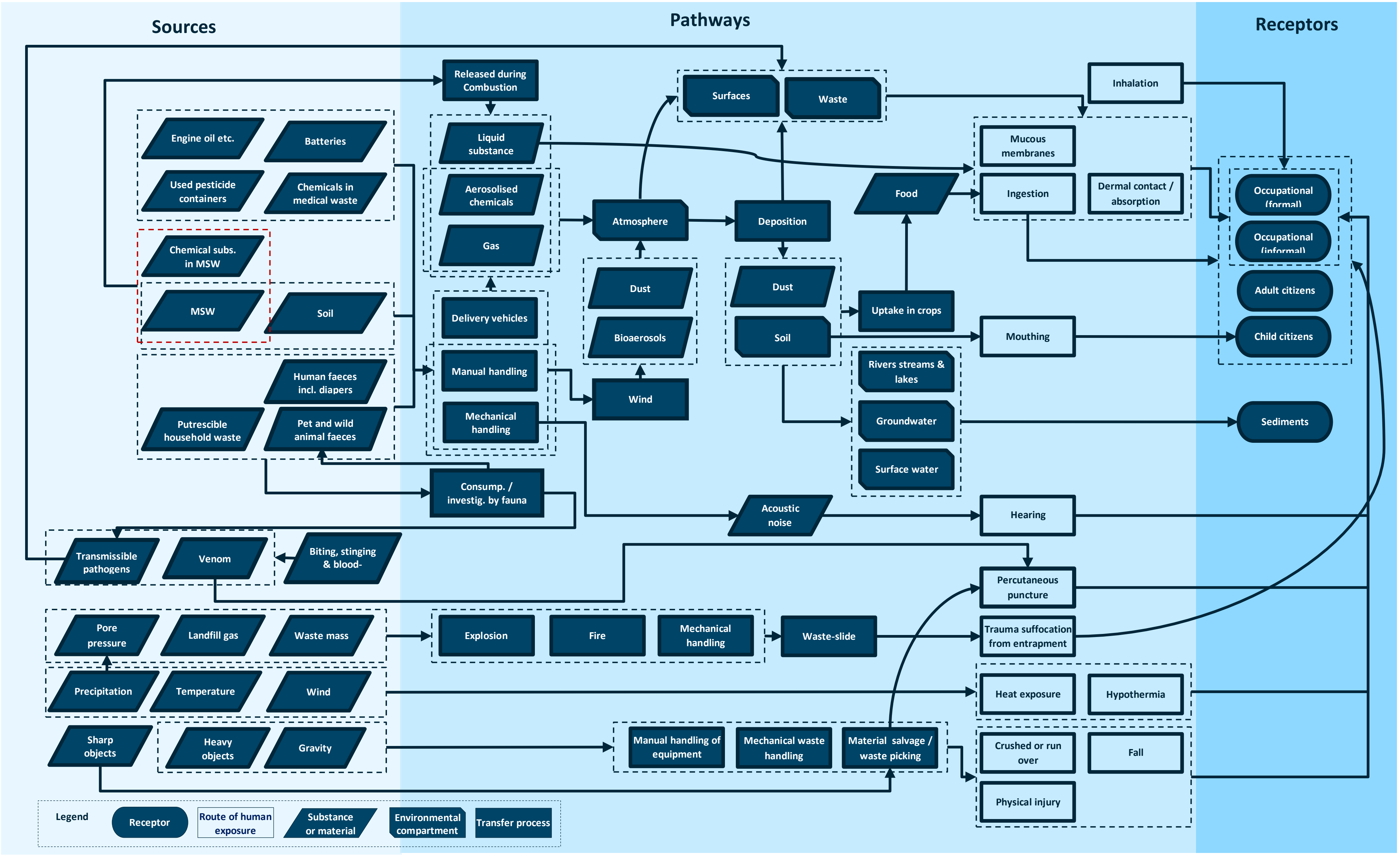


Figure 2: Hazard exposure conceptual model (source – pathway – receptor) associated with land disposal of municipal solid waste (MSW).

2.2. Risk based approach

The likelihood and severity in each hazard-pathway-receptor combination, were assigned an indicative risk score that was used to rank and compare them, based on an approach reported by Cook et al. (2020) that was adapted from World Health Organization (2012), Hunter et al. (2003), Kaya et al. (2018) and Burns et al. (2019) (**Table 1** and **Table 2**). This process does not constitute an assessment of risk in each case and is no substitute for a quantitative risk assessment. The intention is that the results can be used to indicate, rank and compare relative risks and support decisions on a future research agenda. The collected results are ranked and shown in **Section S.5**.

Table 1: Matrix used to calculate the relative risk of each hazard-pathway-receptor scenario.

			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.

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. Challenge 1: Biological hazards on land disposal sites

The high levels of biological material on land disposal sites, such as pet faeces, animal carcasses, food and human excrement, can result in an array of potential biological hazards (Gerba et al., 2011). Aside from the infection risk to those coming into physical contact with the waste, mechanical or manual agitation coupled with high heat causes the aerosolisation of biological material that can be inhaled by those in close proximity (Mirskaya and Agranovski, 2018). Animals, such as snakes, wild dogs, rodents and airborne insects, result in further risk to humans working or living near to land disposal sites when they puncture skin or deposit their faeces resulting in a further pathogen transmission risk (Afon, 2012; Mothiba, 2016). A conceptual diagram illustrating the source-pathway-receptor linkages for biological hazards is presented in **Figure 3**.

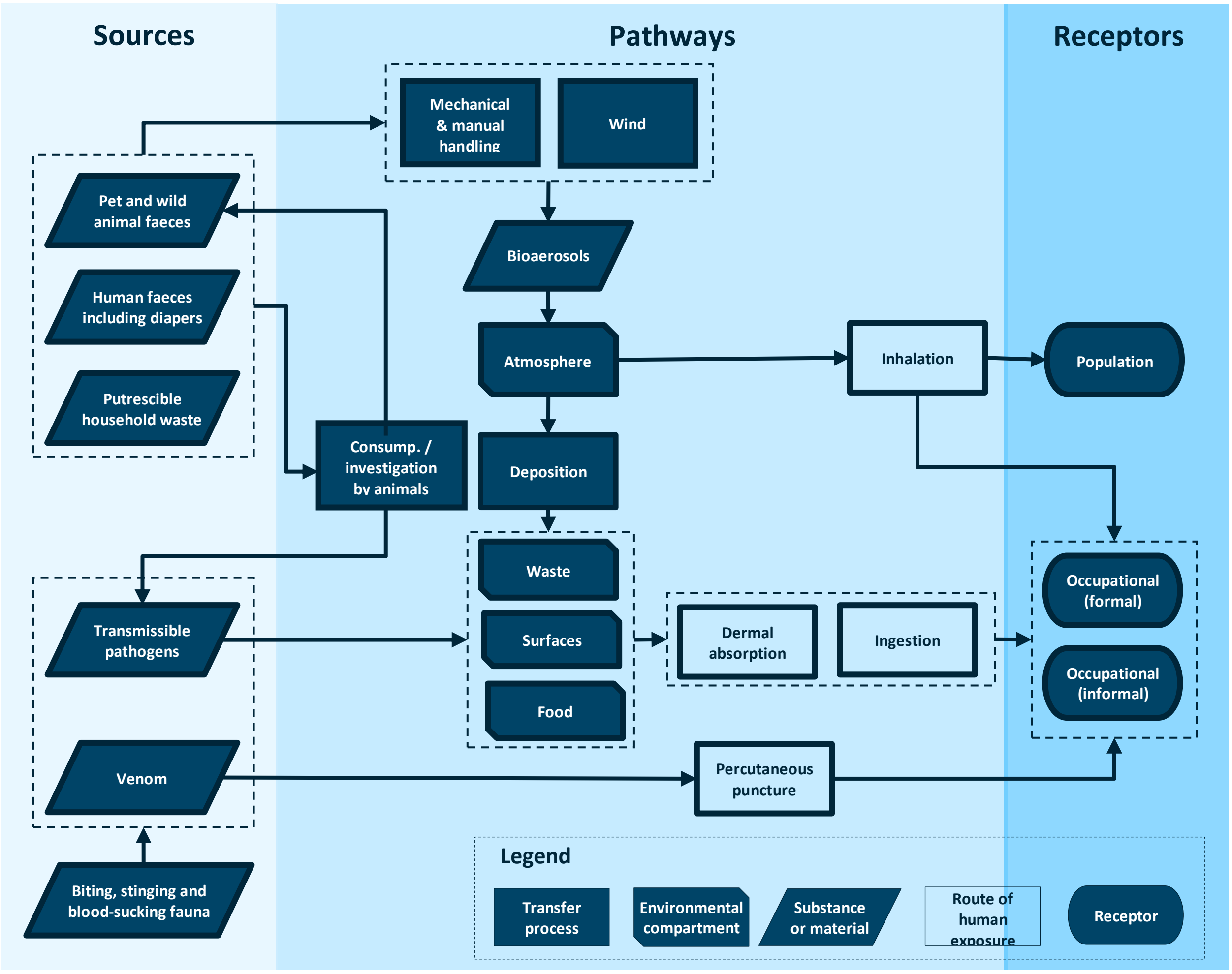


Figure 3: Hazard exposure conceptual model (source – pathway – receptor) associated with biological hazards on land disposal sites.

3.1. Bioaerosols

The combination of readily available carbon, moisture and heat in landfills and dumpsites provides an ideal environment for bacteria, fungi and archaea to proliferate. As they do so, physical processes on land disposal sites, such as boundary layer turbulence, and mechanical or manual activity, result in the introduction of these microorganisms into the atmosphere, aerosolising them (Mirskaya and Agranovski, 2018); hence the term bioaerosols. In addition to live micro-organisms, the term bioaerosol includes non-living organisms; cells; fragments of cells and organisms; viruses; pollen; bacterial endotoxins; mycotoxins; glucans; and any other biological material that is suspended in the atmosphere (Górny, 2020; Pearson et al., 2015).

The potential impact of bioaerosols on the health of waste workers has been studied increasingly since the turn of the 21st century as research, such as Heldal et al. (2003), began to emerge that correlated exposure with raised white blood cell count and harmful effects among waste sector workers, including a range of respiratory and cardiovascular problems. The majority of studies have focused on composting facilities, and at least four major studies (Douwes et al., 2003; Humbal et al., 2018; Pearson et al., 2015; Robertson et al., 2019) have reviewed the link between bioaerosol exposure and morbidity amongst workers and the public, concluding insufficient and inconsistent quantitative evidence to establish a causative link. However, acknowledging this, Pearson et al. (2015) suggests that there is enough data to recommend a precautionary approach for the purposes of regulating to mitigate exposure.

3.1.1. Bioaerosol concentrations

Historical studies investigating bioaerosol exposure on land disposal sites are scant in comparison to those carried out on compositing sites. We identified nine relevant studies carried out in Poland (n=6), Egypt (n=1), South Africa (n=1) and Nigeria (n=1) (Table 3). Most of the studies reported 'total bacteria' and 'total fungi', with several reporting actinomycetes (a type of diazotrophic bacteria), Gram-negative bacteria and other specific bacterial species, such as Pseudomonas fluorescens (a type of Gram-negative bacteria), α-haemolytic bacteria, and β-Haemolytic bacteria. All reported on the basis of CFU which are the number of viable bacteria fungal cells grown on a petri dish following capture of material on a filter during sampling. Although the exposure response relationship between bioaerosol exposure and negative health outcomes is highly uncertain, the concentrations of several bioaerosols reported in Table 3 are compared with the tentative guidelines suggested by the Environment Agency (Frederickson et al., 2013) for reference.

Table 3: Studies quantifying bioaerosol exposure on land disposal sites and surrounding areas.

Ref.	Geog.	Site type	Sampling locations	Receptor	Microorganisms	Conc. (CFU m^{-3}) Mean	Range	
			Weighbridge office (indoor, near trucks)		Bacteria		2,000*–72,000*	
					Fungi		310–7,300	
			Bookkeeper's office (indoor, in same building)		Bacteria		1,000–13,000*	
					Fungi		230–2,100	
			Near the building (outdoor)		Bacteria		640–40,000*	
					Fungi		200–12,000	
			Sorting unit (semi-protected)		Bacteria	6,100*		
					Fungi	1,000		
					Bacteria		70–41,000*	
Lis et al. (2004)	POL	Landfill	Collection area	Formal workers	Fungi		260–6,300	
			Zero point (waste piles on site)		Bacteria		7,140*–832,500*	
					Actinomycetes		0–7,360	N
					Fungi		426.6–10,880	N
			150 m		Bacteria		4,350*–855,400*	
					Actinomycetes		0–2,986	N
					Fungi		213–5,120	N
					Bacteria		1,066*–304,000*	
					Actinomycetes		0–107	N
Mansour (2012)	EGY	Landfill	300 m	Formal workers	Fungi		90–460	N
			-50 m	Formal workers	Bacteria (Enterobacterace ae)	850		
					β-Haemolytic bacteria	Uncountable		
					Yeasts, yeast-like fungi	-		
			0 m (landfill fence, ref. point)	Formal workers	Bacteria (Enterobacterace ae)	480		
					β-Haemolytic bacteria	220		
					Yeasts, yeast-like fungi	35		
			400 m	Residents	Bacteria (Enterobacterace ae)	110		
					β-Haemolytic bacteria	231		
					Yeasts, yeast-like fungi	19		
Kaźmierczuk and Bojanowicz-Bablok (2014)	POL	Landfill	1,200 m	Residents	Bacteria (Enterobacterace ae)	16		
					β-Haemolytic bacteria	5		
					Yeasts, yeast-like fungi	2		

Ref.	Geog.	Site type	Sampling locations	Receptor	Microorganisms	Conc. (CFU m^{-3}) Mean	Range	
					Total bacteria (n=13)	1,900*	274–2,994*	(10)*
					GNB (n=13)	2,200†	1,980†–2,439†	(13)†
					A. fumigatus (n=13)	280	62–479	N
			Active area of dumpsite (50 m from active point)	Waste pickers & formal workers	Total fungi (n=13)	600	231–1,116	N
					Total bacteria (n=13)	1,100*	884–1,379*	(12)*
					GNB (n=13)	1,400†	939†–2,521†	(13)†
					A. fumigatus (n=13)	43	7.21–121	N
			Dormant area of dumpsite (531 m from active point)	Waste pickers & formal workers[e]	Total fungi (n=13)	310	189–842	N
					Total bacteria (n=13)	740	195–1630*	(5)*
					GNB (n=13)	1,200†	311†–2,257†	(13)†
					A.fumigatus (n=13)	5,100	35–71	N
			Dumpsite boundary (788 m from active point)		Total fungi (n=13)	340	166–485	N
					Total bacteria	600,000*		
					GNB	210,000†		
					A.fumigatus	300,000‡		
				Site supervision	Total fungi	-		
					Total bacteria	480,000*		
					GNB	1,740,000†		
					A.fumigatus	90,000‡		
				Sorting	Total fungi	-		
					Total bacteria	1,170,000*		
					GNB	3,000,000†		
					A.fumigatus	67,500‡		
			Activity based sampling (n=2)	Waste pickers	Total fungi	-		
					Total bacteria	1,100*		
					GNB	1,500†		
					A.fumigatus	63		
Akpeimeh et al. (2019)	NGA	Dumpsite	Ambient air sampling (n=13)		Total fungi	370		
					Mesophilic bacteria		30–4,520*	
							0–763	
					α-Haemolytic bacteria		2–168	
					β-Haemolytic bacteria		0–85	
Burkowska et al. (2011)	POL	Landfill	Operative landfill	Formal workers	Actinomycetes		0–129	

Ref.	Geog.	Site type	Sampling locations	Receptor	Microorganisms	Conc. (CFU m^{-3}) Mean	Range	
					Moulds		47–6,313	
					Mesophilic bacteria		23–1,347*	
					Mannitol-positive staphylococci		0–712	
					α-Haemolytic bacteria		0–58	
					β-Haemolytic bacteria		0–62	
					Actinomycetes		0–213	
			Reclaimed landfill	Formal workers	Moulds		25–3,737	
					Mesophilic bacteria		36–646	
					Mannitol-positive staphylococci		0–143	
					α-Haemolytic bacteria		3–17	
					β-Haemolytic bacteria		0–37	
					Actinomycetes		0–98	
			Surrounding landfill	Formal workers	Moulds		5–2,256	
					Bacteria		5,400*–6,100*	
			Top of active landfill area		Fungi		320–1,000	
					Bacteria		2,600*–5,600*	
			Top of filled landfill area		Fungi		480–1,200	
					Bacteria	680		
Buczyńska et al. (2006)	POL	Landfill	Wastewater run off collection area (200 m)	Formal workers	Fungi	360		
					Total bacteria		78–54,200*[bc]	
					Pseudomonas fluorescens		2–670[bc]	
					Actinomycetes		10–485[bc]	
					Fungi (moulds)		65–3,800[b]	
			Active sector of landfill site[a]	Formal workers	Fungi (yeast-like)		0–287[b]	N
					Total bacteria		133–1,095*[b]	
					Pseudomonas fluorescens		0–18[b]	
					Actinomycetes		4–84[b]	
					Fungi (moulds)		48–1,010[b]	
Breza-Boruta (2012)	POL	Landfill	~200 m east of facility[a]	Residents	Fungi (yeast-like)		0–50[b]	N
				Formal workers (n= 12)	GNB	6,800†	40–28,000†	
					Fungi	3,200	400–8,200	
				Machine operators (n=4)	GNB	22,000†	600†-120,000†	
Ncube et al. (2017a)	ZAF	Landfill	Active landfilling site		Fungi	21,000	300–100,000	

						Conc. (CFU m^{-3})		
Ref.	**Geog.**	**Site type**	**Sampling locations**	**Receptor**	**Microorganisms**	**Mean**	**Range**	
					GNB	6,200†	20–24,000†	
				Site samples (n=4)	Fungi	2,800	20–7,400	
					TVB	3,940*[d]		N
			Active landfilling site	Formal workers	GNB	658†[d]		N
			Meadows, forests & farmland, distant from the landfill		TVB		1,281*–1,654*[d]	N
Cyprowski et al. (2019)	POL	Landfill		Residents	GNB		39–77[d]	N

[a] Air measurements made in four replications; [b] research sampling conducted during different months (obtained concentration of microorganisms showed large, statistically significant differences both within and between the seasons); [c] heavily polluted air in spring and summer period; [d] median concentration of bioaerosols; [e] sorting and loading of recovered recycled materials into trucks; [ß] Reported as landfill, but re-allocated as dumpsite based on likelihood of being an engineered landfill. N= not significant; n= sample size; Bracketed numbers indicate the number of days when the Environment Agency limits (Frederickson et al., 2013) were exceeded where reported; * Exceeded Environment Agency Guideline concentration for total bacteria of 1,000 CFU m^{-3}; † Exceeded Environment Agency Guideline concentration for Gram-negative bacteria of 300 CFU m^{-3}; ‡ Exceeded Environment Agency Guideline concentration *Aspergillus fumigatus* of 500 CFU m^{-3}. Abbreviations: total viable bacteria (TVB); Gram-negative bacteria (GNB); concentration (conc.); geographical context of the study (geog.)

Many of the concentrations of total bacteria reviewed showed high levels in comparison to the Environment Agency (Frederickson et al., 2013) guidelines of 1,000 CFU m^{-3} for total bacteria (**Table 3**) such as Lis et al. (2004), Buczyńska et al. (2006), Breza-Boruta (2012), Burkowska et al. (2011) and Cyprowski et al. (2019). Several extremely high concentrations were observed, for instance by Mansour (2012) reported total bacteria 700-800 times greater on the site; between 400-850 times greater 150 metres away; and up to 300 times greater 300 metres away. It is worth noting that the definition of dumpsite and landfill is imprecisely reported by all authors. For instance, in the case of Mansour (2012), it is highly likely that the 'landfill' in Egypt would fall into our definition of a 'dumpsite'.

The study by Akpeimeh et al. (2019) stands out because their static samplers showed much lower concentrations in comparison to the landfill sites investigated by all of the other authors. Additionally, Akpeimeh et al. (2019) also attached personal air samplers to supervisors, waste sorters and waste pickers and observed extremely high concentrations at an average of 600, 500 and 1,100 times greater than the static samplers respectively. These findings are commensurate with Gram-negative bacteria concentrations observed by Ncube et al. (2017a) who also employed personal air samplers, finding concentrations of total bacteria experienced by site workers and machine operators to be 22-73 times higher than the Environment Agency guidelines respectively. Assessing the concentration of Gram-negative bacteria is important, not only because many are pathogenic, but also because their external membranes comprise the lipids, proteins and lipopolysaccharides that are classified as endotoxins (Liebers et al., 2008). It is the lipopolysaccharide content of endotoxins that is thought to have the main biological effect, resulting in an inflammatory response from the respiratory system, and a strong suggested longer term effect including chronic bronchitis, dyspnoea and diminished lung function. Endotoxins are not carcinogenic or mutagenic, but there is unexplained evidence from the textile industry of a negative correlation between endotoxin exposure and lung cancer (Health Council of the Netherlands, 2010). The Health Council of the Netherlands recommends a guideline maximum workplace exposure limit of 90 EU m^{-3} (eight hour TWA).

3.1.2. Distance from activity (source)

Surprisingly or not, concentrations of bioaerosols were reported to be generally lower the further samples were taken from activity (the 'source') involving the agitation of waste, either mechanically or manually. For instance, Ncube et al. (2017a) found that machine operators were exposed to mean concentrations of 22,000 CFU m^{-3} of Gram-negative bacteria, a value that is about three times higher than the exposure of site workers who were exposed to a mean of 6,800 CFU m^{-3}. Although not significantly different, the personal air sampling data obtained by Akpeimeh et al. (2019) indicated that waste pickers were exposed to concentrations of bioaerosols two to three orders of magnitude greater than the mean of the static samplers (specific data not shown).

Three authors (Akpeimeh et al., 2019; Cyprowski et al., 2019; Mansour, 2012) used statistics to assess this (**Table 3**). Mansour (2012) found a significant ($p < 0.0001$) decrease in concentrations of bacteria, Actinomycetes and fungi at 150 m and 300 m from the source, but downwind, the difference was only significant at 300 m, indicating that the displacement was not strong in the short-range or that the suspended particles were undergoing frequent replenishment.

3.2. Non-aerosolised pathogens and biological agents

Bacteria, viruses, fungi exist on land disposal sites at many hundreds or thousands of times the concentrations in homes and workplaces (Kalwasińska et al., 2014), as a result of the inclusion of faecal matter and human bodily fluids in waste or through the colonisation of abundant carbon sources in the waste coupled with plenty of moisture and warmth. In a review of the contribution made by pathogens in MSW to public health risk, Gerba et al. (2011) presented data on the proportional contribution of different waste components in the United States to the pathogenic load (**Figure 4**), indicating that pet faeces is the largest single contributor to pathogenic load in MSW. The main exception is norovirus, a pathogen which results from human shedding in bio-solids (mainly human faeces).

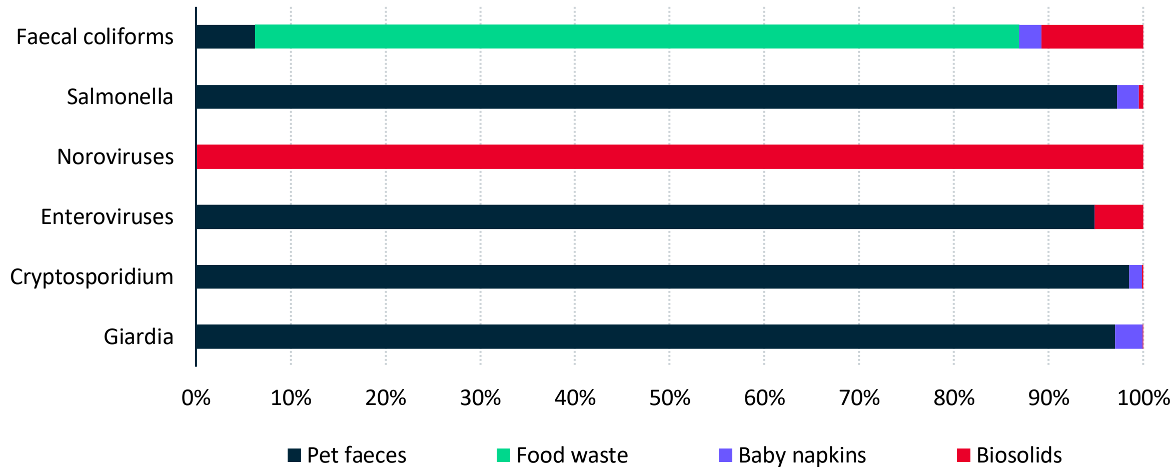


Figure 4: Proportional contribution of municipal solid waste (MSW) components in the United States to pathogenic load; after Gerba et al. (2011).

As well as the myriad microbial communities that colonise these facilities, land disposal sites also attract larger, wild fauna such as rodents, cats, dogs, snakes and avian species that recognise the large and comparatively immobile and abundant food source. Moreover, cattle, sheep, goats and pigs, may graze on dumpsites, either deliberately encouraged by their owners or by their own volition (Afon, 2012; Mothiba, 2016). These animals distribute their own faeces and urine around land disposal sites, harbouring pathogens that can be exposed to humans who live and work there. In closer interactions, many animals and insects (for example termites, flies, scorpions and mosquitos) bite, sting or suck blood, exposing people to pathogens, or defensive agents such as venoms which are tailored to cause harm to those who come into contact with them. Four main non-aerosol pathways are indicated through which humans may interact with pathogens and other biological agents:

- Dermal contact with waste or animals
- Percutaneous puncture
- Exposure through mucous membranes
- Bites or stings

Five studies that reported exposure to pathogens and other biological agents on land disposal sites are presented in **Table 4**. Three (Afon, 2012; Jayakrishnan et al., 2013; Mothiba, 2016) reported exposure to animal bites and insect stings for waste pickers and formal workers. Of these, Afon (2012) surveyed 112 waste pickers in Nigeria, of which 83.9% had suffered an insect sting, and 15.2% from snake bite. Insect stings were the main environmental hazard that waste pickers were exposed to, accounting for 17.1% of those reported. Malaria infection was reported by 63% of waste pickers. Similarly, Mothiba (2016) reported that 91% of surveyed landfill waste pickers in South Africa were exposed to stings and bites from flies, rats and mosquitoes.

Table 4: Biological exposure to hazards on land disposal sites reported through surveys.

Ref.	Geog.	Site type	Receptor	n	Hazard/hazardous phenomenon or health effect	Exposure
Mothiba (2016)	ZAF	Landfill	Waste pickers	176	Exposed to flies, rats and mosquitoes	91%
					Exposed to faeces, blood (from nappies etc.)	24%
					Stomach pain	1.7% (n=3)
					Diarrhoea	2.3% (n=4)
					Stomach pains and diarrhoea	2.3% (n=4)
Jayakrishnan et al. (2013)	IND	Dumpsite	Formal workers	313	Mosquito borne disease	0.6% (n=2)
					Animal bites	9.6% (n=30)
					Water borne disease	5.5% (n=17)
					Leptospirosis	1% (n=3)
					Malaria and dengue	0.3% (n= 1)
Afon (2012)	NGA	Dumpsite	Waste pickers	112	Insect sting	83.9% (n=94)
					Snake bite	15.2% (n=17)
					Malaria	63% (n=71)

Abbreviations: geographical location of study (Geog.); number of samples (n).

Blood sampling carried out by Cruvinel et al. (2019) (**Table 5**) showed levels of uric acid, creatinine, GT range, and glucose outside the normal range for large numbers of waste pickers surveyed. This may indicate chronic exposure, however the study cautioned that follow up tests would be required to support the assertion. The positive cases of human immunodeficiency virus (HIV) (n=6) and hepatitis B virus (HBV) (n=33) may indicate infection from pathogens present in hospital waste. However as with many of the observed morbidities among informal waste workers, environmental, behavioural and lifestyle factors may also be a cause of infection. Data are not included here, but Cruvinel et al. (2019) also identified 28 cases of syphilis among the cohort, indicating that sexual transmission may be an important source for the other infections.

Table 5: Blood sample analysis of land disposal site workers.

Ref.	Geog.	Site type	Receptor	n	Analyte	Values outside reference limit or positive cases
Cruvinel et al. (2019)	Latin America	Dumpsite	Waste pickers	770	Uric acid	23.89% (n=184)
				775	Creatinine	54.06% (n=419)
				757	GT range	16.24% (n=123)
				774	Glucose	35.52% (n=275)
				764	HIV/AIDS infections	0.77% (n=6)
				770	Hepatitis B	4.3% (n=33)
Juma et al. (2019)	KRI	Dumpsite	Formal workers	89	*Toxoplasma IgG*	25.8% (n=23)
					Rubella IgG1	63% (n=56)
					Cytomegalovirus IgG	13.5% (n=12)

Abbreviations: acquired immunodeficiency syndrome (AIDS); human immunodeficiency virus (HIV); Immunoglobulin G1 (IgG1).

The analysis of dumpsite workers' (n=89) blood carried out by Juma et al. (2019) found 23 with toxoplasma levels outside of the normal range, indicating a previous potential infection with T. gondii protozoa (toxoplasmosis). Possible sources of infection are through animal (cat) faeces or through ingestion of food contaminated with it (Centers for Disease Control and Prevention, 2018). Another source may be through undercooked game that harbours the infection. Twelve of the cohort observed by Juma et al. (2019) showed levels of Cytomegalovirus outside the normal range. This pathogen can be transmitted human to human but also through ingestion of human faeces. Rubella is only transmitted between humans and therefore the high levels identified among the cohort infer poor control and high vulnerability of waste pickers to human to human transmitted infection, an occupational hazard.

Waste pickers are particularly vulnerable to pathogens and other biological agents as they work closely with the waste, typically without the use of protective equipment. Moreover, they may also be unaware of the hazards or have no choice but to endure them to sustain their livelihoods. Cointreau (2006) reported a relatively old survey from 1986 of waste pickers who were asked about the prevalence of selected morbidities before and after engaging in informal waste collection activities (**Figure 5**). The participants reported considerably higher rates of disease and ill health after becoming waste pickers in comparison to the time when they were occupied in other activities.

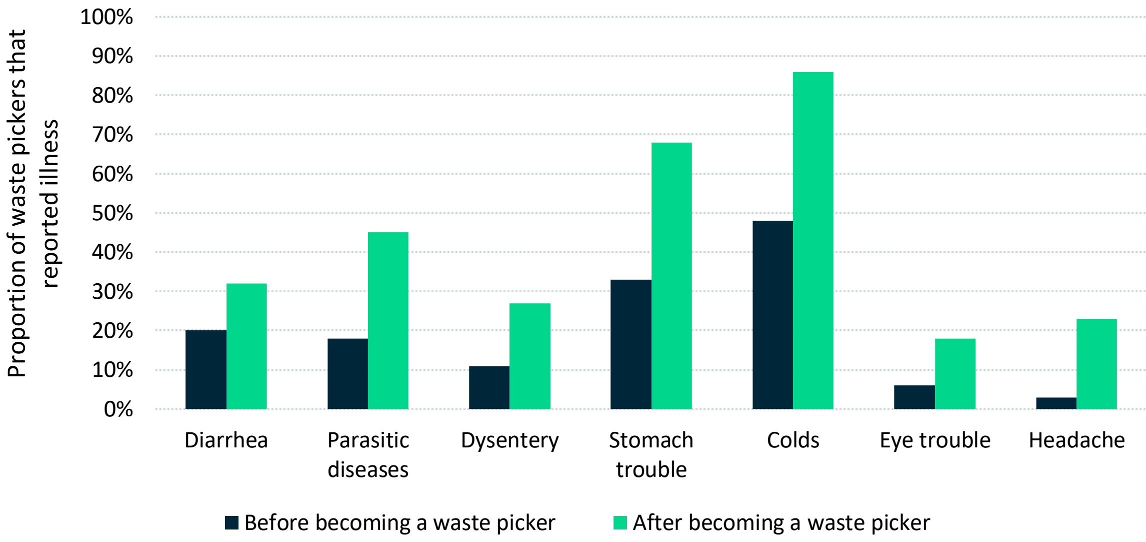


Figure 5: Incidences of morbidity reported by waste pickers before and post occupational exposure to waste; after Cointreau (2006).

Mothiba (2016) reported that flies and insects can cause the contamination of food and drink, contributing to intestinal infection. Proper sanitation facilities are rarely present on dumpsites. Similarly, Afon (2012) reported that stings and bites may be the cause of the high prevalence (63%) of skin rashes and malaria among surveyed waste pickers. As a vector for dengue fever, mosquitos such as Aedes aegypti favour containers, tyres, and tin cans present in waste piles for breeding (Jayakrishnan et al., 2013).

Three studies published health effects reported by waste pickers working on dumpsites independently of causative factors (**Table 6**). Speculatively, the rates of ill health and infection appear higher than would be expected for a similar population demographic. However the studies did not report consistent categories or make comparisons with control groups so strong positive assertions are problematic. Future work would benefit from a more standardised method of data collection and reporting so that studies can be compared to inform interventions to reduce future harm to this group of vulnerable workers.

Table 6: Morbidities reported by waste pickers at dumpsites.

Ref.	Geog.	n	Reported health effects	Prevalence
			Respiratory disease	0.6% (n=60)
			Eye problems	33.2% (n=104)
			Skin problems	36.4% (n=114)
			Nail infections	47% (n=147)
			Genitourinary problems	33.5% (n=105)
Jayakrishnan et al. (2013)	IND	313	Musculoskeletal morbidity	17-39% (n=54-123)
			Typhoid infection	50% (n=56)
			Dysentery	38.4% (n=43)
			Cholera	25% (n=28)
			Asthma	10.7% (n=12)
			Burns	60.7% (n=68)
			Pneumonia	33% (n=37)
Afon (2012)	NGA	112	Skin infection	42.9% (n=48)
			Low back pain	65%
			Fever	44%
			Common cold	39%
			Headache	69%
			Gastric pain	34%
			Skin rashes	14%
			Asthma	15%
			Diarrhoea	25%
			Sleeping disturbance	10%
Mitra (2016)	BGD	200	Small cuts and injuries	47%

Abbreviations: geographical location of study (Geog.); number of samples (n).

3.3. Risk characterisation for biological hazards on land disposal sites

The semi-quantitative risk assessment for aerosolised and non-aerosolised biological hazards showed generally medium-low to medium-high risk for most source-pathway-receptor combinations (**Table 7**). The risk of infection from pathogens and other biological agents was highest for waste pickers compared to formal workers. This group is inherently more vulnerable due to the high levels of contact with waste, poor levels of sanitation in the workplace and lack of protective equipment and absence of health and safety procedures.

Bioaerosol exposure to formal and informal workers was tentatively scored on a par with non-aerosolised pathways of infection, despite the inconclusive evidence to indicate morbidity as a consequence of exposure. This is in part, due to the very high concentrations in the ambient air on dumpsites and the closeness to which workers interact with those concentrations without access to PPE. Only the LIMIC context was considered in the risk assessment for the bioaerosols because the risk was considered to be comparatively trivial for formal workers in HICs where they have little close interaction with the waste.

Table 7: Risk characterisation summary for biological hazards on land disposal sites.

Haz.	Pathway	Receptor	Geo. research context	Evidence and justification for risk assessment	Uncertainty (aleatoric and epistemic)	Receptor vulnerability	L	S	R	Global receptor context
Bioaerosol	Breathing/ inhalation	Land disposal workers (formal)	POL, EGY, ZAF, NGA	• Evidence of high concentrations of several bioaerosols in the atmosphere on land disposal sites in comparison to UK Environment Agency (Frederickson et al., 2013) guidelines, which decrease with distance from the source (Akpeimeh et al., 2019; Breza-Boruta, 2012; Buczyńska et al., 2006; Burkowska et al., 2011; Cyprowski et al., 2019; Kaźmierczuk and Bojanowicz-Bablok, 2014; Lis et al., 2004; Mansour, 2012). • Personal air sampling concentrations (Akpeimeh et al., 2019; Cyprowski et al., 2019) were extremely high in comparison to static samplers, particularly for waste pickers who it is suggested suffer greater exposure due to proximity to mechanical waste handling activities (Akpeimeh et al., 2019). • Evidence indicates that detected bioaerosol is associated with chronic respiratory symptoms (Akpeimeh et al., 2019; Cyprowski et al., 2019), whereby the presence of bacteria is associated with various respiratory diseases, tract inflammation, toxic and allergic pneumonia, and fungi shown to induce cytotoxic, neurotoxic, teratogenic and carcinogenic effects. Though the evidence for exposure-response relationship is inconclusive (Douwes et al., 2003; Humbal et al., 2018; Pearson et al., 2015; Robertson et al., 2019).	• Robust analysis of concentrations with the following uncertainties: • Reported health effects are challenging to correlate with exposure, making it difficult to determine an exposure-response relationship. • No internationally agreed reference limits for occupational exposure. • The choice of sampling locations may have introduced bias. • Most studies did not consider other cofounding factors such as emissions from other nearby sources. • Samples were case specific whereby the reported concentrations are specifically related to the sampling locations and the employed sampling method is case specific.	• Landfill workers in HICs are often well protected through safe systems of work.	2	3	**6**	LIMIC
		Waste pickers				• Workers in LIMICs may be less aware of the potential hazards posed by bioaerosols. • Both formal and informal workers often operate without respiratory protective equipment.	3	4	**12**	LIMIC
		Nearby residents				• Adults and children have no choice to avoid exposure if they live near land disposal sites.	1	3	**3**	LIMIC
Non-aerosolised pathogens & biological agents	Dermal contact; percutaneous puncture; mucous membranes; bites or stings	Land disposal workers (formal)	ZAF, Latin America, KRI, IND, NGA	• Strong evidence (Gerba et al., 2011) of high pathogenic load on land disposal sites. • Three studies (Afon, 2012; Jayakrishnan et al., 2013; Mothiba, 2016) reported a significantly high exposure of dumpsite waste pickers and workers as well as landfill waste pickers to animal bites and insect siting. • Juma et al. (2019) tested the presence of three types of parasite and viruses and found that a small number of tested dumpsite workers had profiling antibodies, indicating a previous exposure to viruses. • Evidence indicates that flies and insects may cause intestinal infection (Mothiba, 2016), while Afon (2012) reported that stings and bites may be the cause of the high prevalence (63% of participants) of malaria among surveyed waste pickers.	• Very few samples reported the related clinical health impacts, making it difficult to determine exposure-response relationship with biological agents.	• Landfill workers in HICs are often well protected through safe systems of work.	2	3	**6**	LIMIC; HIC
		Waste pickers				• Workers in LIMICs may be less aware of the potential hazards posed by biological agents and pathogens. • Both formal and informal workers often operate without protective equipment.	3	4	**12**	LIMIC

Abbreviations: likelihood (L); severity (S); risk (R); hazard being assessed (Haz.); geographical (Geo.); total viable bacteria (TVB); Gram-negative bacteria (GNB); low income and middle income countries (LIMIC); high income countries (HICs).

4. Challenge 2: Potentially hazardous chemical substances and aerosolised particles (dust) on land disposal sites

4.1. Chemical substances in waste

A wide range of factors could be included in this section which explores exposure to chemical hazards and dust on land disposal sites, however the data to provide a comprehensive picture were lacking. Workers that come into close contact with waste will be potentially exposed to almost every material and substance within it. Agitation and compaction of the waste may hasten exposure, as substances are volatilised or propelled by mechanical plant during manual separation or during inspection by inquisitive waste pickers who may suspect value. The potential for chemical hazard exposure is illustrated in a conceptual diagram in **Figure 6**.

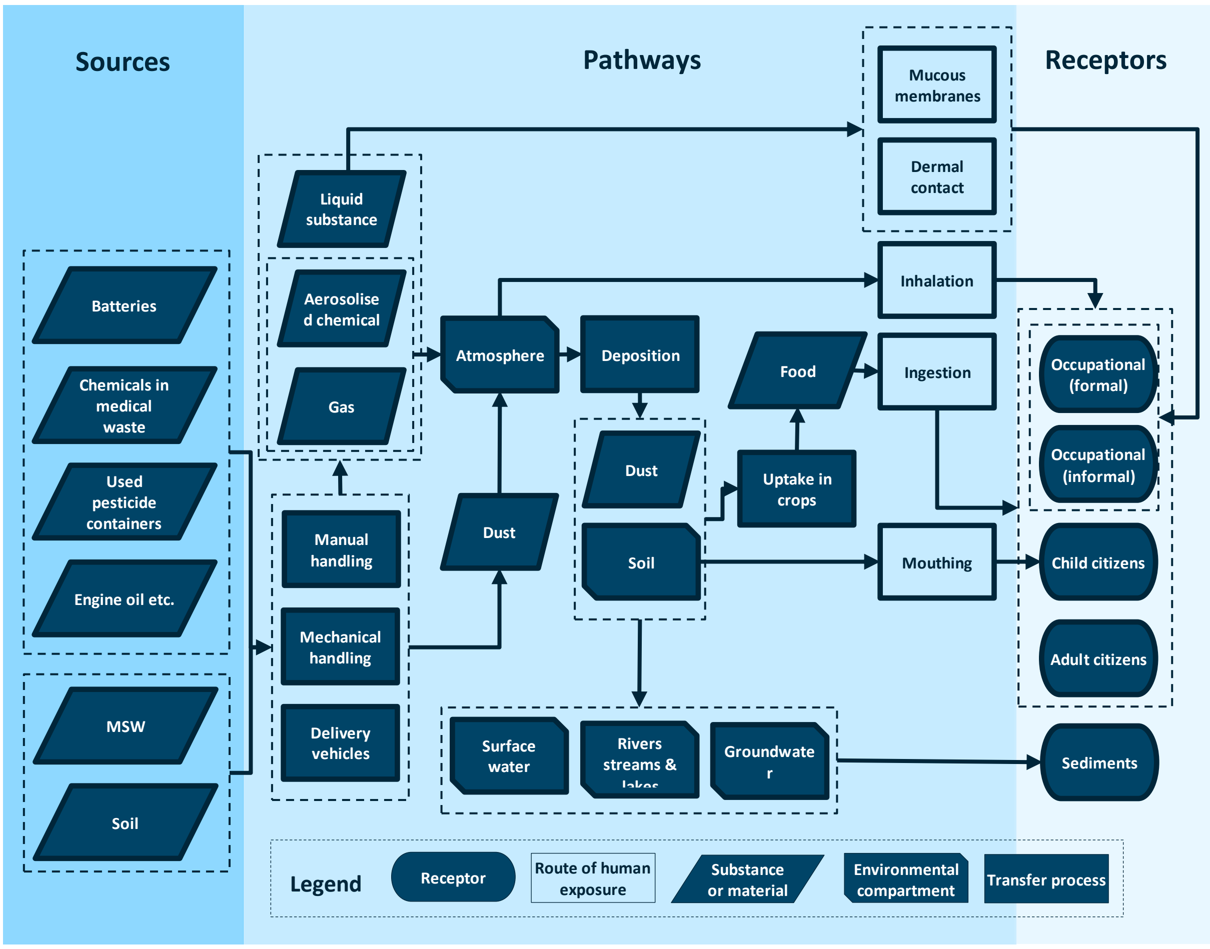


Figure 6: Hazard exposure conceptual model (source – pathway – receptor) associated with chemical and dust hazards on land disposal sites. Abbreviations: municipal solid waste (MSW)

Examples of chemical substance in waste include cleaning products, paint, medicines, oil, grease, solvents, pesticides, batteries, hospital and clinical waste, cars, and containers under pressure, assessed by four studies summarised in **Table 8**. For instance, Da Silva et al. (2005) surveyed 455 waste pickers, most of whom had come into contact with empty chemical containers or those containing residues; cleaning products or containers thereof, paints and medicines. Nearly 40% had also encountered aerosols, oil, grease, solvent, or insecticides and a third had encountered batteries. The level of exposure was in stark contrast to the control group (data not shown) who on average experienced approximately half the level of exposure across most categories.

Table 8: Accidents and injuries due to interaction with chemical agents on land disposal sites.

Ref.	Geog.	Disposal site	Receptor	Sample	Hazard	Reported exposure
Da Silva et al. (2005)	BRA	Dumpsite	Waste pickers	Surveyed=455	Bottle of chemicals	89%
					Dust	84%
					Cleaning products	74%
					Paint	54%
					Medicines	41%
					Aerosols, oil, grease, solvent, & insecticides	38%
					Batteries	33%
					Hospital waste	28%
					Natural gas	15%
Ministry of the Environment Energy and the Sea (2016)	FRA	Dumpsite	Workers (formal)	Accidents=71	Discharge of hazardous/ polluting substances	1%
Tlotleng et al. (2019)	ZAF	Dumpsite	Waste pickers	Exposures=365	Exposure to chemicals*	66.38%

* Specifically they were asked whether they handled household detergents, paint and pesticide containers.

Tlotleng et al. (2019) also reported a high prevalence of interaction between waste pickers on South African dumpsites and chemical substances, finding a statistically significant (p = 0.001) correlation between this exposure and respiratory symptoms (**Table 8**). In contrast, Lorraine reported just 1% of French dumpsite workers coming into contact with chemical substances, probably indicating the fact that workers in France have limited contact with the waste itself as is the case in many HIC contexts.

Evidence of exposure to chemical substances on land disposal sites can be found by measuring concentrations in the blood and bodily fluids of dumpsite workers. For example, Cuadra (2005) analysed blood of teenagers and children (n=103) living and working in Nicaraguan dumpsites, finding higher concentrations of Pb, Hg and Cd compared to the reference group (**Table 9**). Approximately 28% of those sampled showed blood lead levels exceeded the Centers for Disease Control and Prevention (2019) limit of 100 $\mu g\ L^{-1}$. Blood levels of Pb even below the CDC limit have been connected with a decrease of children's mental skills and development (Jusko et al., 2008; Koller et al., 2004; Schnaas et al., 2006). It is noted that teenagers are considered as particularly vulnerable to lead poisoning, because they highly absorb it (Grigg, 2004; Safi et al., 2006).

Table 9: Blood concentrations of elements and selected chemical agents in children and teenagers living and working on dumpsites in Nicaragua; after Cuadra (2005).

Substance			**Units**	**Work, live**	**Work**	**Children living nearby (1)**	**Children living nearby (2)**	**Control**
		lw		1,600	1,200	990	1,000	990
	4,4'-DDE[a]	fw		5.7	4.4	3.8	3.8	3.7
		lw		35	27	20	12	nd
	4,4'-DDT[a]	fw		0.12	0.1	0.08	0.05	<0.03
		lw		540	530	390	230	160
	ΣPCB[a,b]	fw		1.9	2	1.5	0.9	0.6
Neutral fraction		lw		42	142	20	10	6
	γ-HCH[a]	fw		0.2	0.5	0.08	0.04	0.02
		lw		1,200	510	480	350	380
	PCP[a]	fw		4.3	1.9	1.8	1.3	1.4
Phenolic fraction		lw		29	29	12	6	3
	4-OH-CB 187[a]	fw	ng g^{-1}	0.1	0.11	0.05	0.02	0.01
	BDE-47			639	70	29	11	14
	BDE-100			110	18	7.3	2	3.4
	BDE-99			308	19	11	4.6	6.5
	BDE-153			46	18	4.5	2.2	2.6
	BDE-183			2.4	2.4	1.1	2.6	1
	BDE-203			0.86	0.7	0.4	0.47	0.5
	BDE-209		pmol $(g\ lw)^{-1}$	5.4	3,6	5.7	7.3	6
	Pb			77.4	66.2	39	42	28
	Hg			1.2	1.28	0.99	0.6	0.62
	Cd			0.21	0.2	0.16	0.17	0.18
	Se			182	197	190	188	191
	Fe		µg L^{-1}	470,000	470,000	460,000	450,000	440,000

[a] Concentrations in ng $(g\ lw)^{-1}$, ppb and ng $(g\ fw)^{-1}$ and ppb; Abbreviations: number of samples (n); frequency (f); lipid weight (lw); fresh weight (fw) brominated diphenyl ethers (BDE); pentachlorophenol (PCP); dichlorodiphenyltrichloroethane (4,4′-DDT); dichlorodiphenyldichloroethylene (4,4'-DDE); gamma-hexachlorocyclohexane (γ-HCH); lead (Pb); mercury (Hg); cadmium (Cd); selenium (Se); iron (Fe).

Pb is of concern due to its neurotoxicity, the ability to cause kidney damage, and anaemia, specifically in children (Järup, 2003). Hg (in its metal form) and Cd are also associated with renal toxicity (Järup, 2003; Järup et al., 1998; Ratcliffe et al., 1996). Cadmium, a potentially toxic element that can bioaccumulate in humans from childhood, is likely to result in adverse impacts on kidney and bone structure (Bernard, 2004) even at concentrations lower than the suggested level of 5µg L^{-1} (Khassouani et al., 2000). Cr and Ni are allergenic, while Cd induces osteoporosis, kidney disease, and osteomalacia. Although Cr exists in nature and is produced by human activity, it is hazardous and carcinogenic even at concentrations that are considered to be small (Alabi et al., 2019). Also, Ni and Cd are characterized as carcinogenic, according to World Health Organization (2004). Generally, exposure to Pb, Ni, Cd and Cr may be responsible for potential genotoxicity, acute and chronic organ and/or systemic toxicities, neurotoxicity, and cancer (Alabi et al., 2019; Leung et al., 2006).

Cuadra (2005) also identified higher concentrations of dichlorodiphenyltrichloroethane (4,4’-DDT), Dichlorodiphenyldichloroethylene (4,4’-DDE), gamma-hexachlorocyclohexane (γ-HCH), several pentachlorophenol (PCB) congeners, PCP and 4-OH-CB187 than those measured in a reference group of non-workers which decreased further from the disposal site, indicating it as the source (**Table 9**). Additionally, the high 4,4’-DDE/4,4’-DDT ratio that was identified may be attributed to the use of 4,4’-DDT against vectors at the disposal site. In the same work, blood samples of teenage workers had the highest blood concentrations of polybrominated diphenyl ether (PBDE).

4.2. Dust

Dust is a common hazard in almost any terrestrial operation that involves vehicles, plant or other agitation of matter and land disposal sites are no exception as highlighted by both Da Silva et al. (2005) and Mothiba (2016) in surveys of waste pickers (**Table 10**). While providing an indication, this type of data presents a rather vague picture as essentially the participants are saying that they have worked in a dusty environment, without any sense of the concentration or duration – most surprising is that 100% did not answer positively in the surveys.

Table 10: Exposure to dust on land disposal sites reported in surveys of waste pickers.

Ref.	**Geog.**	**Disposal site**	**Sample**	**Prevalence**
Da Silva et al. (2005)	BRA	Dumpsite	455	84%
Mothiba (2016)	ZAF	Landfill	176	95%

In two quantitative studies, Ncube et al. (2017a) and Searl and Crawford (2012) observed very high levels of dust on landfill sites in South Africa and the UK respectively, exceeding for instance, the European Union Directive 2008/50/EC (European Union, 2008) (**Table S3**) upper and lower thresholds for particulate matter < 10 µm (PM_{10}) by an order of magnitude in many cases (**Table 11**).

Table 11: Studies quantifying dust exposure and risk to human health on active landfill sites.

Ref.	Geog.	Receptor	Concentration µg m^{-3} Mean	Range	Reported health effects
Ncube et al. (2017a)	ZAF	Site workers (n= 12)	400 [a b]	200 [a b] – 800 [a b]	Respiratory problems
		Machine operators (n=4)	600 [a b]	1,400 [a b] – 2,200 [a b]	
		Site samples (n=4)	300 [a b]	100 [a b] – 800 [a b]	
Searl and Crawford (2012)	GBR	LF worker (cab windows open)		58 [a b] – 2,100 [a b]	Chronic respiratory ill
		LF worker (cab closed)		25 – 920 [a b]	
		LF worker (cab closed and air filtration)		8.3 – 310 [a b]	

Exceeded the following concentration thresholds set by Directive 2008/50/EC (European Union, 2008) (**Table S 3**): [a] 24 hour average upper assessment of PM_{10}; [b] 24 hour average lower assessment of PM_{10}. Abbreviations: particulate matter < 10 µm (PM_{10}).

In particular, Searl and Crawford (2012) compared dust levels for plant operators on landfill sites in the UK, demonstrating that closing the windows and doors on the cab reduces the amount of dust to which the drivers are exposed. It is worth noting that both Ncube et al. (2017a) and Searl and Crawford (2012) observed relatively small samples, and that neither reported reference samples at the same sites, something that would have assisted with contextualising the results.

4.3. Risk characterisation for chemical hazards on land disposal sites

The semi-quantitative risk assessment for chemical hazards were scored medium-low for formal workers and medium-high for waste pickers who have both greater contact with the waste and less access to protective equipment and procedural safety (**Table 12**). Surprisingly, few studies were found to evidence chemical exposure to workers on land disposal sites, leading to speculation that this is either not an important hazard category or that it is one that has been under-reported.

The risk of harm through dust exposure was scored medium-low for both formal and informal workers on land disposal sites in LIMICs. Levels of dust exposure reported to be very high in two studies, but samples were small and controls were not reported.

Table 12: Risk characterisation summary for chemical hazards and dust on land disposal sites.

Haz.	Pathway	Receptor	Geog.	Evidence and justification for risk assessment	Uncertainty (aleatoric and epistemic)	L	S	R	Global receptor context
Chemical substances in waste	Ingestion, dermal absorption and inhalation	Land disposal workers (formal)	BRA, FRA, NIC, ZAF	• High prevalence of interaction with potentially hazardous substances among informal workers (Da Silva et al., 2005; Tlotleng et al., 2019). Very low for formal workers in HICs (Ministry of the Environment Energy and the Sea, 2016).		2	4	**8**	LIMIC
		Waste pickers		• Blood samples from teenagers and children living and working on dumpsites indicates exposure to pesticides, PTEs and BFRs – linked to dumpsite (Cuadra, 2005).	• Further analysis is needed to assess the risks from individual chemical substances.	3	4	**12**	
Dust	Inhalation	Land disposal workers (formal)	BRA, ZAF, GBR	• Very high levels of dust reported on dumpsites in ZAF Ncube et al. (2017a) and GBR Searl and Crawford (2012) exceeding European Union thresholds for PM10 by an order of magnitude.		4	2	**8**	LIMIC
		Waste pickers		• Control measures (close door) lessen exposure, but many values remain above threshold Searl and Crawford (2012). • Waste pickers and formal workers in LIMICS unlikely to wear sufficient respiratory protective equipment therefore greater vulnerability.	• Small samples sizes • Control samples not provided	4	2	**8**	

Abbreviations: likelihood (L); severity (S); risk (R); hazard being assessed (Haz.); total suspended matter (TSM), persistent organochlorine pollutants (POPs); polybrominated diphenyl ether (PBDE); geographical (Geo.); low income and middle income countries (LIMIC); high income countries (HICs).

5. Challenge 3: Combustion on land disposal sites

The practice of open burning of MSW is thought to be widespread in many LIMICs (Wiedinmyer et al., 2014). While controlled incinerators incorporate technological and management practices to reduce emissions of harmful substances, open, uncontrolled fires do not combust material consistently, meaning that potentially hazardous substances are released rather than being destroyed and that new substances may be created, such as dioxins and related compounds (DRCs) that are often more harmful than any substances already present in the waste (**Figure 7**).

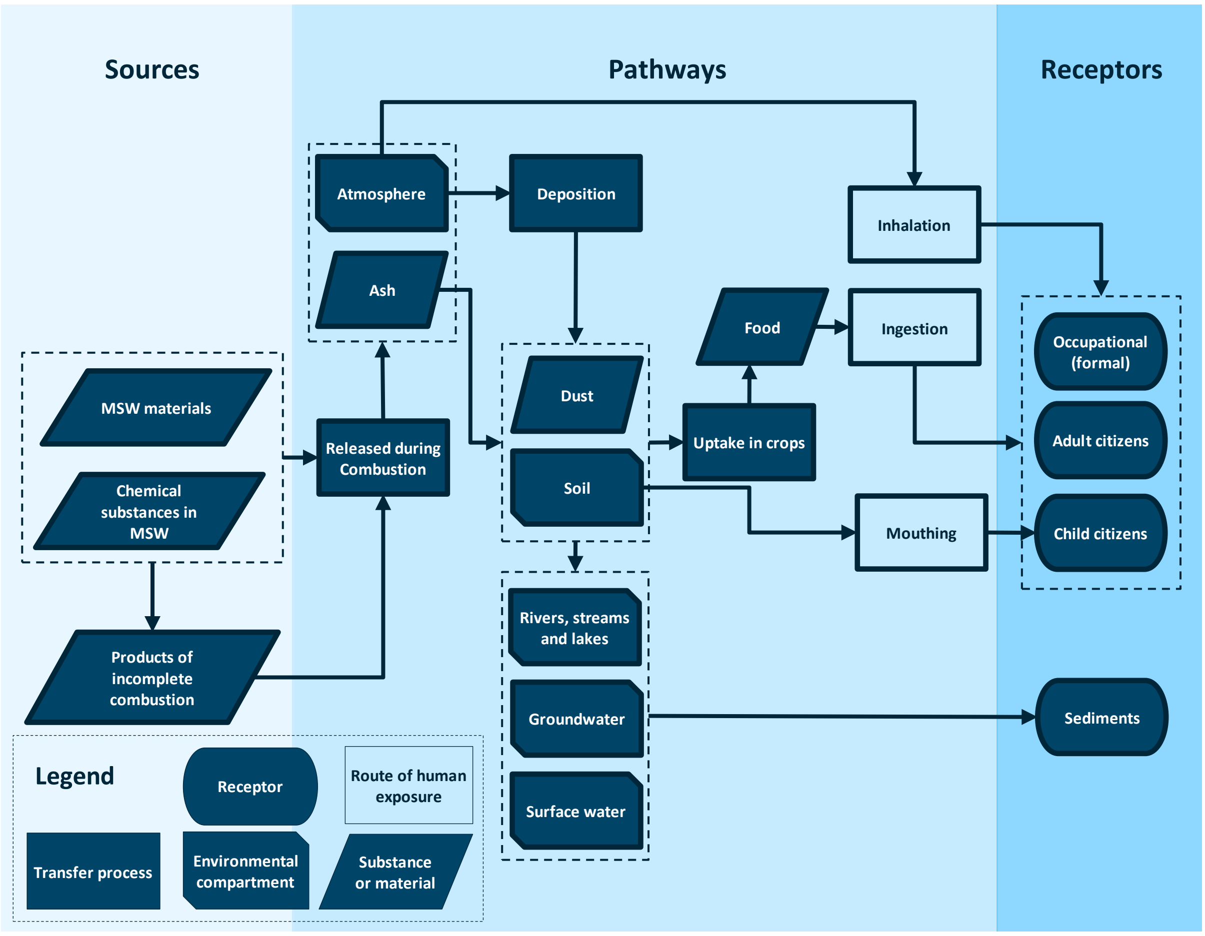


Figure 7: Hazard exposure conceptual model (source – pathway – receptor) associated with open (uncontrolled) burning of municipal solid waste (MSW) (from substances contained and combustion products).

5.1. Causes of fires on land disposal sites

Landfill fires can start spontaneously, deliberately, or accidentally and are often categorised by those that are on the surface and those that are below (Frid et al., 2010). Spontaneous fires, are usually deep seated (below the surface) and are thought to start when heat from anoxic decomposition occurs in combination with oxygen to ignite hydrocarbons in waste materials (Lönnermark et al., 2008). The ignition sources are not well understood, though it has been suggested that already hot or smouldering items may be buried in the waste (Copping et al., 2007), fragments of glass that act as a lens to intensify sunlight (Lönnermark et al., 2008), or sparks from machinery used to manipulate waste may be the cause (Øygard et al., 2005). Other flammable substances such as methane, carbon monoxide, hydrogen, volatile organic compounds and hydrogen sulphide may also be involved as they all occur in land disposal sites to a degree (Copping et al., 2007). According to data from New South Wales (Fattal, 2016), more than 50% of landfill fires have unknown causes; 18% are related to arson; 8% are caused by dumping of hot coal/ash; and 16% are caused by spontaneous combustion.

Surface fires may be started deliberately by waste pickers for instance who burn easily combustible materials so that they may access valuable metals within waste piles (Agarwal et al., 2020; Coffey and Coad, 2010; Rouse, 2006) or simply wish to keep warm. In addition, there is some evidence that waste on dumpsites is deliberately combusted by the authorities in order to reduce its mass and volume (Pansuk et al., 2018).

5.2. Surface fires (open burning) on land disposal sites

Open burning (uncontrolled combustion) of waste on land disposal sites is reported to be a common practice throughout LIMICs (Estrellan and Lino, 2010), however as reported by The Secretariat of the Stockholm Convention on Persistent Organic Pollutants (2008) there are no reliable estimates for the mass combusted. Several have been proposed in recent years, though only two for the mass open burned specifically on dumpsites, both of which were derived either from assumptions or interviews with officials (**Table 13**). No primary data to indicate the mass open burned on dumpsites were identified, leaving a conspicuous gap in the scientific record.

Table 13: Estimates of the proportion of municipal solid waste (MSW) undergoing open burning in different geographical and socio-economic contexts.

Denominator	Ref.	Country	Basis	Context	Rurality	Prop.
Dumpsite waste	Wiedinmyer et al. (2014)	Global	Assumption (IPCC) (Guendehou et al., 2006)	LIMIC	Urban and rural	60%
				HIC	Urban and rural	13%
Landfilled waste[a]	National Environmental Engineering Research Institute (2010)	IND, Mumbai	Interviews with officials	LIMIC	Urban	10%

[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: low income and middle income countries (LIMIC); high income country (HIC); Intergovernmental Panel on Climate Change (IPCC).

The estimate by Wiedinmyer et al. (2014) of the mass off material open burned is based on an assumption from Guendehou et al. (2006) who derived their data from an expert elicitation exercise. The estimate from the National Environmental Engineering Research Institute (2010), applies to Mumbai landfills, and was based on interviewees with officials. Whilst these provide some tangible basis for further development and modelling in the absence of anything more robust, these estimates should be treated with caution as they are not based on observation and measurement.

5.3. Land disposal site fire prevalence

Historically, fires have been an extremely common occurrence on land disposal sites (El-Fadel et al., 1997) numbering many hundreds or thousands in some countries as shown in **Table 14** where incidents reported in HICs are compared. Whether these are deep seated or on the surface isn't always reported, with the exception of Ettala et al. (1996), who indicated that of the 380 fires each year in landfill sites in Finland, one quarter were below ground. Uniquely, Ettala et al. (1996) also calculated the mass that was associated with these fires, estimating that 84,000 tonnes per year on average between 1990 and 1992.

Table 14: Prevalence of below surface fires on land disposal sites.

Ref.	Secondary source	Geog.	Basis	Prevalence
	Operator estimate	GBR	Constant	80% (50-100%)
	Recorded by fire authority	GBR (Northamptonshire)	1998-2003	26
	Bergstrom & Bjorner (1992)	SWE	1988-1989	217 spontaneous
			Daily	10%
			Weekly	20%
			Monthly	20%
	Chiblow (2004)	CAN (Ontario)	Never	40%
Bates (2004)	Bothman (1994)	DEU	> four years prior to 1994	13 out of 63
				380 (25% deep)
Ettala et al. (1996)		FIN	1990-1992	84,000 tpa
		GBR	Annual	300
Foss-Smith (2010)		AUS	Annual	12,000
TriData Corporation (2002)		USA	Annual	8,300
Hogland and Marques (2003)		SWE	Annual	'Hundreds'
		FIN	Annual	'Hundreds'

Abbreviations: tonnes per annum (tpa)

No reliable data on landfill fires in the last decade were identified during this review as it is not commonplace for incidents to be reported separately to other incidents as is the case in the UK, which aggregates incidents with all refuse fires (Home Office, 2020). All of the sources identified were at least a decade old, which may indicate a lack of interest in the research, or that engineering and management controls such as those detailed by Copping et al. (2007) or ISWA Working Group on Landfill (2019).

5.4. Emissions from fires on land disposal sites

Emissions from landfill fires contain a wide range of potentially hazardous compounds, determined by the heat of the fire, oxygenation and material and chemical composition of the waste (Weichenthal et al., 2015). Typical emission profiles include dioxins/furans polycyclic aromatic hydrocarbons and respirable PM (Escobar-Arnanz et al., 2018). Building on the estimates by Wiedinmyer et al. (2014) and using additional factors from Lemieux et al. (2004), Cogut (2016) reported global emissions of various atmospheric pollutants from the open burning of solid waste, much of which may be attributed to open burning on land disposal sites **Table 15**.

Table 15: Pollutants from open burning of solid waste with identified potential health impacts; after Cogut (2016).

Pollutant	**Global emission of pollutant due to open burning (kg y^{-1})**	**% of total global emissions of pollutant due to open burning**	**Potential serious health impacts[a]**
Carbon dioxide (CO_2)	1.4 Trillion	5	• Cardiorespiratory failure • Climate change associated risks
Methane (CH_4)	3.6 Billion	1	• Respiratory arrest • Climate change associated risks
Carbon monoxide (CO)	37 Billion	7	• Ataxia • Seizures
Coarse particulates (PM10)	12 Billion	24	• Lung cancer • Respiratory disease • Heart failure
Fine particulates (PM2.5)	10 Billion	29	
Black carbon (BC)	632 Million	11	
Organic carbon (OC)	5.1 Billion	43	
Polycyclic aromatic hydrocarbons (PAH)	334 Million	39	• Skin, bladder and lung cancer • Poor cognitive development
Total polychlorinated biphenyls (PCB)	123,000	N/A	• Lymphoma • Leukaemia • Lung cancer • Reproductive issues • Neurodevelopmental issue • Developmental issues
Polychlorinated dibenzodioxins/furans (PCDD/F) toxic equivalency (TEQ)	206	N/A	
Polybrominated dibenzodioxins/furans (PBDD/F) toxic equivalency (TEQ)	80	N/A	
Benzene (C_6H_6)	875 Million	25	• Chromosomal mutations • Acute myeloid leukaemia
Hydrochloric acid(HCL)	3.5 Billion	39-58	• Respiratory issues • Glaucoma and cataracts
Formaldehyde (CH_2O)	603 Million	50	• Eye irritation and burning • Nasal cancer
Mercury (Hg)	204,000	5-20	• Motor impairment • Cognitive impairment • Memory loss

[a] Correspondence between pollutants and health impacts are presented as in Cogut and not directly substantiated by individual sources, therefore should be treated as indicative.

Several further studies have been carried out to develop emission factors from deep seated waste fires. For instance Lönnermark et al. (2008) combusted approximately 3.5 tonnes of waste collected from 25 waste collection vehicles under three sets of conditions, combustion, combustion with layer removal, and combustion with extinguishments. They then analysed the atmospheric and residual emissions including those from the process water. In a field study near a landfill in Greece that had recently suffered a large fire, (Chrysikou et al., 2008) sampled vegetation for prevalence of polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), potentially toxic elements and organochlorine pesticides (OCPs). The study found that concentrations of virtually all substances were unremarkable compared to the background concentrations expected in Greece. Close to the same site, both Vassiliadou et al. (2009) and Vosniakos et al. (2011) analysed food samples in the surrounding area finding all samples were at normal levels except for some analysed by Vassiliadou et al. (2009) which were slightly above European Union limits in some cases.

A comprehensive review of emissions from all kinds of open burning was carried out by Estrellan and Lino (2010), which built on Lemieux et al. (2004), included a section on disposal sites, providing a range of factors for emissions of DRCs, BFRs and PAHs.

5.5. Health effects of fires on land disposal sites

In an effort to determine the outcomes of pregnancies where mothers had gestated near to the site of a landfill fire in Sicily in 2012, Mazzucco et al. (2019) studied 551 live and stillbirths of mothers living in the area who had conceived within 40 weeks of the incident. The study found preterm birth was 3.41 times (95% CI: 1.04 to 11.16) more likely compared to the 22, 341 Sicilian births over the same study period and that very low birthweight was 4.64 more likely (95% CI: 1.04 to 20.6).

In another study Gjoka et al. (2012) determined the risk to human health from open burning and spontaneous fires of various receptors working on land disposal site in Albania. The study determined hazard indices from inhalation and dermal contact for formal and informal workers on the site, as well as for residents (off-site receptors) living nearby. As shown in **Table 16**, the Hazard Index calculated for each substance and receptor far exceeded World Health Organization Standards, although these were not fully explained in the paper.

Table 16: Hazard exposure from fires at a landfill site (operated as dumpsite) in Albania ; after Gjoka et al. (2012)

Receptor	Specific hazard/ hazardous phenomenon	Reported exposure / risk
Formal workers	TSM (total suspended matter), PM_{10}, SO_2 NO_2	Hazard index on average between 2 and 23 times greater than the World Health Organization standard
Waste pickers Residents	dioxins furans	Hazard index on average between 20 and 300 times greater than World Health Organization standard
Residents	dioxins furans	Hazard index on average between 10 and 180 times greater than World Health Organization standard

Abbreviations: geographical context of study (Geog.); sulphur dioxide (SO2); niu8trogen dioxide (NO2); particulate matter > 10µg (PM_{10}).

5.6. Accidents involving fire on land disposal sites

Ministry of the Environment Energy and the Sea (2016) reported a high prevalence (80%) of accidents involving fires on landfill sites in France (**Table 17**). On dumpsites the prevalence was 53%, but the prevalence of accidents involving explosions was 37%. In contrast, fire and burns represented just 1.6% of injuries observed in the study by Jayakrishnan et al. (2013). Although this difference appears stark, there are considerable inconsistencies in the two studies, one of which analysed accident data, and the other interviewed workers. Reported accidents often exclude less serious accidents or those which workers may wish to keep secret from their employers (reporting bias) whereas interview data are potentially subject to recall bias.

Table 17: Accidents and injuries due to interaction with chemical agents on land disposal sites.

Ref.	Geog.	Site type	Receptor	Sample	Hazard	Reported exposure
Ministry of the Environment Energy and the Sea (2016)	FRA	Landfill	Workers (formal)	Accidents=178	Fire	80%
					Explosion	2%
		Dumpsite	Workers (formal)	Accidents=71	Fire	53%
					Explosion	37%
Jayakrishnan et al. (2013)	IND	Dumpsite	Workers (formal)	Surveyed=313	Fire burns	1.6% (n=5)

Abbreviations: geographical context of study (Geog.).

5.7. Risk characterisation for combustion hazards on land disposal sites

Combustion on land disposal sites scored medium high and very high for both deliberate open burning and landfill fires, which can be caused by accident from fires deliberately started or spontaneously when heat and landfill gas interact with a source of ignition (**Table 18**). The risk to waste pickers was considered to be the greatest as they are acutely vulnerable to open burning at close range. 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. Landfill fires and open burning activities also pose a medium to high risk to populations living in close proximity and they often have few options but to endure the harmful emissions produced.

Table 18: Risk characterisation summary for combustion hazards on land disposal sites

Haz.	Pathway	Receptor	Geog.	Evidence and justification for risk assessment	Uncertainty (aleatoric and epistemic)	Receptor vulnerability	L	S	R	Global receptor context
Open burning	Atmosphere/ inhalation	Land disposal workers (formal)	Global, IND, THA	• Strong evidence of widespread open burning across both LIMICs and HICs (Bundhoo, 2018; Chanchampee, 2010; Christian et al., 2010; Cogut, 2016; Kumari et al., 2017; Nagpure et al., 2015; National Environmental Engineering Research Institute, 2010; Pansuk et al., 2018; Premakumara et al., 2018; Reyna-Bensusan et al., 2018; US Environmental Protection Agency, 2001), however although some data exists to evidence open burning on land disposal sites, it is limited and variable (National Environmental Engineering Research Institute, 2010; Pansuk et al., 2018; Wiedinmyer et al., 2014). • The practice undoubtedly takes place and is referred to in academic literature (Chanchampee, 2010; Oyegunle, 2016; Rim-Rukeh, 2014), film footage (Human Rights Watch, 2017; Lenkiewicz, 2019) and newspaper articles (Chandrashekar and Satyanarayan, 2016; Doshi, 2016). • Emissions from waste open burning have been characterised (Cogut, 2016) though the quantities are based on potentially unreliable estimates (Guendehou et al., 2006).	• Unlike open burning studies in urban, rural and domestic environments, no studies were identified that quantified open burning activities on land disposal sites. • Though there are three estimates available, they are subject to bias in each case. Only one has a large sample size but is from survey data from potentially compromised sources.	• Formal waste workers in HICs not generally exposed, however in LIMICs they may not be provided with respiratory protective equipment and safe systems of work and are therefore highly vulnerable to exposure.	3	4	12	LIMIC
		Waste pickers				• 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	LIMIC
		Population				• Population living in proximity to open burning activities may be more exposed than those who are not and they may have no choice but to endure their exposure to atmospheric pollution. • Children are more vulnerable to exposure due to lower body weight and propensity for mouthing.	3	4	12	LIMIC
Landfill fires emissions	Inhalation	Land disposal workers (formal)	FRA, ALB, ITA, GBR, USA, FIN, SWE ,	• There is evidence (Abdou, 2007; Bates, 2004; Gjoka et al., 2012; Ministry of the Environment Energy and the Sea, 2016) that landfill fires are a common phenomenon in many countries, constituting the main cause of accidents occurring at landfills or dumpsites. • A study (Gjoka et al., 2012) identified that waste pickers and on-site workers were exposed to the highest concentrations of PM10, SO2, NO2, dioxin and furans, exceeding acceptable values by two to three hundred times.	• Did not examine the associated health effects and thus could not demonstrate a causality relationship by extrapolating the recorded exposure findings of waste workers at disposal sites or surrounding population.	• Formal waste workers in HICs not generally exposed, however in LIMICs they may not be provided with respiratory protective equipment and safe systems of work and are therefore highly vulnerable to exposure.	3	4	12	LIMIC/ HIC
		Waste pickers				• 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	

Haz.	Pathway	Receptor	Geog.	Evidence and justification for risk assessment	Uncertainty (aleatoric and epistemic)	Receptor vulnerability	L	S	R	Global receptor context
		Population			• More data is needed to ascertain the prevalence of this phenomenon	• Population living in proximity to open burning activities may be more exposed than those who are not and they may have no choice but to endure their exposure to atmospheric pollution. • Children are more vulnerable to exposure due to lower body weight and propensity for mouthing.	3	4	12	

Abbreviations: likelihood (L); severity (S); risk (R); hazard being assessed (Haz.); total suspended matter (TSM), persistent organochlorine pollutants (POPs); polybrominated diphenyl ether (PBDE); geographical (Geo.); low income and middle income countries (LIMIC); high income countries (HICs).

6. Challenge 4: Physical injury and hearing loss on land disposal sites

6.1. Physical injuries

The heterogeneous nature and wide array of substances, materials and objects on land disposal sites results in an inherent risk of injury to those who work in these facilities or live nearby. Machinery used for handling waste and the vehicles that deliver it to the site add an extra layer of risk, particularly when they operate in close proximity to pedestrians. A summary of the various exposure pathways is shown in the conceptual diagram in **Figure 8**.

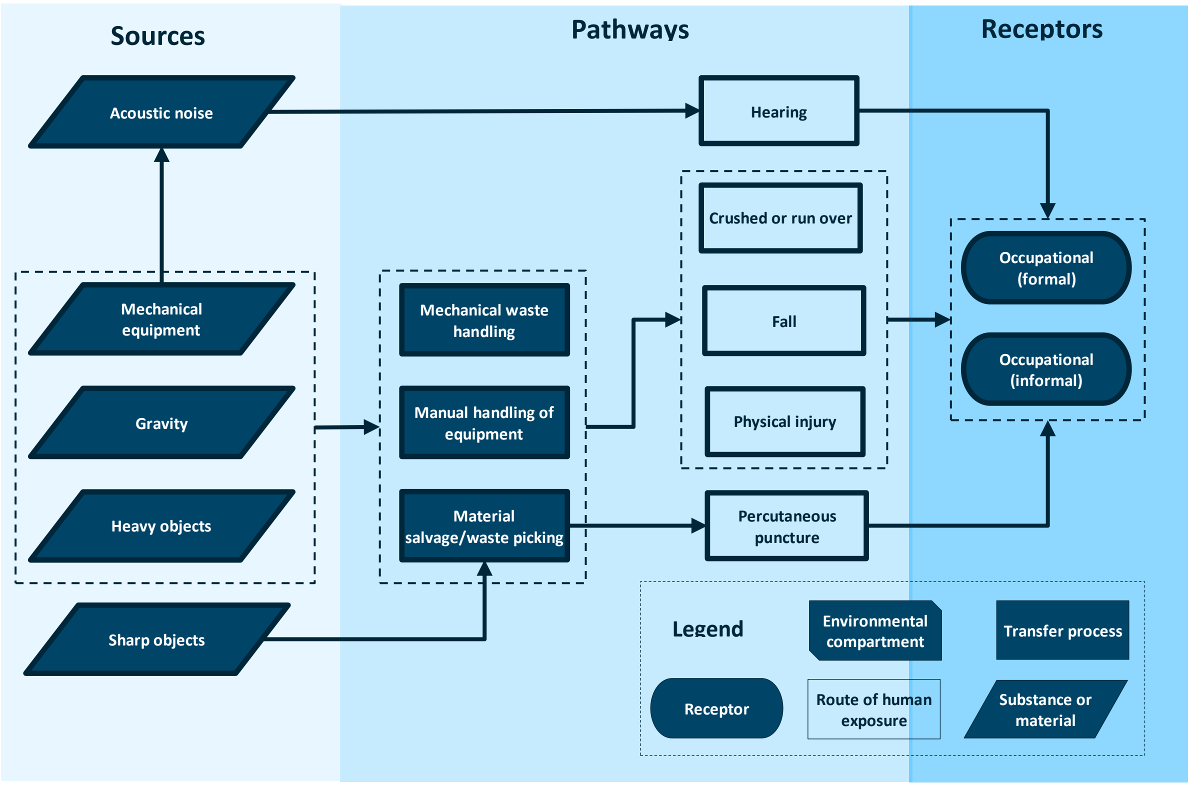


Figure 8: Hazard exposure conceptual model (source – pathway – receptor) associated with accidents, injuries and hearing loss on land disposal sites.

Eight studies reported accident and injury data at land disposal sites (**Table 19**). Abdou (2007) analysed a relatively small number of accident reports at a landfill site in Saudi Arabia, finding that 60% of accidents involved the waste itself, 20% falls from vehicles and 20% involving errors in dealing with 'instruments' (assumed translation is mechanical plant). By contrast, another study of formal workers from the US Department of Labor Bureau of

Labor Statistics (2019) (n=630), found 75% of accidents did not appear to involve waste but were classified as accidents involving transport (8%), over exertion (29%), falls, trips, slips (38%). These categories are only partly comparable but perhaps provide an indication of different approaches to safe working in the US and Saudi Arabia.

Table 19: Injuries on land disposal sites.

Ref.	Geog.	Site type	Receptor	Sample	Specific hazard/hazardous phenomenon	Reported exposure	Reported health effects
Abdou (2007)	SAU	Landfill	Formal workers, supervisors, drivers, others (n=29)	Accidents=28	Accidents involving machinery Fall from vehicles Handling of heavy containers Contact with sharp objects Waste handling	20% 20% 60%	• 60% of musculoskeletal injuries such as fractures, contusions, wounds etc. (17.2 % of health problems, f=5) is due to falls. • Bone and muscle disorders. • 20% of Musculoskeletal injuries (17.2 % of health problems, f=5) is due to sharps. • Respiratory infections and/or allergy (65.5% among reported health problems, f=19), eye infections (48.3%, f=14), and skin infections (3.4%, f=1).
Mothiba (2016)	ZAF	Landfill	Waste pickers	Surveyed=176	Bottle/glass cut Wire cut Injured by metal Total contact sharp object Falls and trips	56% 13% 8% 96% 13%	• Injuries: 22% of participants. • Skin problems (rash, irritation, bruise, cut): 17% of the participants. • Musculoskeletal problems (joint and back pains): 54% of participants • Respiratory problems (cough and shortness of breath): 25% of participants.
US Department of Labor Bureau of Labor Statistics (2019)	USA	Landfill	Workers (formal)	Surveyed=630	Contact object, equipment Falls, slips, trips Overexertion and bodily reaction Transport incidents	22% 38% 29% 8%	• Lower extremities: 16% of participants. • Upper extremities: 33% of participants. • Sprains, strains, tears: 33% of participants. • Cuts, lacerations, punctures: 13% of participants. • Multiple traumatic injuries: 19% of participants.
Ministry of the Environment Energy and the Sea (2016)	FRA	Landfill Dumpsite	Workers (formal)	Accidents=178 Accidents=71	Accidents per facility Accidents per facility	8% 2%	• 22.5% of all the accidents produce negligible or not even known damages.
Jayakrishnan et al. (2013)	IND	Dumpsite	Workers (formal)	Surveyed=313	Fall from vehicle Sharp objects	63.6% (n=199) 73.2% (n=229)	• Respiratory disease: 0.6% of participants (n=60) • Eye problems: 33.2% of participants (n=104) • Skin problems: 36.4% of participants (n=114) • Nail infections: 47% of participants (n=147) • Genitourinary problems: 33.5% of participants (n=105) • Musculoskeletal morbidity: 17-39% of participants (n=54-123)
Afon (2012)	NGA	Dumpsite	Waste pickers	Surveyed=112	Sharp objects Fall from vehicle	61.6% (n=69) 9.8% (n=11)	• Typhoid infection: 50% of participants (n=56) • Dysentery: 38.4% of participants (n=43) • Cholera: 25% of participants (n=28) • Asthma: 10.7% of participants (n=12) • Burns: 60.7% of participants (n=68) • Pneumonia: 33% of participants (n=37) • Skin infection: 42.9% of participants (n=48)
Mitra (2016)	BGD	Dumpsite	Waste pickers	Surveyed=200	Sharp objects	43%	• Low back pain (65% of participants), fever (44%), common colds (39%), and headache (69%)

Ref.	Geog.	Site type	Receptor	Sample	Specific hazard/hazardous phenomenon	Reported exposure	Reported health effects
							• Gastric pain (34% of participants), skin rashes (14%), asthma (15%), & diarrhoea (25%) • Sleeping disturbance: 10% of participants • Small cut and injuries: 47% of participants
Da Silva et al. (2005)	BRA	Dumpsite	Waste pickers	Surveyed=455	Repetitive motion Carrying heavy loads, lifting Frequent body vibration (carts bouncing) Static posture Standing Contact with needles, syringes	91% 84% 54% 78% 84% 27%	• Injuries: 80% of participants, such as cuts (59%), scrapes (15%), hits/contusions (10%), and punctures (9%) • Pain in the lower extremities (upper leg, knee, lower leg, and ankle): 45.1% of participants • Low back pain: 49.2% of participants

Abbreviations: geographical context of the study (Geog.), number (n); frequency (f).

Jayakrishnan et al. (2013), Afon (2012) and Mitra (2016) all reported a high prevalence of sharps injuries among cohorts working on dumpsites, among waste pickers (61.6% & 43%) and formal workers (73.2%). These injuries are possible sources of hepatitis, AIDS, tetanus and other life-threatening diseases (Afon, 2012).

Of the formal dumpsite workers observed by Jayakrishnan et al. (2013), 63.6% had suffered an accident as a result of falling from vehicles, compared to 9.8% among the informal workers observed by Afon (2012). Abdou (2007) also reported falls from vehicles and operating equipment among formal workers on a landfill site in Saudi Arabia, to be a major cause of musculoskeletal injuries (including fractures, contusions and wounds); accounting for 60% of injuries. Sharp objects accounted for 20% of causes. In another study, Mavropoulos (2015) reported that 'errors' in dealing with equipment, such as bulldozers or trucks carrying waste, have led to the death or serious injury of dumpsite workers and informal recyclers.

The majority of studies were based on surveys of workers and just two (Abdou, 2007; Ministry of the Environment Energy and the Sea, 2016) analysed accident report data. Both methods result in some uncertainty, with survey data being subject to recall bias and accident report data subject to reporting bias. The categories were largely inconsistent, with only a few common categories reported making them hard to compare. Improving consistency across studies would be a tremendous benefit to future researchers' analysis. One of the key shortcomings with all the studies was that they were unable to link causality with environmental and occupational exposure, as in many cases to do so would be time-consuming and limited in cohort studies. Longitudinal studies would undoubtedly present an opportunity to determine causality, however these studies are expensive and time-consuming and the transient and informal nature of many of the subjects could lead to considerable drop-out rates over time.

Sarigiannis (2017) and Sarigiannis and Karakitsios (2018) proposed an approach described as the 'exposome concept', which combines mechanistic system modelling with observed exposure and clinical evidence over time to determine causality. While it is beyond the scope here to assess the applicability and efficacy of this approach to determining risk, the premise appears to address some of the shortcomings presented by the data reviewed here.

6.2. Hearing loss

This review identified one study (Ncube et al., 2017a) that quantified worker's exposure to noise on a landfill site in South Africa, identifying the engines of waste collection vehicles and waste handling machinery as being the main sources generating on average 84.32 dBA (A-weighted decibels).

Monotonous noise occurring during offloading of waste and noise connected with handling of specific materials (glass, metal tins) were also reported. The authors note that none of the collection vehicles had noise reduction mechanisms. The mean noise levels measured were below the threshold limit value (85dBA), the highest were measured in the central waste collection points and the lowest were inside the collection vehicles themselves. Two of the workers complained about temporary hearing loss. However, none of the workers wore hearing protection equipment. This suggests that wearing protection devices can be generally recommended as a precautionary measure.

6.3. Risk characterisation: physical injury and hearing loss on land disposal sites

The semi-quantitative risk assessment from physical injury and hearing loss on land disposal sites is shown in (**Table 20**). Contact with sharp objects was scored as a medium-low potential risk for formal workers but a very high risk to waste pickers who are particularly vulnerable to injury and resultant infection. Evidence showed that most of the interviewed landfill and dumpsite workers reported contact with sharp objects, causing injuries.

Falls from vehicles were scored medium-low for both formal workers and waste pickers, indicating it was the major cause of musculoskeletal injuries, and was highly reported among most of the disposal site workers interviewed. However, for both hazard groups evidence was dependent on qualitative data, such as using verbal reports from research participants or face-to-face interviews that might have presented bias results. Further research is recommended to ascertain the prevalence and specifically quantify physical injuries focusing on landfill or dumpsite workers rather than occupational accidents of MSW workers in general.

Risk of hearing loss from noise on landfill sites was scored low in this assessment, acknowledging that the evidence provided was extremely limited and possibly not sufficient to carry out the assessment at all. It is recommended that further research is carried out to establish the potential risk of harm from noise.

Table 20: Risk characterisation summary for physical injury and hearing loss on land disposal sites.

Haz.	Pathway	Receptor	Geog.	Evidence and justification for risk assessment	Uncertainty (aleatoric and epistemic)	Receptor vulnerability	L	S	R	Global receptor context
Contact with sharp objects	Direct contact	Land disposal workers (formal)	BGD, Latin America, BRA, IND, NGA, KSA, ZAF, USA	• Contact with sharp objects was reported among most of dumpsite (Afon, 2012; Cruvinel et al., 2019; Da Silva et al., 2005; Jayakrishnan et al., 2013; Mitra, 2016) (43% to 69%) and landfill (Abdou, 2007; Mothiba, 2016; US Department of Labor Bureau of Labor Statistics, 2019) (96%) workers.	• Sampling size in many studies was relatively small. • Reported exposure-health findings are based on surveyed data, subjective inquiries, or face-to-face interviews and do not link to clinically assessed health outcomes. • Many studies did not focus on accidents specifically in the disposal site but on the waste sector in general. • The type of activities were not always specified in the study.	• While workers in HICs are either prevented from coming into contact with waste through safe systems of work and PPE, in LIMICs many of these measures are unlikely to be implemented leaving them vulnerable to exposure.	3	4	12	LIMIC / HIC
		Waste pickers				• Waste pickers are unlikely to wear ballistic hand or leg protection.	4	4	16	LIMIC
Falls from vehicles	Direct contact	Land disposal workers (formal)	KSA, ZAF, USA, IND, NGA	• Studies (Abdou, 2007; Afon, 2012; Jayakrishnan et al., 2013; Mothiba, 2016; US Department of Labor Bureau of Labor Statistics, 2019) indicate that falls from vehicles were highly prevalent and were reported among 9.8% to 63.6% of interviewed landfill and dumpsite workers.		• While workers in HICs are either prevented from coming into contact with waste through safe systems of work, in LIMICs these may be less likely to be implemented.	3	3	9	LIMIC / HIC
		Waste pickers				• Waste pickers less likely to be riding on vehicles on dumpsites compared to formal workers though they may have less awareness of the safe systems of work which could prevent occurrence.	2	3	6	LIMIC
Acoustic noise	Atmosphere	Land disposal workers (formal) esp. machine operators	ZAF	• One study (Lavigne et al., 2014) measured mean noise levels, which were below the threshold limit value. However, none of the workers wore hearing protection equipment.	• Further studies are needed to assess and quantify noise levels in disposal sites.	• Many workers in LIMICs are not provided with hearing protection.	2	2	4	LIMIC
		Waste pickers				• Waste pickers are unlikely to wear hearing protection.	2	2	4	LIMIC

Though there is evidence for other ergonomic hazard groups, such as waste handling, handling of heavy containers and equipment, slips, trips, errors in dealing with machinery or machinery failures, and regular repeated motions and body vibration, the evidence to link the observed hazards to negative health outcomes is insufficient to carry out an indicative risk assessment, such as that presented here. Therefore, these occupational accidents and hazards were not scored in this assessment. Abbreviations: likelihood (L); severity (S); risk (R); hazard being assessed (Haz.); geographical (Geo.); low income and middle income countries (LIMIC); high income countries (HICs).

7. Challenge 5: Meteorological and geophysical hazards on land disposal sites

7.1. Context

Land disposal sites may contain several million tonnes of waste, resulting in a large structural matrix of heterogeneous material that forms a new feature in the landscape. These structures are susceptible to meteorological conditions, as well as biological and chemical processes that occur as the waste interacts with biota, producing heat and gas which may combust or explode, and in extreme circumstances collapse. Meteorological processes can also affect the lives of those who are occupationally exposed to them, resulting in poor health and in some cases, fatality from exposure to the elements illustrated in **Figure 9**.

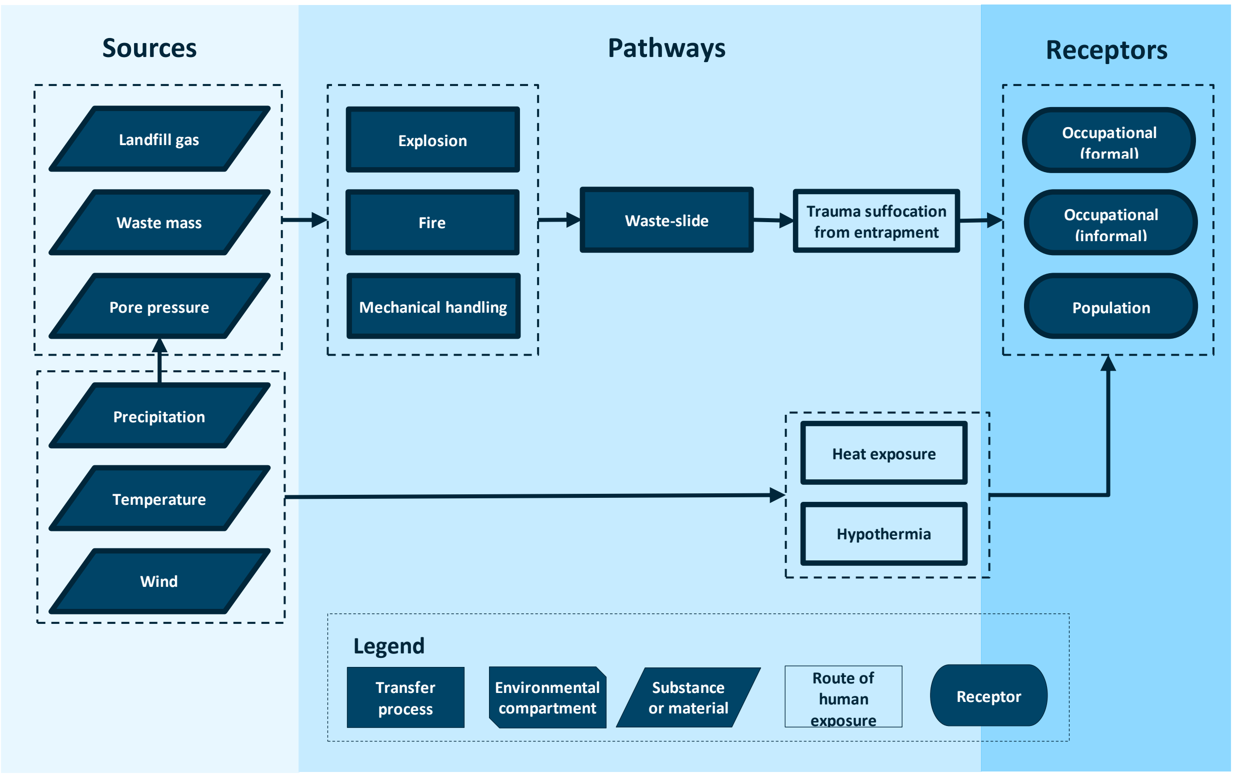


Figure 9: Hazard exposure conceptual model (source – pathway – receptor) associated with meteorological and geophysical hazards on land disposal sites.

7.2. Waste-slope failure

Waste-slope failure on dumpsites and landfills can have catastrophic consequences for those who work or live close to these facilities. There have been three reviews of structural waste-slope failure incidents on land disposal sites since 1977. Here we report their findings and add four further reports from more recent events which total 28 incidents and 866 confirmed fatalities since 1992 (approximately 31 per annum) (**Table S4**). As shown in **Figure 10**, several accidents with large numbers of fatalities have taken place since the early 1990s. It should be pointed out that this part of the review was not comprehensive and it is a recommendation that further intelligence is gathered to ascertain the scale of this phenomenon as it is likely that many incidents go unreported, especially if few injuries are sustained.

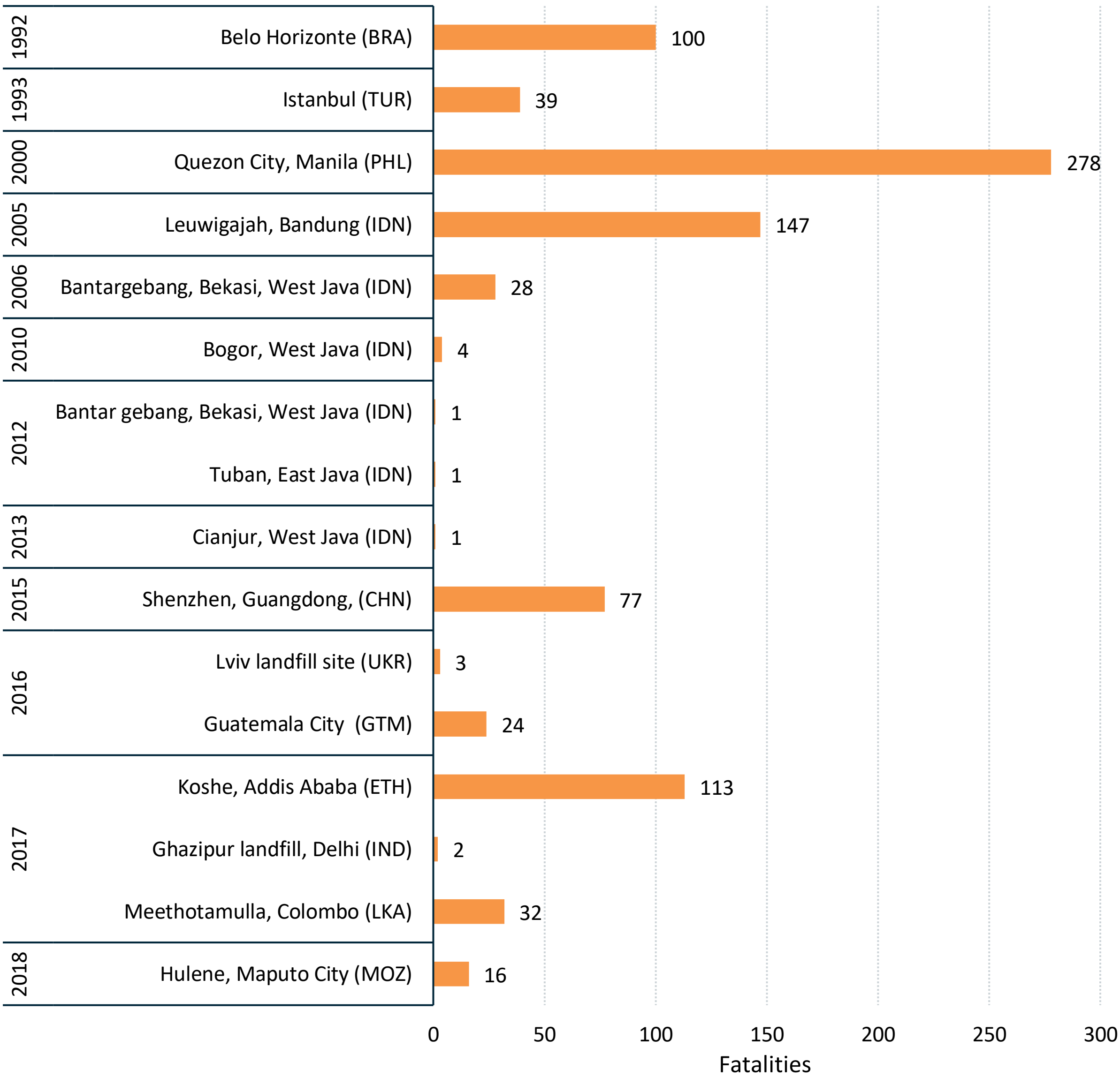


Figure 10: Number of confirmed fatalities at reported waste-slope failures on land disposal sites since 1992 (Data source: references in Table S4 in Section S.5).

The underlying reasons for structural waste-slope failure often combine a range of factors, all of which involve too much waste being deposited in a pile. As moisture builds up within the waste matrix, the pore pressure increases. However, it is the interface between the sub-soil surface and the waste that may be the most important factor as indicated by Koelsch et al. (2005) who carried out forensic analysis of the catastrophic failure at Bandung dumpsite in 2005 that claimed 147 lives and destroyed 71 houses. Koelsch et al. (2005) indicated that a deep-seated fire had damaged waste particles that reinforce shear stability. Combined with high water pressure at the waste sub-soil interface, the pile became mobile. According to Yang et al. (2008), insufficient waste compaction practices may also contribute to slope instability as a higher compaction ratio increases friction between the waste and sub-surface. The activities of the informal recycling sector have also been suggested as a cause of slope instability, created due to participants' efforts to 'mine' valuable materials from the waste matrix (Petley, 2017). This suggestion is entirely anecdotal however, it may present a topic for future research into slope failure mitigation.

Though there are examples of waste slope failures in HICs, virtually all cases and all of the deaths reported take place in LIMICs. A detailed analysis was not carried out here, however the large numbers of deaths appear to affect the poorest people who either work on dumpsites or live very close by. It isn't known how many people are currently at risk from waste slope failure, as there is no comprehensive assessment of the location and magnitude of the world's dumpsites. One study, by D-Waste et al. (2014) aimed to survey the world's 50 largest dumpsites, 42 of which have settlements within 2 km and which are reported to be the workplace of 52,620 waste pickers. The study reported annual deposits of 21.5 Mt y^{-1} in these 50 sites, which means they represent 5.5% of the total annual deposits (392 Mt y^{-1}), an indication of the number of dumpsites that exist, and for which there is no centralised record. This conspicuous gap in our global understanding of dumpsites is a significant barrier toward determining the risk to human health, not only from waste slope failure but from other hazards reported here.

7.3. Meteorological conditions

Two studies assessing exposure to weather and thermal conditions were reviewed (**Table 21**). Ncube (2017) found that workers on disposal sites were performing landfill activities under hot weather conditions with high temperatures, reaching a mean value of 33.3 °C during summer, and often under the sun. The study determined that most of the waste workers complained of headaches, heat stress, dehydration, sunburn, excessive sweating, and difficulty concentrating, as well as nuisance from odours and fly infestation. The author proposed reorganisation of working activities so that they take place during hours with cooler temperatures as well as encouraging workers to take regular breaks and properly rehydrate.

Table 21: Studies quantifying thermal exposure and risk to human health in disposal sites.

Ref.	Geog.	Site type	Receptor	Sample	Average T (°C)	Reported health effects
Ncube (2017)	ZAF	Landfill	Waste workers (formal)	Site workers & machine operators[a]	33.29[b]	• Sweating • Heat stress • Headaches • Sunburn • Dehydration • Difficulties in concentration in assigned tasks
Mothiba (2016)	ZAF	Landfill	Waste pickers	Surveyed =176		• 66% of the waste pickers working on landfill sites answered that they worked continuously, even during rainfall.

[a] Manning waste disposal sites; [b] resulting in offensive odours and high fly infestation from increased organic.

In the study by Mothiba (2016), 66% of the waste pickers working on landfill sites answered that they worked continuously, even during rainfalls. Moreover, waste pickers reported that they used protective equipment against rain, but the author observed the opposite (**Table 21**).

7.4. Risk characterisation for meteorological and geophysical hazards on land disposal sites

The results of the semi-quantitative risk assessment of meteorological and geophysical hazards on land disposal sites showed very high risks from landslides with a strong evidential basis (**Table 22**). Meteorological conditions were scored medium-low risk, however the evidence is lacking to assess the prevalence of harm from these hazards.

Table 22: Risk characterisation for meteorological and geophysical hazards on land disposal sites.

Haz.	Receptor	Geog.	Evidence and justification for risk assessment	Uncertainty (aleatoric and epistemic)	Receptor vulnerability	L	S	R	Global receptor context
Waste-slides	Land disposal workers (formal)	YUG, BIH, USA, BRA, IDN, TUR, SPN, COL, ZAF, ISR, PHL, GRC, CHN, LKA, UKR	• Evidence of 28 waste-slides since 1977 resulting in 866 fatalities since 1992 (approximately 31 per annum) (Blight, 2008; Jayaweera et al., 2019; Lavigne et al., 2014; Nikulishyn et al., 2020; Xu et al., 2017; Yin et al., 2016). • These incidents impact local area swamping land, destroying houses and ruining communities.	• Incidents likely to be an underestimate and it is recommended that further work is carried out to establish the prevalence of these incidents	• Workers may have no control of foresight of a potentially unstable mass	4	5	20	LIMIC
	Waste pickers					4	5	20	LIMIC
	Residents nearby				• Residents have no choice but to live near to unstable landfills and dumpsites	4	5	20	LIMIC
Meteorological conditions	Land disposal workers (formal), esp. machine operators	ZAF	• One study (Mothiba, 2016) identified that 66% of the waste pickers working on landfill sites answered that they worked continuously, even during rainfalls. • Another study (Afon, 2012) found that workers at manning disposal sites were performing landfill activities under hot weather conditions with high temperatures, reaching a mean value of 33.3 °C.	• Further studies are needed to assess and quantify temperature concentrations and level of exposure among workers in disposal sites.	• While workers in HICs are either prevented from contacting waste through safe systems of work, in LIMICs these may be less likely to be implemented.	2	3	6	LIMIC
	Waste pickers				• Waste pickers have no choice but to continue to work in inclement conditions	3	3	9	LIMIC

Abbreviations: likelihood (L); severity (S); risk (R); hazard being assessed (Haz.); geographical (Geo.); low income and middle income countries (LIMIC); high income countries (HICs); upper middle income countries (UMIC); low income and middle income countries (LIMIC); high income countries (HICs).

8. Challenge 6: Psychosocial hazards on land disposal sites

8.1. Context

Psychosocial hazards include anything that may have a negative impact on the mental health or well-being of an individual; for instance, working under stressful conditions, managing emergencies, working long and erratic working days, working night shifts, moving between vehicles and people, sexual harassment and abuse and working in an unpleasant environment (e.g. strong smells, presence of wild animals, insects, rodents, exposure to animal and human faeces, and body parts).

These hazards may manifest as psychological conditions, for example Da Silva et al. (2005), and Afon (2012) who observed that female waste-pickers experience low self-esteem and paranoia. Psychosocial hazards may also affect residents living nearby a dumpsite. For instance, Ziraba et al. (2016) observed that people living adjacent to dumpsites are typically impacted by stench, the sight of scavenging animals and social stigma. Some extreme examples exist where body parts and foetuses have been found, resulting in potential impact to the emotional well-being of the local population engaged in the activity (Schenck et al., 2019).

Although many of the studies reviewed here inferred activities that may result in psychosocial hazard exposure, for instance (Gutberlet, 2012), no quantitative assessments were forthcoming. Nonetheless, two studies (**Table 23**) reported experiences suffered by waste pickers that may result in psychosocial harm. Da Silva et al. (2005) reported that about 50% of the 455 waste pickers interviewed felt discriminated by society. Mothiba (2016) recorded that 38% of landfill waste pickers experienced abuse and 2% were beaten by formal waste workers.

Table 23: Surveys of psychosocial hazards experienced by waste pickers on disposal sites.

Ref.	**Geog.**	**Site type**	**Receptor**	**Sample**	**Experience**	**Reported exposure**
Da Silva et al. (2005)	BRA	Dumpsite	Waste pickers	455	Discrimination by society	50%
					Experienced abuse	38%
Mothiba (2016)	ZAF	Landfill	Waste pickers	176	Beaten by waste depositors	2%

9. Conclusions

In response to the lack of consolidated and arranged literature on occupational and public safety relating to on-land disposal sites, a systematic review was carried out for the first time based on PRISMA guidelines (Moher et al., 2009). Our underlying purpose was to identify the aspects of land disposal sites that result in the most harm to human health and life. Whereas the majority of land disposal sites in HICs are technologically mature and well-managed, the lack of financial resources to implement the same level of engineering and organisation are beyond the reach of operators in many LIMICs. Dumpsites (uncontrolled land disposal facilities) persist across the world, and it is likely that this will continue for many decades.

Here, we have focussed our efforts on land disposal sites in LIMICs, and in particular, the risks faced by the estimated 4.2 million waste pickers and 74,000 formal operatives that work under sub-standard conditions. Using hazard-pathway-receptor combinations identified in the literature, we semi-quantitatively assessed and ranked risks to allow comparison and direct the focus of future mitigation efforts; mapping them onto conceptual diagrams for each ‘challenge’, combined in **Error! Reference source not found.**.

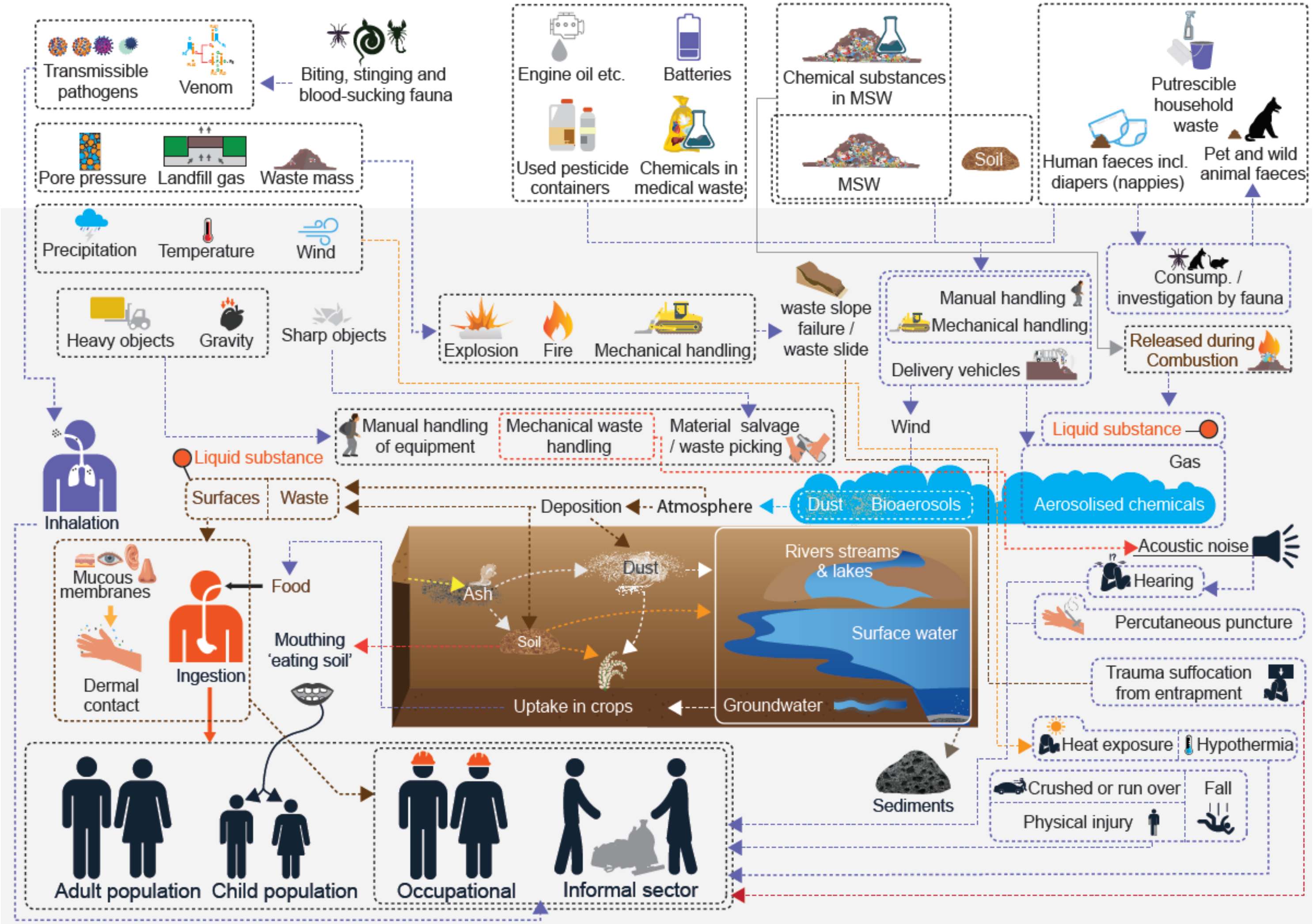


Figure 11: Hazard exposure conceptual model (source–pathway–receptor) for on-land disposal sites for solid waste (from dumpsites to engineered landfills).

Waste pickers (informal recyclers, IRS) spend their days working extremely closely with the waste that is deposited on land disposal sites, walking and rummaging through large piles, and risking interaction with potentially hazardous substances, objects and vehicles that move and deposit waste. Injuries amongst both formal and informal waste workers are common on land disposal sites in LIMICs, particularly with sharp objects some of which may be of medical origin. Our semi-quantitative assessment of the comparative risk indicates a high risk to human health from infection with pathogens introduced into the body via percutaneous puncture with sharp objects. However, the sample sizes and number of studies to indicate harm are small; it is therefore challenging to compare and derive a quantitative risk to human health given these shortcomings without more detailed research.

In contrast to accident data, a much larger body of research exists that has quantified exposure to bioaerosols on land disposal sites, in which the majority of studies have been carried out at facilities in Poland. Whilst it is clear that a high level of potential exposure is experienced by land disposal workers, there is great uncertainty over the effect of bioaerosols on human health; and as such, the thresholds set by regulators are precautionary. The proximity to the waste in which waste pickers work, coupled with their lack of protective equipment makes them particularly vulnerable to bioaerosol inhalation. Waste pickers experience a range of morbidities that may be associated with the close contact with both bioaerosol and non-aerosolised pathogens; however, the studies reviewed here, did not control for confounding factors and therefore any causative link is speculative.

The closeness with which waste pickers and other land disposal staff work to low temperature open waste fires was identified as one of the greatest causes for concern as many dumpsites and landfill sites, particularly in LIMICs, are on fire to some degree. Fires start spontaneously, accidentally and deliberately and may smoulder for many years, yet there is no data on the mass of material that is combusted in these facilities beyond two estimates that lack empirical basis. Uncontrolled burning of mixed MSW releases a cocktail of potentially hazardous substances that can potentially affect the health of entire populations who live nearby. However, waste pickers have an intrinsic vulnerability to exposure because they need to work nearby to fires (which they may also be responsible for starting) so that they can access the material upon which their livelihoods depend.

Together with high waste mass and moisture, fires are thought to be, at least partially, the cause of waste slope failure, a phenomenon that can result in the collapse of large piles of waste that have been deposited in dumpsites when a loss of shear stability occurs between the waste mass and the ground beneath. Here, we updated several previous reviews of the prevalence of waste slope failure dating back several decades, finding that on average, 31 people have lost their lives every year since 1992 due to these catastrophic occurrences. The proximity in which some of the world's poorest people live to large piles of waste (informal settlements upon or next to dumpsites) that continue to accumulate is an unacceptably high risk given the potential consequences of collapse. However, our lack of knowledge about where these sites exists, makes an assessment of potential risk challenging.

The hazard-pathway-receptor combinations derived from our systematic review were grouped into six 'challenges' to allow the considerable data to be easily digested, arranged and so that research-gaps could be revealed. With the exception of Challenge 1, we found the evidence to support understanding of each challenge to be sparse and generally incomplete to the point where a fully comprehensive view could be taken on where to focus efforts. However as we have described, we have provided some direction for future researchers to build upon such as for open burning and waste slope failure.

Many studies reviewed here were unable to correct for confounding factors, reporting for instance high rates of disease or infection in populations that may have had high rates anyway, regardless of their involvement with waste. We found that although the informal recycling sector workforce was many times larger than the formal cohort, that the data were generally more comprehensive for formal workers, indicating a possible bias and misidentification of the most sensitive or vulnerable receptor to which hazards may be exposed. Overall, this review highlights some critical research needs, that given the risk to human health and life posed by increasing, uncontrolled, waste accumulating in dumpsites should be urgently addressed.

CRediT author statement

Amani Maalouf: Data curation; Formal Analysis; Investigation; Writing – original draft; Writing – review & editing. **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. **Antonis Mavropoulos:** Formal Analysis; Funding acquisition; Project administration; Resources; Supervision; Visualization; Writing – original draft; Writing – review & editing. **Linda Godfrey:** Methodology; Resources; Validation; Writing – review & editing. **Harris Kamariotakis:** Data curation; Investigation; Writing – original draft.

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