Construction and demolition waste management: A systematic review of risks to occupational and public health

Ed Cook[a], Costas A. Velis[a,*]

[a]*School of Civil Engineering, University of Leeds, Leeds, LS2 9JT, UK*

*Corresponding author: c.velis@leeds.ac.uk; Telephone: +44 (0) 113 3432327; Room 304, School of Civil Engineering, University of Leeds, Leeds, LS2 9JT, United Kingdom

Abstract

Despite the relatively benign material composition of construction and demolition waste (CDW), its mismanagement can result in considerable harm to human health, not only for the 200 million workers in the sector but also for those who live and work in proximity to construction and demolition activities. The population and workforce in low- and middle-income countries (LIMICs) is most at risk, and therefore we have focussed the attention of a systematic review of evidence that associates CDW with negative health and safety outcomes in those countries. We used PRISMA adapted guidelines to review more than 3,000 publications, narrowed to 49 key sources that provide data on hazard generation, exposure and/or risk. Subsequently, hazard-pathway-receptor scenarios/combinations were formulated, enabling indicative ranking and comparison of the relative harm caused to different groups. Though the evidential basis is sparse, there is a strong indication that the combustible fraction of CDW is mismanaged and disposed of by open burning in many LIMICs, including increasing quantities of plastics used in the sector. It is likely that the off-cuts/residues of these materials will be burned; the high chlorides-content PVC represents a serious risk when combusted in open, uncontrolled fires due to the release of dioxins and related substances. A long-standing and well-known hazard, asbestos continues to represent a threat to construction and demolition workers throughout the world. Despite being banned in most countries, exposure to asbestos particles is thought to claim the lives of a quarter of a million people every year. Though much of this risk is concentrated in high income countries where it has been used over more than half century, it is anticipated that more than half of all deaths from asbestos in the coming decades will take place in India where many asbestos products are still on the market, without any sign of prohibition. Overall highest comparatively risks are concentrated in LIMICs where the majority of workers are informal and highly vulnerable to hazard exposure. Combined with the sheer quantities of CDW, the risks can anticipated to persist – urgent attention to risk mitigation and control is needed.

Keywords: Construction and demolition waste; Safety; Solid Waste; Health and safety; Waste; Informal recycling sector; Recycling; Resource recovery; Circular economy; Global South; Risk; Hazardous waste; Asbestos; PVC; Chromated copper arsenate; Hydrogen sulphide; Potentially toxic elements; Low- and middle-income countries; SDGs; Dioxins; Systematic review.

Abbreviations

ASCC	Australian Safety & Compensation Council
BDEs	brominated diphenyl ethers
BDL	below detection limit
Bq	becquerels
CC	chlorocresoles
CCA	chromated copper arsenate
CDW	construction and demolition waste
CHLs	chlordanes
conc.	concentration
CP	chlorophenols
DO	dissolved oxygen
DRCs	dioxins and related compounds
EPS	expanded polystyrene
ESAW	European Statistics on Accidents at Work
ESAW	Eurostat
EWP	engineered wood products
H_2S	hydrogen sulphide
HBCD	hexabromocyclododecane
HBCD	hexabromocyclododecane
HEPA	high efficiency particulate or arrestance
hepta-BDE	hepta-brominated diphenyl ether
hexa-BDE	hexa-brominated diphenyl ether
HI	hazard index
HIC	high income countries
HSE	Health and Safety Executive
ind.	industrial
L/S	liquid to solid ratio
LF	landfill
LIC	low income countries
LIMIC	low income and middle income countries
LMC	lower middle income countries
MSW	municipal solid waste
Mt	million metric tonnes
n	number of samples
NGOs	non-governmental organisations
NH4-N	ammoniacal nitrogen
ORP	redox potential
OSHA	Occupational Safety and Health Administration
PA	phenoxy acids
PBDEs	polybrominated diphenyl ethers
PCA	pentachloroanisole
PCB	polychlorinated biphenyls
PCDD	polychlorinated dibenzo-p-dioxins
PCDD/Fs	polychlorinated dibenzo-p-dioxins and polychlorinated dibenzo-p-furans
PCDF	polychlorinated dibenzofuran
PCNs	polychloronaphthalenes
PCP	pentachlorophenol
penta-BDE	penta-brominated diphenyl ether
PM	particulate matter

$PM_{0.1}$	particulate matter < 0.1 µm
PM_{10}	particulate matter < 10 µm
$PM_{2.5}$	particulate matter < 2.5 µm
POP	persistent organic pollutants
PPE	personal protective equipment
ppm	parts per million
PUR	polyurethane
PVC	polyvinyl chloride
PVC	polyvinyl chloride
res.	residential
RQ	research question
SD	standard deviation
SGV	soil guideline values
t	metric tonnes (1,000 kg)
TDS	total dissolved solids
tetra-BDE	tetra-brominated diphenyl ether
TN	total nitrogen
TOC	total organic carbon
TS	total solids
TSS	total suspended solids
TVS	total volatile solids
UK	United Kingdom
UMC	upper middle income countries
US	United States
USD	United States dollars
USEPA	United States Environmental Protection Agency
VSS	volatile suspended solids
WHO	World Health Organization
wt.	weight (i.e. on a weight reporting basis)
XPS	extruded polystyrene

1. Introduction

Construction and demolition waste (CDW) receives considerably less attention in the literature compared to municipal solid waste (MSW) despite being a huge global contributor towards total solid waste generation (estimated 33%) (Balaras et al., 2007). Partly, this can be explained because many of the constituents of CDW are comparatively benign. CDW is characterised (on a weight basis) by mainly high-density materials such as concrete, bricks, metals, soil and gypsum, as well as plastics, along with of a range of composites and assemblies of items and other materials. Because it is often generated during commercial activities, any negative effects on the environment or public health emerge away from the public eye.

CDW is defined a material generated during: construction of new buildings; renovation of old structures; deconstruction of old buildings; and during building demolition. Both construction and demolition wastes share characteristics in that they are comprised of materials that were intended for a similar purpose. However, the mode of generation is often quite different and the materials themselves are subject to quite different conditions during the use-phase. Construction waste could be considered as more easily controlled and separated compared to demolition waste, as its constituents are yet to be bonded into complex assemblies and structures, and are therefore more easily identifiable and separable. For this reason, in high income countries (HIC), CDW has been managed with increasing circularity over recent decades (Ginga et al., 2020).

Historically, the construction and demolition sector has had a poor record for injury and deaths (Sirrs, 2016). This appears to be ongoing, according to data published by the International Labour Organization (2020a) indicating that 20% of all workplace fatalities reported to its database were in the construction industry, more than double the proportion of people working in the sector (8.6%) (Mella and Savage, 2018).

Possibly close to a quarter of a billion people work in the construction sector, of which as much as 80% can come from the informal economy in low- and middle-income countries (LIMICs) and 16% in high income countries (Jewell et al., 2005). In fact, in countries such as India, the Palestinian Occupied Territories and Pakistan, approximately 96-97% of the workforce is estimated to be informal (Mella and Savage, 2018). The high inferred accident and fatality rate and the level of informality in this sector may have profound consequences for the health safety and wellbeing for construction and demolition workers. According to strong anecdotal evidence, informal workers are less likely to operate with safe systems of work, less likely to have medical insurance and often work without personal protective equipment; leaving them with a much higher vulnerability to exposure from chemical and particle exposure (e.g. asbestos) and accidents (Ferronato and Torretta, 2019).

As CDW management is a subset of the construction sector, accident and safety data are rarely reported separately. Several narrowly scoped reviews address demolition safety, such as by Ertaş and Erdoğan (2017), who investigated accident data in the UK and Australia; and by Gürcanli and Müngen (2013), who carried out a similar study analysing prosecution records in Turkey. A large body of data also exists regarding the occupational and public health implications of the management specific CDW components; the most prominent being asbestos, which has claimed many thousands of lives since its commercialisation in the early 20th century and which is expected to continue to do so for several more decades (Driscoll et al., 2005; Furuya et al., 2018b; Odgerel et al., 2017). However, there is very little disaggregated data on CDW management and its safety in the public domain, and no reviews to specifically summarise and critically assess the overall evidence.

In response to the research gap and its relevance due to the large and inherently vulnerable global workforce and the large quantities of CDW being generated, we carry out here a systematic review, taking a material flow systems approach (**Figure 1**). It seeks to bring together, for the first time, a wide range of literature, indicating occupational and public health risks from CDW. The review is divided into three sections, arranged into three activity-based generic 'challenges': (1) Handling and physical processing; (2) Land disposal; and (3): Thermal deconstruction and processing. The intention of these groupings is to help the reader to link identified safety challenges directly with CDW management activities carried out in practice, rather than provide raw data from which they have to abstractly connect with real world activities. For each challenge, we arrange individual risks into hazard-pathway-receptor combinations and semi-quantitatively assign risk scores to indicate and rank the relative harm of various activities within the sector. As a matter control, we specifically exclude the Management of CDW from disasters, war and conflict are kept of scope here, as specific sub-cases warrant a specialist review; these are as shown outside the system boundary (**Figure 1).**

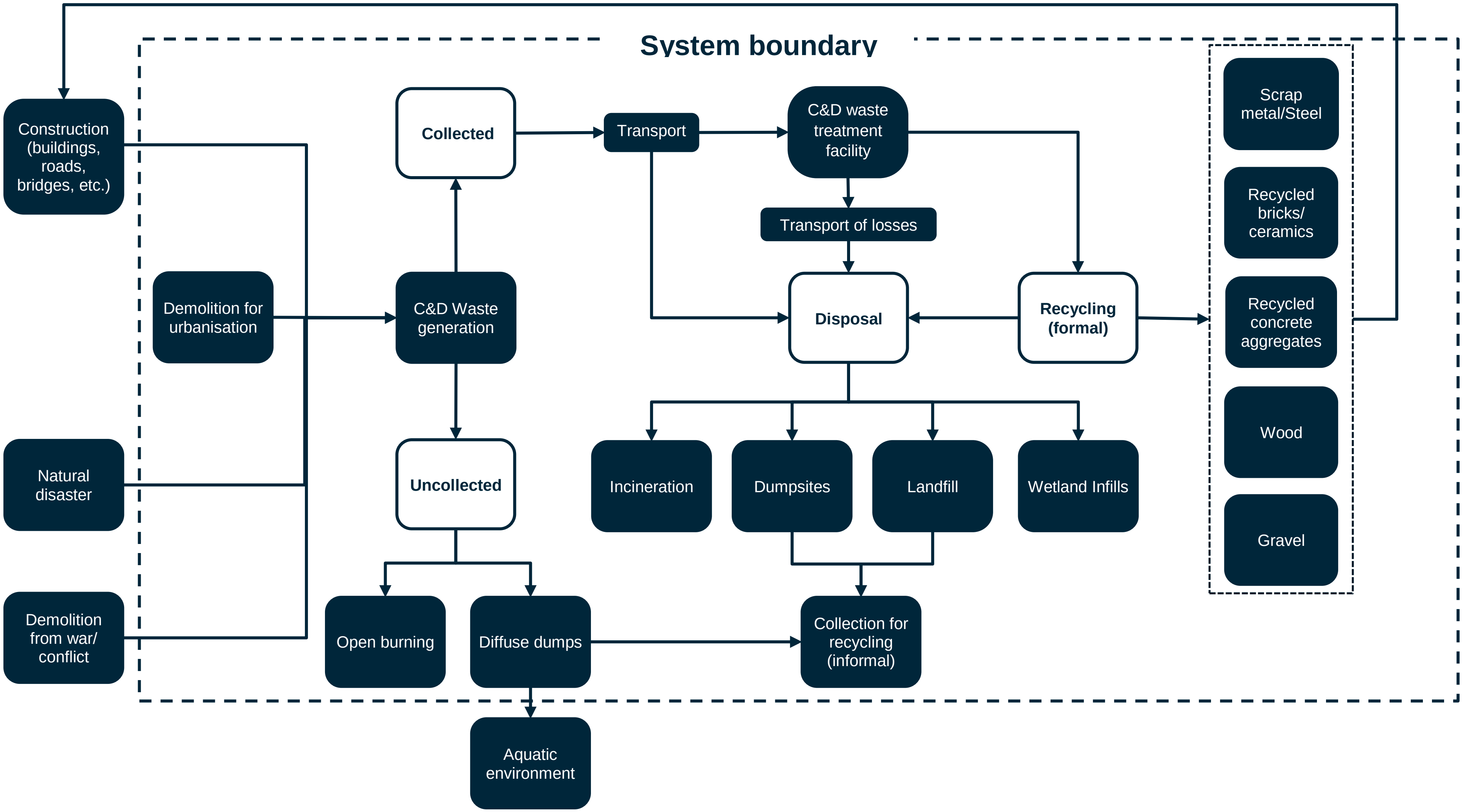


Figure 1: Material flow system for construction and demolition waste (CDW).

2. Methods

2.1. Systematic review

PRISMA guidelines (Moher et al., 2009) were adapted according to a method reported by Cook et al. (2020) to carry out a systematic review to explore the following research questions (RQ):

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

One at a time sensitivity analysis was used to optimise Boolean search terms (listed in **Section S.1.1)** to retrieve literature from Scopus, Web of Science and Google Scholar. Sources were included and excluded according to the criteria in **Table S1** (**Section S.1.2**). Snowball and citation searching (Cooper et al., 2018) was used to obtain further relevant information that had not been revealed during the systematic search. Several further relevant sources were searched in more detail, such as The World Bank (2020), International Labour Organization (2020c), World Health Organization (2020), Health and Safety Executive (2020b) (HSE).

Combinations of hazards, pathways and receptors were identified from the literature and arranged on the basis of realistically experienced scenarios as described by Cook et al. (2020); enabling the preparation of source-pathway-receptor flow diagrams as illustrated in **Figure 2**.

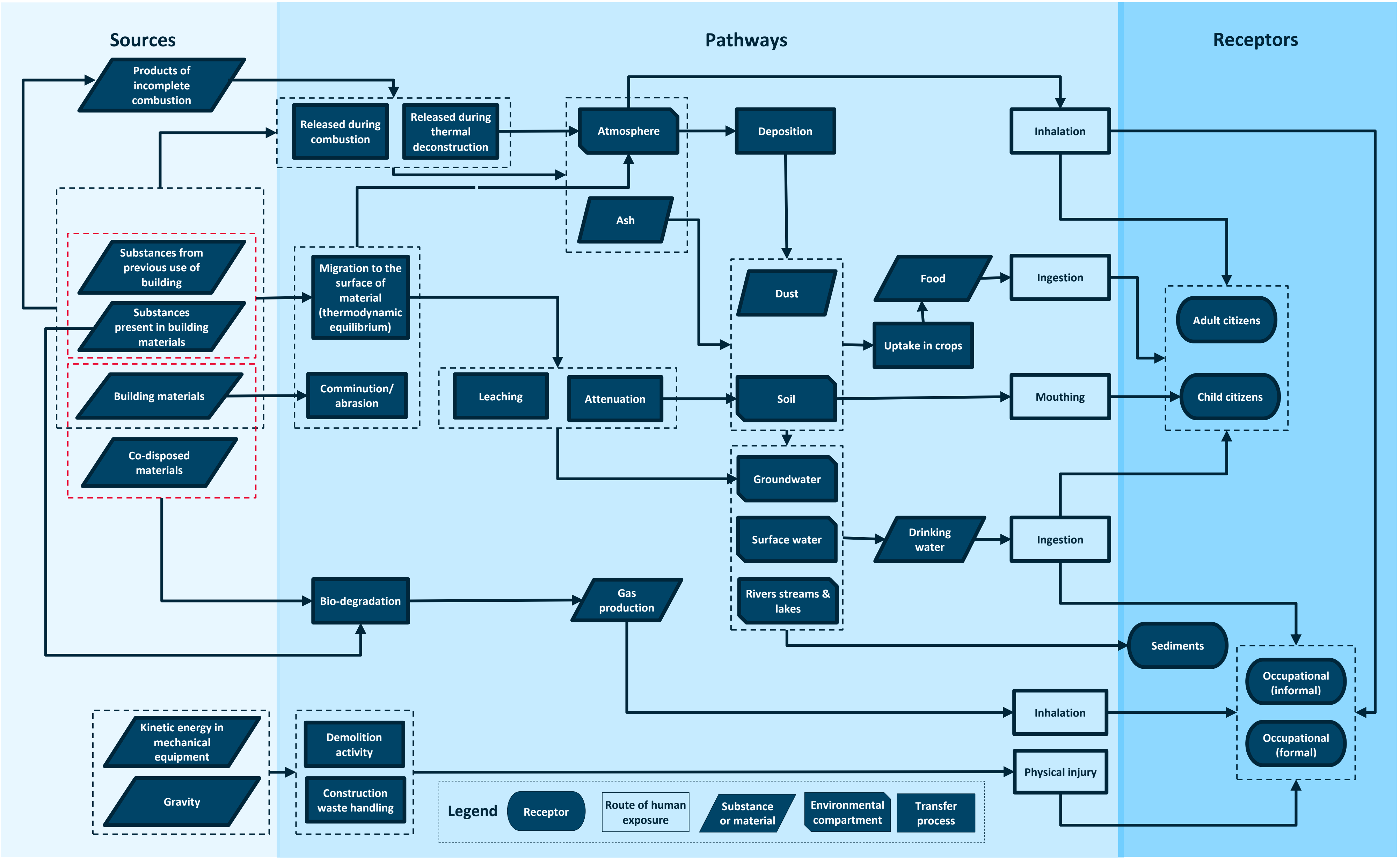


Figure 2: Summary of the main sources, pathways and receptors for hazards associated with construction and demolition waste (CDW).

2.2. Risk based approach

Each hazard-pathway-receptor combination was indicatively assigned a risk score based on the likelihood of it occurring and potential severity to different receptors (**Table 1** and **Table 2**) based on an approach described 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). The reader should note that this process was not intended to quantitatively assess risk, but to indicate and rank the relative risks to prioritise future research agenda; the combined and ranked results are shown in **Table S4** (**Section S.4**).

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: Handling and physical processing of construction and demolition waste (CDW)

3.1. Context

The hazard-pathway-receptor (H-P-R) linkages necessary for potential hazards to be actualised on construction and demolition sites as a consequence of handling and physical processing are shown in **Figure 3**. Broadly these are delineated here by: hazards that exist from materials or substances in construction waste or the previous use of buildings, and physical accidents that take place during deconstruction (demolition) and/or waste removal activities.

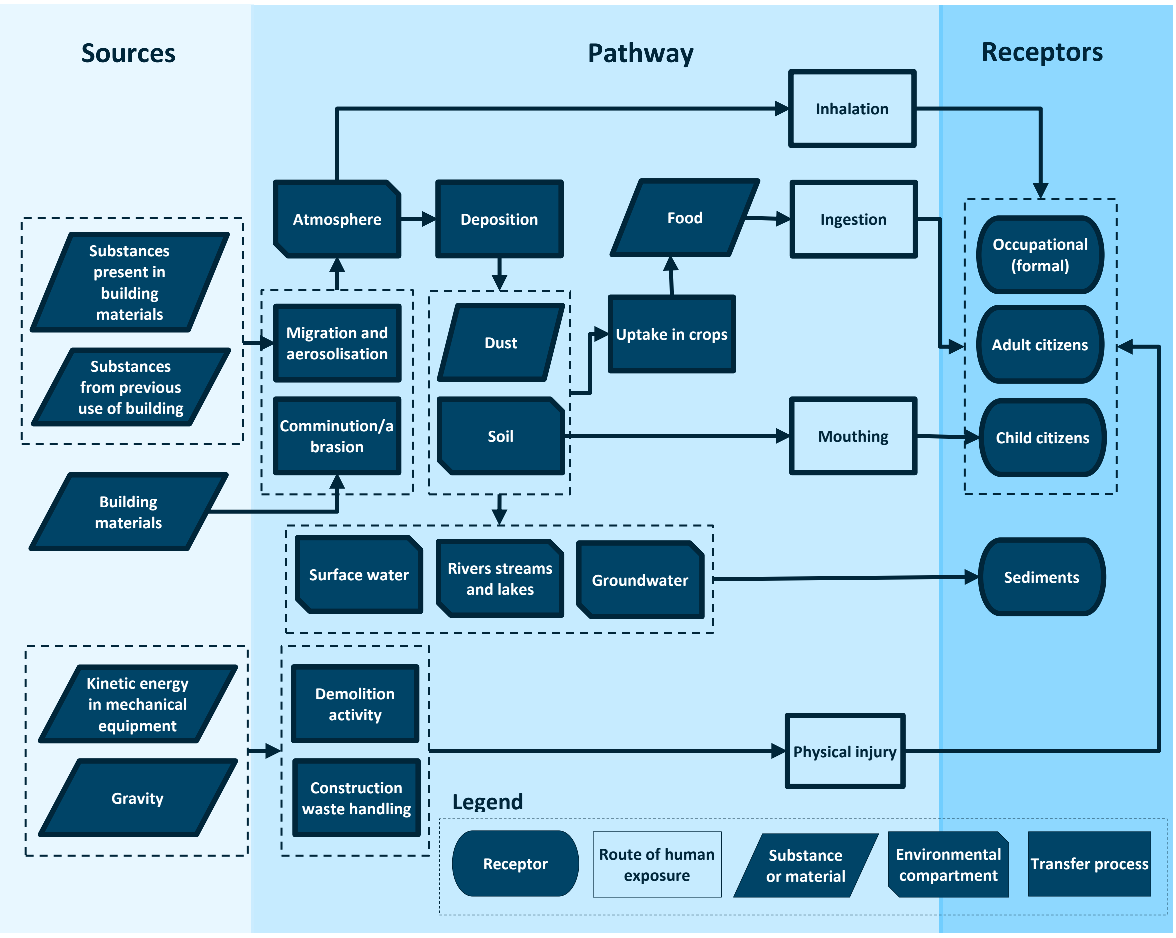


Figure 3: Hazard exposure conceptual model (hazard–pathway–receptor) associated with the handling and physical processing of construction and demolition waste (CDW).

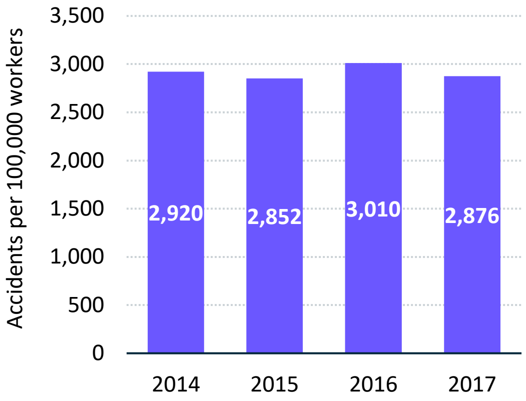
3.2. Accidents involving CDW

Occupational accident data are available from a variety of sources worldwide including from national government institutions, supra-national sources such as the European Union (EU) and from international non-governmental organisations (NGOs) such as the International Labour Organization. According to data from 2016, 20% of all workplace fatalities occurred in the construction and demolition sector (International Labour Organization, 2020a), a category that is rarely reported as two separate components. This is more than twice the proportion of workers participating in this economic activity according to (Mella and Savage, 2018), who suggest it that 8.6% of the global workforce are engaged in construction. Non-fatal accidents are lower than the fatalities as a proportion of the workforce representing 10% of reported non-fatal injuries, (International Labour Organization, 2020b), but still disproportionately higher.

Specific data related to waste and CDW are uncommon. Eurostat (2020) publishes accident statistics reported by European Union member states under their obligations to abide by Regulation 1338/2008 (European Union, 2008b). Data are reported by businesses and institutions to their relevant national governments and then published on Eurostat by NACE (economic) activity. Only accidents requiring more than three days absence from work and fatalities are reported (hereafter '>3 day accidents'); therefore, accidents or near misses that do not result in significant injury are not included in the statistics (European Commission, 2009). Furthermore, Eurostat highlights that many accidents may not be captured because of the data collection method (Eurostat, 2019). For example, if health insurance companies are the source of data collection (as is the case for several member states), then the uninsured may be not be included. There are also several other potentially underrepresented parties, such as self-employed workers who may not report accidents; and public sector, mining and fishing workers who may be covered under specific insurance schemes that do not necessarily submit data (European Commission, 2009).

Some member states provide more granular ('Phase III') information on the 'mode of injury', 'deviation', and 'material agent' involved in accidents reported (Eurostat, 2010). However, these categories are not reported comprehensively as the member states are not obliged to do so. In practice, some member states report under every category, some one or two, and others none at all (European Commission, 2009).

One of the Phase III accident categories reported is 'bulk waste'. Queried together with the NACE category for 'construction and demolition', >3 day accidents involving bulk waste per 100,000 people are shown in **Figure 4** and **Figure 5**. In all cases, the rate has changed little over the four year period, with approximately 3,000 >3 day accidents per 100,000 people reported in the construction and demolition sector, of which approximately five are related to bulky waste.



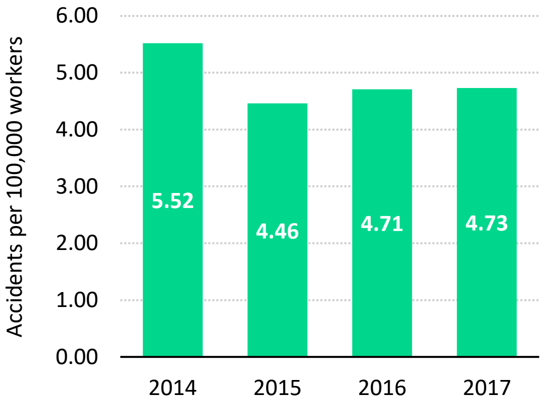
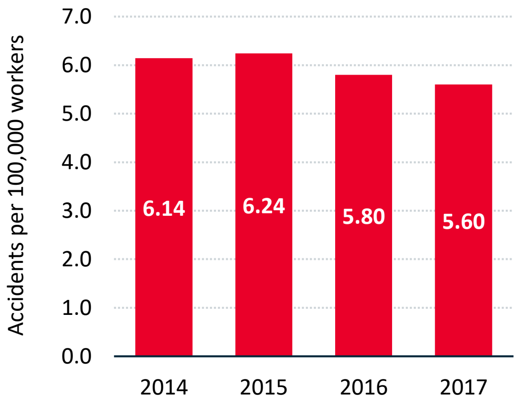


Figure 4: Rate of accidents in the EU28 resulting in more than three days absence from work; NACE activity: construction; after Eurostat (2020).

Figure 5: Rate of accidents in the EU28 resulting in more than three days absence from work; NACE activity: construction; material agent: bulk waste; after Eurostat (2020).

In **Figure 6** and **Figure 7**, the annual fatality rates for construction and demolition and bulky waste are shown respectively, with apparently little change in the four year period in each category.



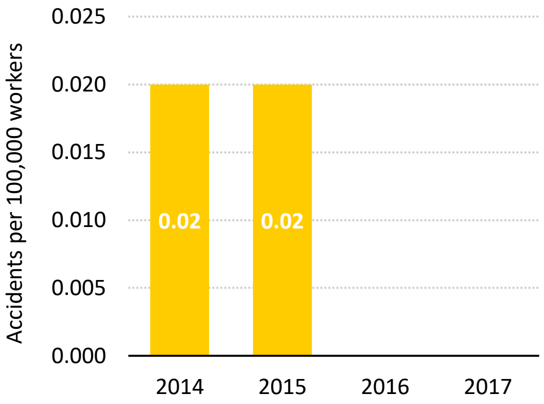


Figure 6: Rate of accidents in the EU28 resulting in a fatality within one year; NACE activity: construction; after Eurostat (2020).

Figure 7: Rate of accidents in the EU28 resulting in a fatality within one year; NACE activity: construction; material agent: bulk waste; after Eurostat (2020).

While the Eurostat data shown in **Figure 5** and **Figure 7** provides an indication of occupational accidents that have been recorded as involving ‘bulk waste’, it is suggested here, that several types of accident involving waste are likely to be omitted from this category and included in others. For instance, exposure to asbestos waste and demolition are grouped under the title ‘construction’ rather than being reported under distinct sub-categories.

3.3. Accidents during the demolition phase

Demolition work is often expected to be faster and less costly than construction work and hence, sometimes results in shortcuts being taken at the expense of occupational health and safety (Ertaş and Erdoğan, 2017). Nonetheless, this section reveals that there is little specific data to evidence the risk of accidents resulting from demolition; a premise supported by at least two other authors (Ertaş and Erdoğan, 2017; Takahashi, 2019; Zaharuddin et al., 2009). Hence, the level of risk exposure to accidents from this important waste activity is poorly understood.

Three sources of information indicate the number of injuries and fatalities from demolition activities as a proportion of all activities (**Table 3**). The data from the European Commission (European Commission, 2009), originate from an older Eurostat dataset than Eurostat (2020) and report a specific Phase III sub-category of ‘Demolition’ for the EU15 in 2005. As discussed, there are significant inconsistencies in reporting of the Phase III categories as well as several other factors that result in under-reporting. Furthermore, the dataset is more than 15 years old at the time of writing. However, given the paucity of data on this subject, and the representative size of the European Commission dataset, (population of EU15 was 384.2 million in 2004 (European Commission, 2006)), it provides the most substantial coverage of demolition accident data revealed in this research.

Table 3: Injuries and fatalities from demolition activities as a proportion of injuries and fatalities from all sectors.

Ref	**Geog.**	**Secondary source / data type**		**n**	**Time-frame**	**Proportion of all fatalities**	**Proportion of all injuries**	**Proportion of all injuries & fatalities**
Maeda et al. (2003)	JPN, Osaka	City forensic post-mortem data	Fatalities	67	1996-2001	7.5%		
European Commission (2009)	EUR	ESAW	Fatalities	2,307	2003-2005 [a]			
			Injuries	1,709,648	2005			
			Total	1,711,955		0.71%	0.16%	0.16%
Zaharuddin et al. (2009)	AUS	ASCC	Total	14,869	2002-2004			0.4%

[a] Sample originally reported over 3 years, therefore divided by three in this table. Abbreviations: Australian Safety & Compensation Council (ASCC); European Statistics on Accidents at Work (ESAW); number of samples (n); geographical context (Geog.).

As a proportion of injuries from all sectors, the European Commission (2009) data indicates that 0.16% of all >3 day injuries and workplace fatalities combined occur in the demolition sector compared to 0.4% in Australia, as reported by Zaharuddin et al. (2009) (**Table 3**). In the EU15, the demolition sector reports a higher proportion (0.71%) of fatalities in comparison to the >3 day injuries. The only other data point that evidences fatalities in the demolition sector is the research by Maeda et al. (2003) who observed a considerably higher proportion of fatalities from demolition activities from a single city in Japan between 1996 and 2001 in comparison to the European Commission. The Maeda et al. (2003) data are alarmingly high in the context of the European Commission rate, which is approximately 10 times lower. There is insufficient evidence from the two studies to explain this large disparity. However, there may be a variety of factors specific to the local conditions in Japan, such as corporate attitudes toward safety; differing regulatory framework; or possibly the influence of a single company’s record. Although the Maeda et al. (2003) dataset is small in comparison to the European Commission dataset, in other studies (Evans, 2014) data on fatalities have been reported to be more reliable than accident data, because almost all fatal injuries are reported to someone, unlike accidents which may not be. In any case, such a high comparative fatality rate warrants further investigation in Japan and other parts of the world to understand the proportion of demolition sector injuries and fatalities that exist elsewhere.

Accident data for the demolition sector as a proportion of construction and demolition as a whole are more numerous than data reported as a proportion of all accidents, with five sources identified (**Table 4**). As the denominator (construction and demolition) is a smaller dataset, it is unsurprising that the proportion of accidents is higher than for demolition activities as a proportion of all categories (reported in **Table 3**).

Table 4: Injuries and fatalities from demolition activities as a proportion of injuries and fatalities from construction and demolition combined.

						Fatalities		**Non-fatal injuries**		**Total**	
Ref	**Geog.**	**Secondary source/data type**	**n**		**Time-frame**	**Number**	**Proportion of all fatalities**	**Number**	**Proportion of all injuries**	**Number**	**Proportion of all injuries and fatalities**
Gürcanli and Müngen (2013)	TUR	Eye-witness accounts from court records	Fatalities	788	1972-2008						
			Injuries	361							
			Total	1,149		30	3.8%	14	3.9%	44	3.8%
Ertaş and Erdoğan (2017)	AUS	Australian Institute of Health and Welfare	Total	8,300	2006-2009					83	1%
	GBR	British Market Research Bureau	Total	5,813	nd					186	3.2%
Zaharuddin et al. (2009)	GBR	Health and Safety Executive (HSE)	Total	659	1997-2005					47	7.13%
European Commission (2009)	EUR	Eurostat – ESAW	Fatalities	1,464	2003-2005 [a]						
			Injuries	226,835	2005						
			Total	227,323		16	1.09%	2,786	1.23%	2,802	1.23%
Takahashi (2019)	JPN	n/a	Fatalities	1,646	2010-2014	107	6.5%				

[a] Sample originally reported over three years, therefore divided by three in this table. Abbreviations: number of samples (n); geographical context (Geog.); European Statistics on Accidents at Work (ESAW).

Whereas the proportions of fatalities and >3 day injuries by the European Commission (2009) in **Table 4** are broadly proportional to those reported in **Table 3**, the overall proportion of accidents and fatalities from demolition reported by Zaharuddin et al. (2009) are nearly six times higher. The Zaharuddin et al. dataset is smaller, and from an earlier timeframe, and the UK has greatly improved its health and safety record for the construction and demolition sector since, as evidenced from the later and larger UK dataset reported by Ertaş and Erdoğan (2017), indicating the accident rate has halved.

The data reported by Takahashi (2019) of demolition fatalities over a five year period in Japan (**Table 4**), have some similarity with the data reported by Maeda et al. (2003) for Osaka, Japan (**Table 3**), in that the fatality rate of the sector is approximately six times higher than the European Commission and nearly twice the proportion reported by Gürcanli and Müngen (2013) in their study of Turkish eye-witness court testimonies. Takahashi et al. noted that it was common practice among demolition workers in Japan to cut a hole in the floor of a building under deconstruction to pass valuable scrap metals through for recycling and that the technique for demolishing walls was to manually weaken the bottom before mechanically pushing walls over with a mechanical plant. While limited evidence was revealed to indicate the underlying causality of accidents, the testimony by Takahashi et al. ought to provide the basis for further investigation of attitudes toward safety in specific cultures. Japan is a HIC, and intuitively ought to possess the resources necessary to train and equip its workforce to carry out potentially hazardous activities under a safe system of work. Speculatively, if conditions are as hazardous as the Japan data suggests, then it is conceivable that many LIMICs with less rigid regulatory frameworks and less ingrained health and safety culture may also have a poor accident and fatality record.

Understanding the types of activity that result in injuries or fatalities and the type of accident itself is crucial to developing safe systems of work to mitigate the probability of them occurring in the future. In studies from both the USA (Ertaş and Erdoğan, 2017) and Japan (Takahashi, 2019), demolition workers were most likely to suffer a fatality as a result of a fall from height or a building collapse (**Table 5**). Zaharuddin et al. (2009) reported a similar proportion for demolition workers in the UK, with approximately 53% of fatal and non-fatal accidents being caused by collapse and 28% caused by a fall. While the data for these four accident types shows some congruence, other accident types reported in **Table 5** are less consistent, making the data challenging to compare.

Table 5: Injuries and fatalities from specific activities or causes as a proportion of injuries and fatalities from demolition activities.

					Fatalities		Non-fatal injuries		Total	
Ref	**Geog.**	**Secondary source/data type**	**Receptor/activity**	**Time-frame**	**Number**	**Proportion of all fatalities**	**Number**	**Proportion of all injuries**	**Number**	**Proportion of all injuries and fatalities**
			Collapse of building		119	31.07%	69	25.56%	188	28.79%
			Fall from height		105	27.42%	66	24.44%	171	26.19%
			Struck by falling object/flying debris		73	19.06%	57	21.11%	130	19.91%
			Machinery		42	10.97%	14	5.19%	56	8.58%
			Slip/trip/fall		14	3.66%	25	9.26%	39	5.97%
			Electric shock		16	4.18%	2	0.74%	18	2.76%
			Fire		3	0.78%	13	4.81%	16	2.45%
			Ballistic injury [a]		2	0.52%	11	4.07%	13	1.99%
			Traffic accident		1	0.26%	1	0.37%	2	0.31%
			Asbestos exposure		0	0.00%	3	1.11%	3	0.46%
			Other		8	2.09%	9	3.33%	17	2.60%
Ertaş and Erdoğan (2017)	USA	OSHA	Total demolition	1984-2012	383	100.00%	270	100.00%	653	100.00%
			Falls						13	27.66%
			Transport						5	10.64%
			Collapse						25	53.19%
			Struck-by						2	4.26%
			Miscellaneous						2	4.26%
Zaharuddin et al. (2009)	GBR	HSE (2008)	Total demolition	1997-2005					47	100.00%
			Fall		56	52%				
			Collapse		20	19%				
			Come flying (Flying object) [b]		9	8%				
			Take crash (Crash) [b]		7	7%				
			Get between (Crush) [b]		6	6%				
			Other		9	8%				
Takahashi (2019)	JPN	Japan (Ministry of Health, Labour and Welfare 2018)	Total demolition	2010-2014	107	100%				

[a] Cuts/scratches/jamming/hitting/puncturing/manual handling; [b] direct descriptions are shown and assumed translations are suggested in brackets. Abbreviations: number of samples (n); health and safety executive (HSE); Occupational Safety and Health Administration (OSHA).

Analysis by Gürcanli and Müngen (2013) of eye-witness accounts of accidents over 36 years in the Turkish construction sector provides some indication of the types of demolition activity that resulted in injuries and fatalities over the period (**Table 6**). Compared to other reports, the injury and fatality data appear low in absolute number terms, with less than one fatality and slightly more than one injury over the 36 year period, compared to Japan which reports approximately 21 fatalities per year between 2010 and 2014 (Takahashi, 2019) (**Table 5**). Gürcanli and Müngen (2013) report an additional reason to query the low reported fatality and injury rates: the country has no specific health and safety legislation, suggesting that the lack of regulatory framework would result in an accident rate that far exceeded other countries where a framework exists.

Table 6: Demolition work activity being carried out at the time of accident; after Gürcanli and Müngen (2013).

	Fatalities		**Non-fatal injuries**		**Total fat and non-fatal**	
Receptor/activity	**Number**	**Proportion of all fatalities**	**Number**	**Proportion of all injuries**	**Number**	**Proportion of all injuries and fatalities**
Demolition roof and slab	3	10.00%	2	14.29%	5	11.36%
Demolition walls	16	53.33%	8	57.14%	24	54.55%
Demolition structural elements [a]	9	30.00%	4	28.57%	13	29.55%
Other demolition	2	6.67%	0	0.00%	2	4.55%
Total demolition	30	100.00%	14	100.00%	44	100.00%

[a] For example, columns and beam; Data sourced from eye-witness accounts from court records in Turkey between 1972 and 2008.

Data reported by Gürcanli and Müngen (2013) only included cases that were examined by the courts, and the authors cautioned that, at the time of writing, official Turkish statistics are unreliable indicators of accidents because they only report injuries and fatalities for which a conviction was successful. If there is a societal aspiration to reduce accidents across the demolition sector, then the data shown in this section highlight the need for a more harmonised global system of reporting, without which cost-effective interventions cannot be targeted where most needed.

3.4. Asbestos

Asbestos is the generalised term used to describe a group of naturally occurring fibrous silicate minerals that have been used in a variety of commercial and industrial applications for many thousands of years (Furuya et al., 2018a). Materially, asbestos has impressive physical properties such as insulation, tensile strength, and low density/strength ratio (lightness) (Dodson and Hammar, 2012). Despite these attributes, asbestos is best known for its carcinogenicity, linked to many thousands of deaths each year worldwide.

There are six main types of asbestos (**Table 7**), three of which have been sold commercially since the first large scale industrial extraction in Quebec in 1876 when approximately 50 tonnes was mined (Henderson and Leigh, 2012).

Table 7: Types of asbestos and their formulae; adapted from Henderson and Leigh (2012).

Common group	**Group type**	**Asbestos type**	**Chemical formula**
White asbestos	Serpentine	Chrysotile	$Mg_3Si_2O_5(OH)_4$
Blue asbestos	Amphiboles: commercial	Crocidolite	$Na_2(Fe_{32}+)(Fe_{23}+)Si_8O_{22}(OH)_2$
Brown asbestos		Amosite	$(Fe, Mg)_7Si_8O_{22}(OH)_2$ Fe>5
Never sold commercially but often found as contaminants in other asbestos products	Amphiboles: non-commercial	Tremolite	$Ca_2Mg_5Si_8O_{22}(OH)_2$
		Anthophyllite	$(Mg, Fe)_7Si_8O_{22}(OH)_2$Mg>6
		Actinolite	$Ca_2(Mg, Fe)_5Si_8O_{22}(OH)_2$

During the 20th century, asbestos became an increasingly popular material and was used in approximately 3,000 to 4,000 product applications, including insulation materials, cement reinforcement, roofing, brakes, fire resistant textiles, gas masks and wine filters (Frank, 2006; Henderson and Leigh, 2012; Ogunseitan, 2015). Production rose sharply following the Second World War, reaching its peak in 1980 (**Figure 8**), after which concerns over its safety resulted in successive bans across Europe and in the US (Kazan-Allen, 2019a).

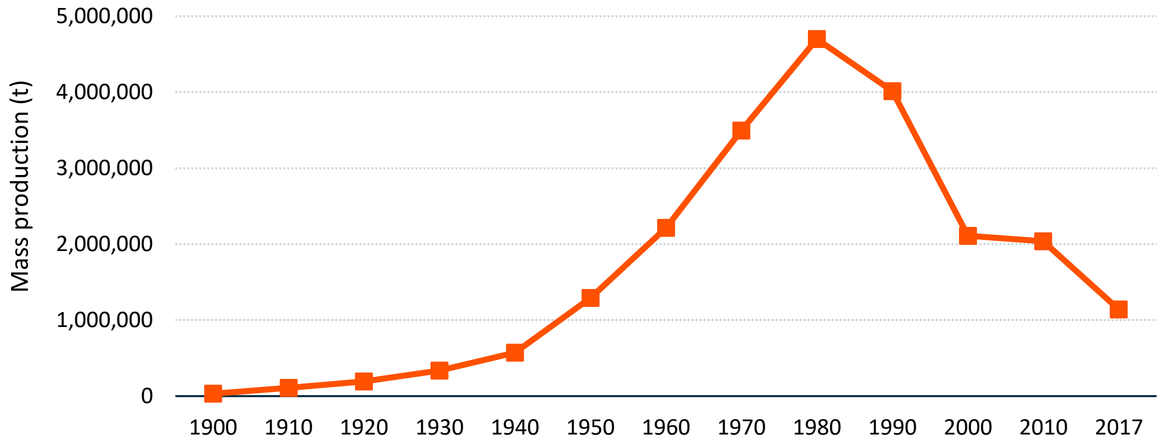


Figure 8: Global asbestos production 1900-2017; data from Virta (2006) and National Minerals Information Center (2018). Abbreviations: metric tonnes (t).

Both Amphiboles (Crocidolite and Amosite) were effectively banned by the mid-1980s in most western countries and chrysotile asbestos has been banned in many countries since. Nonetheless, asbestos was still consumed in 39 countries worldwide in 2017 (**Figure 9**) and production continued in four, with Russia producing nearly two thirds of the 1.1 Mt consumed worldwide that year (**Figure 10**).

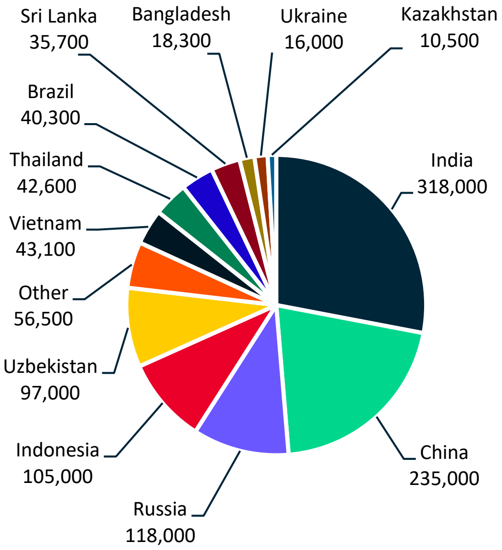


Figure 9: Asbestos consumption by country in 2017 (tonnes); data after National Minerals Information Center (2018).

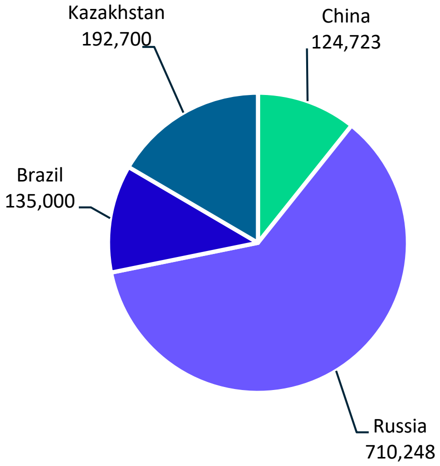


Figure 10: Asbestos production by country in 2017 (tonnes); data after National Minerals Information Center (2018).

According to Flanagan (2020), reliable data on global asbestos production and consumption have not been published in recent years. There is also an apparent continuing downward trend in production, including the closure of the last mine extracting asbestos in Brazil in 2020 that accounted for 12% of global production in 2017 (**Figure 10**). India and China are the largest asbestos consuming countries, representing nearly half of global consumption. Although the data since 2010 indicates a general reduction in consumption in Russia and China, continued use is apparent in India (**Figure 11**), where there are no restrictions on its production and consumption (Jadhav and Gawde, 2019). Specific data are not available, but it has been reported that in India almost all asbestos is used in cement bonded sheet material (Burki, 2010), and the International Chrysotile Association (nd) reports a similar picture elsewhere. Of course other applications continue, including: insulating protective equipment for fire-fighting and brakes for automobiles (Frank, 2006; Henderson and Leigh, 2012; Ogunseitan, 2015).

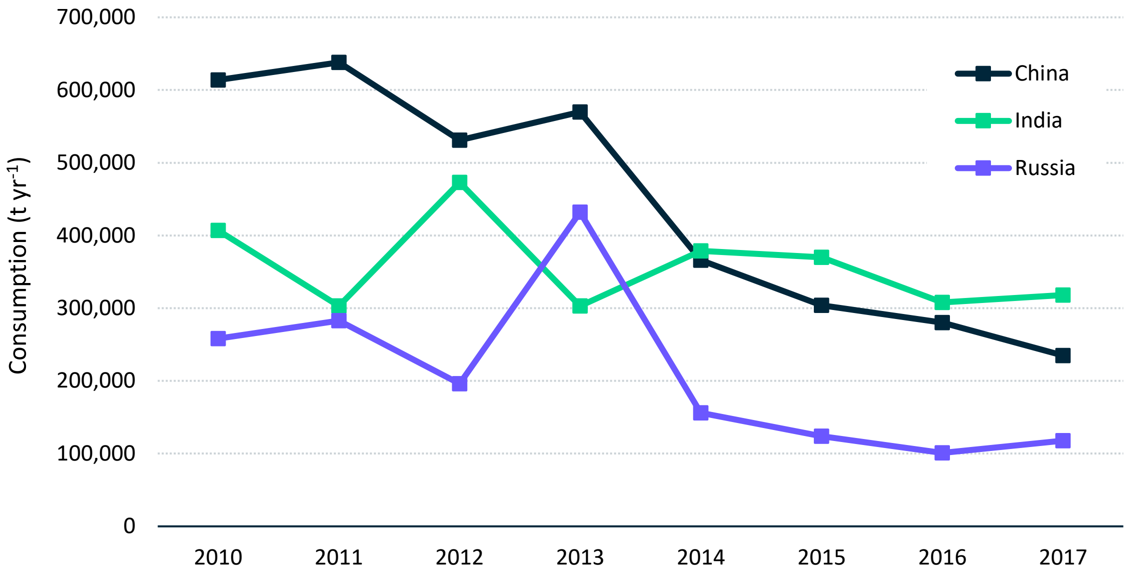


Figure 11: Asbestos consumption trends for the top three consuming countries; data after National Minerals Information Center (2020).

Undisturbed, most forms of asbestos pose little danger to those in close proximity, particularly when the fibres have been encapsulated in resin (for example, floor tiles) or cement (for example roofing sheets) (Siegel, 1991). Asbestos fibres are mineral and do not volatilise, so they only represent a hazard when they have been weathered or otherwise abraded from the material after which solid particles can easily aerosolise (become suspended in the atmosphere) and be potentially inhaled (IARC Working Group on the Evaluation of Carcinogenic Risks to Humans, 2012). In the lungs, the barbed asbestos particles become lodged, causing inflammation and scarring over time, and resulting in several diseases. The link between mesothelioma, a malignant cancer of the pleura, and both occupational and non-occupational exposure to asbestos was established in the 1960s (Henderson and Leigh, 2012) and since then, occupational asbestos exposure has been the subject of more than 100 cohort studies and several reviews (Concha-Barrientos et al., 2004); the World Health Organization (WHO) estimates that approximately 125 million living people have been exposed (Spasiano and Pirozzi, 2017).

Estimates of the number of deaths caused by asbestos exposure vary. Although it is linked to several diseases, including lung cancer, ovarian cancer and kidney cancer (Frank and Joshi, 2014), the death rate for mesothelioma is a strong indicator as virtually all are thought to be a result of asbestos exposure (Driscoll et al., 2005; Stayner et al., 2013). The WHO Mortality Database (World Health Organization, 2019) provides a record of reported cases of mesothelioma from countries that submit data. Vanya et al. (2011) analysed the database entries from 1994 to 2008, finding generally low levels of reporting. For instance, in 1995 just four countries submitted data, rising to 75 in 2003 and 100 by 2007. As shown in **Table 8**, cases were almost three times higher between 2001 and 2008 compared to 1994 to 2000. Almost 88% of cases reported were in high income countries, with negligible numbers reported in low income countries. This is partly explained by the number of countries that submitted data; clearly much greater in the HICs. However, mesothelioma is still a comparatively rare condition that is not always easy to diagnose; often requiring cumulative experience which can take many years for the medical profession to accumulate (Odgerel et al., 2017). Therefore it is likely that many cases in LIMICs are not classified as mesothelioma and are consequently not reported, rather than the low numbers of cases being a reflection of safe working practices around asbestos (Li et al., 2014).

Table 8: Deaths from mesothelioma reported to the World Health Organization (2019), as analysed by Vanya et al. (2011).

			Deaths		
Geog.	**n**	**Temporal scope**	**All**	**Male**	**Female**
	63	1994-2000	22,305		
	77	2001-2008	69,984		
Global	83	1994-2008	92,253	72,000	20,252
High income	39		81,313		
Middle income	37		10,906		
Low income	2		22		
Not available	5	1994-2008	12		

Abbreviations: number of samples (n).

Taking a mean of the global deaths reported between 2001 and 2008 (**Table 8**), indicates 8,748 annual cases of mesothelioma each year, considerably lower than a previous estimate of 43,000 per annum estimated in 2005 by Driscoll et al. (2005). To estimate the unreported cases, Odgerel et al. (2017) used the WHO Mortality Database (World Health Organization, 2019) to model deaths from mesothelioma in the countries that either didn’t report or appeared to underreport. The study based the estimates on the historical use of asbestos in each country, the level of employment in the construction sector, and the continental average.

For example, in **Figure 12**, the continental adjusted data are compared with the reported data, revealing huge underreporting in Asia and Africa.

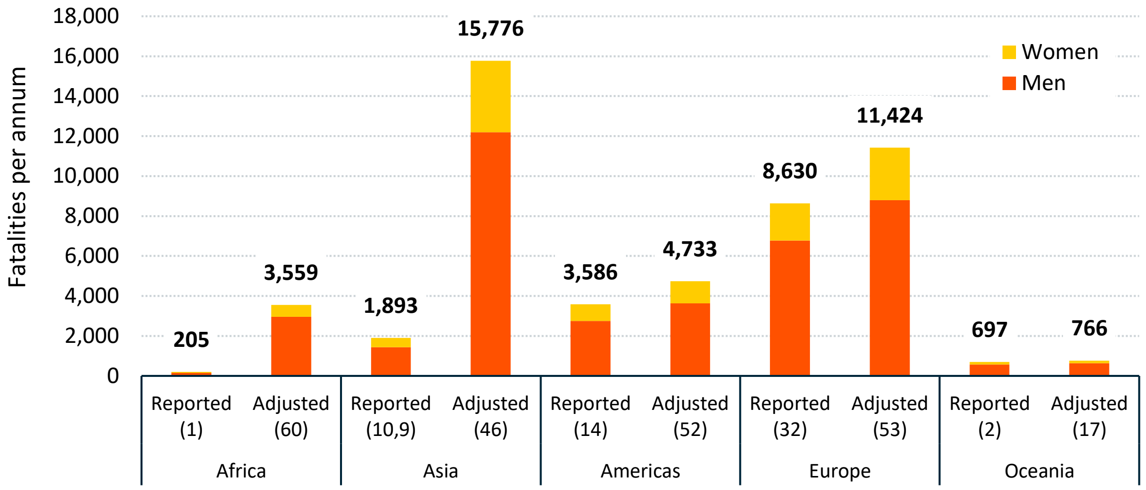


Figure 12: Global mesothelioma deaths region reported to the World Health Organization (2019) alongside adjusted data calculated by Odgerel et al. (2017).

As with the reported data, the proportion of women dying from mesothelioma in the estimated (adjusted) data were approximately 23%, a likely reflection of the number of men working in construction compared to women worldwide.

When stratified by the World Bank income category (The World Bank, nd), the differences between the reported deaths and modelled deaths are stark (**Figure 13**), with virtually all reporting taking place in HICs and almost none in lower middle income countries (LMCs) or low income countries (LICs).

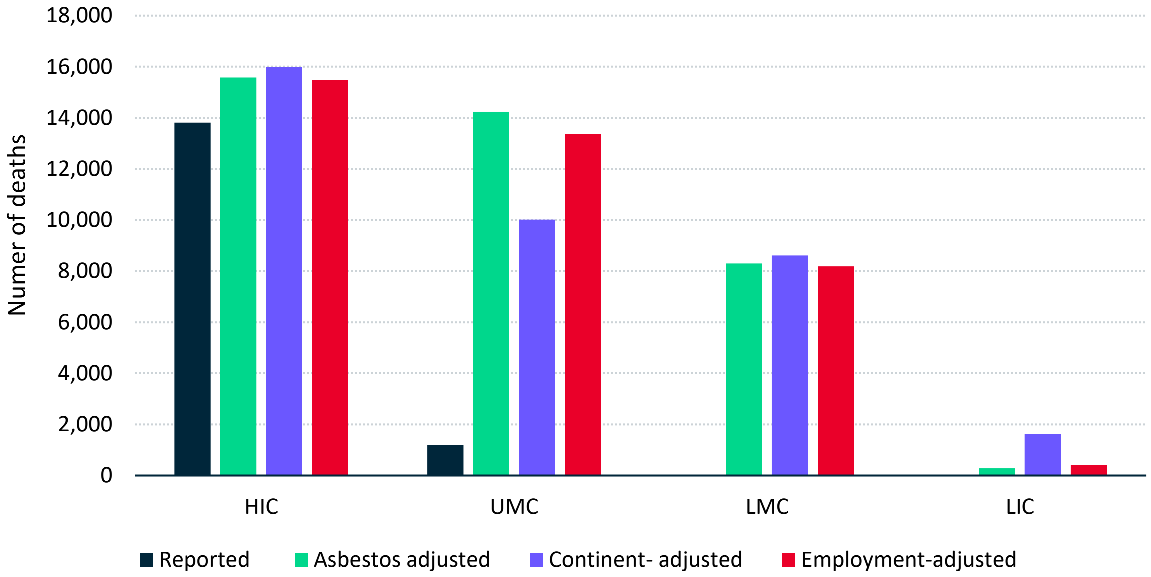


Figure 13: Global mesothelioma deaths by income category reported to the World Health Organization (2019) alongside adjusted data calculated by (Odgerel et al., 2017). Income categories were assigned to the estimated data according to each county's categorisation in the last year of the three year averaged estimates reported by Odgerel et al. Abbreviations: high-income country (HIC); upper-middle-income country (UMC); lower-middle-income country (LMC); low-income country (LIC).

Odgerel et al. (2017) proffered their 'asbestos use' adjustment as the most reliable estimate of the three adjustments; with an annual average death rate of 38,400, it was fairly close to the 43,000 estimated by Driscoll et al. (2005) a decade earlier. However, although mesothelioma deaths are a reliable indicator, they are only one of several diseases that are attributable to asbestos exposure. Various estimates have been suggested for the total number of deaths from all asbestos related diseases, ranging from 90,000 to 112,000 (Furuya et al., 2018b; Henderson and Leigh, 2012). Estimates by Furuya et al. (2018b) (**Figure 14**) suggested that the real figure may be as much as 255,000 deaths (243,223 to 260,029) of which 233,000 deaths (222,322 to 242,802) are occupational, with the greatest contribution from lung cancer, particularly in HICs. Other diseases made a comparatively small contribution to global mortality from occupational exposure to asbestos, with approximately 2,000 in each of UMCs and LMCs, and less than 300 in LICs.

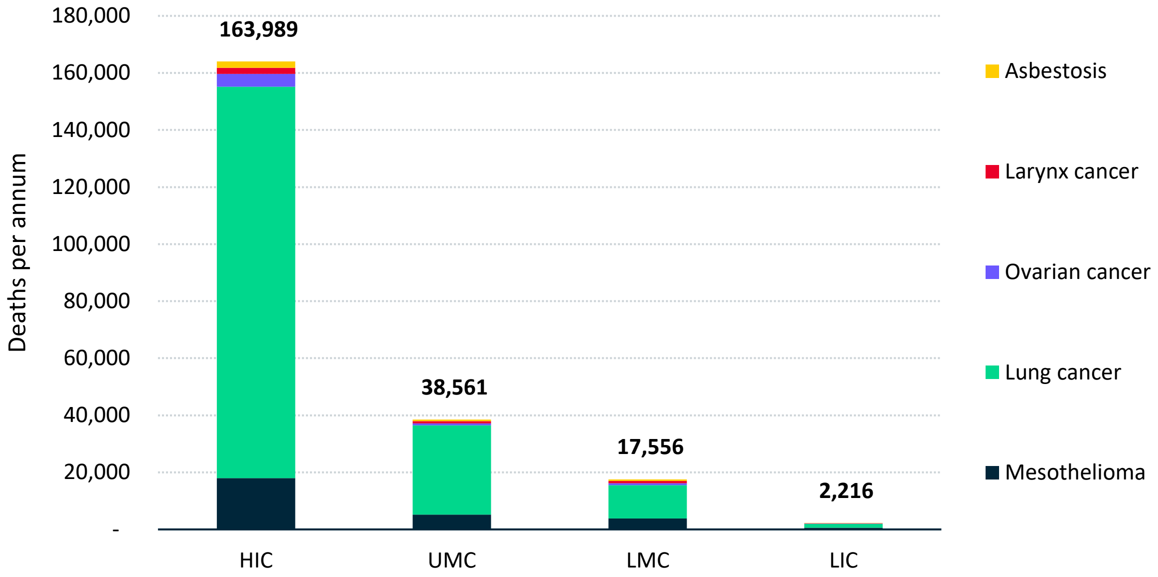


Figure 14: Global deaths from all diseases as a result of occupational exposure to asbestos; data from Furuya et al. (2018b). Abbreviations: high-income country (HIC); upper-middle-income country (UMC); lower-middle-income country (LMC; low-income country (LIC).

As of July 2019, 67 countries have banned asbestos (Kazan-Allen, 2019b), yet it is likely that the pandemic of asbestos related deaths is likely to continue to increase in the future despite apparent reductions in some countries, such as Sweden and the Netherlands which were some of the early countries to ban asbestos in the 1970s (Stayner et al., 2013). The analysis by Furuya et al. (2018b) indicated that deaths may at least continue at the same rate while acknowledging that the lack of data in LIMICs makes these kind of predictions challenging.

Nonetheless, while countries such as India continue to permit unabated consumption of asbestos, it is likely that the death rate from asbestos exposure will continue to rise. It has been predicted that of the 1.25 million people who are expected to suffer from asbestos related cancer in the coming years, more than half will be in India (Jadhav and Gawde, 2019).

3.5. Other particulate matter

Collectively, construction and demolition activities are an important source of particulate matter (PM) emissions (Font et al., 2014). In London (UK), for instance, construction and demolition activities were estimated to contribute to 1.4% of total PM_{10} emissions in 2010 (Font et al., 2014) and a study by Fuller and Green (2004) between 1999 and 2001 of over 80 sites across the city found that construction and demolition activities contributed to mean daily concentrations of >50 µg m^{-3} at 25% of the sites observed each year.

This review has a specific focus on ‘construction waste’ and ‘demolition waste and activities,’ therefore ‘construction activities’ that do not involve waste are excluded. This presents a challenge in this section because most studies of PM emissions present data that is aggregated together with ‘construction’, ‘demolition’ and ‘construction waste’. Furthermore, because this section focuses on mechanical (non-thermal) emissions of particulate matter, the scope is narrowed further to focus on emissions that arise when materials, such as ceramics, undergo mechanical attrition and aerosolisation. In layman’s terms, this section will discuss dust, defined variously as PM that is <75 µm or <100 µm in diameter (World Health Organization, 1999).

Two studies in the UK (Stacey et al., 2011) and Iran (Normohammadi et al., 2016) reported concentrations of total dust and respirable silica in and around demolition sites (**Table 9**). The first, Stacey et al. (2011) visited 13 construction and demolition sites in the UK and found that the concentrations of respirable dust were not significantly different from background samples, except for the demolition activity which showed a significantly different concentration (p <0.001). Silica dust exposure is an increasing public and occupational health issue and is known to cause silicosis, a fibrotic disease of the lung (Leung et al., 2012) as well as being linked to lung cancer, pulmonary tuberculosis and other diseases as well as an indicative, but less studied, link with cardio-vascular diseases (Chen et al., 2012). Nonetheless, although the time weighted average concentrations of respirable silica reported by Stacey et al. were higher during demolition activities, they were still far below the recently imposed absolute limit of 100 µg m^{-3} stipulated in Directive (EU) 2017/2398 (European Union, 2009).

Table 9: Concentrations of total dust and respirable silica in air around construction and demolition activities (µg m^{-3}).

Ref.	Geog.	Activity context	Substance	n	Median	Mean[a]	Min	Max
Stacey et al. (2011)	GBR	Urban air	Respirable dust (ISO/CEN Convention)	11	17.5			34.4
		General activities		9	24		17.4	29.5
		Road building		10	29		24	41
		Block cutting		7	35.1		17.5	76.9
		Demolition		22	40.6		15.4	229
		Urban air	Non-combustible and non-volatile respirable dust	11	4.7		2.8	12.6
		General activities		9	7.3		4.7	11.6
		Road building		10	12.7		3.8	21.3
		Block cutting		7	10.1		2.8	58.9
		Demolition		22	10.1		1.7	186

Ref.	Geog.	Activity context	Substance	n	Median	Mean^a	Min	Max
		Urban air	Respirable silica	8	0.24		0.08	0.44
		General activities		9	0.19		0.08	0.39
		Road building		10	0.64		0.11	1.04
		Block cutting		7	1.2 (1.8*)		0.16 (0.33*)	11.9 (12.8*)
		Demolition		22	0.94 (2.1*)		0 (0.31*)	11.5 (13.5*)
Normohammadi et al. (2016)	IRN	South	Respirable silica	15	155	206		
		East		15	185	209		
		West		15	95	148		
		Centre		15	165	195		
		Total		60	155	206		
		South	Total dust	15		14,990	5,000	28,000
		East		15		11,860	5,200	18,000
		West		15		11,930	5,600	28,000
		Centre		15		14,680	11,460	20,790
		Total		60		13,370	5,000	28,000

*Time weighted average; ^{a}arithmetic mean. Abbreviations: number of samples (n); geographical context (geog.); European Standards Organization (CEN); International Organization for Standardization (ISO).

The The Air Quality Standards Regulations (2010) in the UK, require that particulate matter < 10 µm (PM_{10}) concentrations must not exceed 50 µg m^{-3} more than 35 times per year or an annual mean of 40 µg m^{-3}. Although the PM_{10} was not measured specifically, two of the concentrations for total dust measured by Stacey et al. (2011) were higher than 50 µg m^{-3}, for block cutting and demolition (**Table 9**). However, the majority were below the 50 µg m^{-3} threshold and although the average for the demolition site for respirable dust (defined as the portion of PM that is capable of reaching the alveoli – gas exchange sacs in the lungs) was slightly higher than the mean average concentration limit in the Air Quality Standards Regulations, the activity did not last for a year and therefore would not exceed the threshold.

The mean and median concentrations of respirable silica measured by Normohammadi et al. (2016) at a demolition site in Tehran, were approximately 100 and 200 times higher respectively than those observed by Stacey et al. (2011) (**Table 9**). All the mean concentrations identified by Normohammadi et al. exceeded the absolute limit of 100 µg m^{-3} stipulated in Directive (EU) 2017/2398 (European Union, 2009), indicating that exposure to workers near these activities was possibly negatively affecting their health.

Three further studies measured concentrations of PM in and around demolition sites in China, Germany and the UK (**Table 10**), with many concentrations exceeding the threshold concentrations in Directive 2008/50/EC (European Union, 2008a) (**Table S1**). Liu et al. (2019) measured concentrations of PM_{10} and particulate matter < 2.5 µm ($PM_{2.5}$) during and following the demolition of a teaching building, finding elevated levels of both particle size profiles during the demolition process. It is worth noting that levels remained high after the demolition activities, indicating a very high background concentration in the area that exceeds the thresholds in Directive 2008/50/EC. Wagner et al. (2017) also found a considerable difference between PM levels during and after blast demolition of a skyscraper in Frankfurt, Germany, with maximum concentrations nearly 16 times greater than the limit value of 50 µg m^{-3}. Both Liu et al. (2019) and Wagner et al. (2017) reported that atmospheric PM concentrations returned to background levels when demolition was not taking place, indicating that the PM generated were either easily dispersed or deposited to the land. In the case of Wagner et al. (2017), the PM cleared within 25 minutes, meaning that the daily average concentration only slightly exceeded the 24 hour lower threshold (25 µg m^{-3}) for PM_{10} stated in the Directive 2008/50/EC.

Table 10: Concentrations of particulate matter (PM) in air during construction and demolition activities (µg m-3).

Ref	**Geog.**	**Activity context**	**Fraction**	**n**	**Mean***	**Min**	**Max**
Liu et al. (2019)	CHN [a]	Demolition	$PM_{2.5}$	296	94.409 [b c]	10.18	432.3 [b c]
			PM_{10}		156.521 [d e]	49.36 [d e]	495.4 [d e]
		After demolition	$PM_{2.5}$	112	59.511 [b c]	10.01	189.24 [b c]
			PM_{10}		92.881 [d e]	28.91	202.2 [d e]
Wagner et al. (2017)	DEU	During skyscraper blast demolition (15 min)	PM_{10}				844.9 [d e]
		Background (25 min later)			27.6 [e]		
		Day average			32.6 [e]		
Azarmi and Kumar (2016)	GBR	Mobile sample collection (A)	PM_1	12	4.7	2.2	8.3
			$PM_{2.5}$		15.5 [c]	7.0	30.9 [b c]
			PM_{10}		162.7 [d e]	24.4	440 [d e]
		Mobile sample collection (B)	PM_1	12	3.5	2.2	4.9
			$PM_{2.5}$		7.5	3.3	12.2 [c]
			PM_{10}		37.2 [d e]	17.9	75.8 [d e]
		Inside excavator cabin	PM_1		75		699
			$PM_{2.5}$		109 [b c]		12 [c], 401 [b c]
			PM_{10}		455 [d e]		54 [e]; 124 [d e]
		Inside temporary site office (normal)	PM_1		8		26
			$PM_{2.5}$		16 [c]		6
			PM_{10}		90 [d e]		2,566 [d e]
		Inside temporary site office (during intense demolition)	PM_1		56		338
			$PM_{2.5}$		144 [b c]		114 [b c]
			PM_{10}		720 [d e]		549 [d e];124 [d e]
		Fixed outdoor downwind of demolition activity	PM_1		15.66		
			$PM_{2.5}$		60.19 [b c]		
			PM_{10}		123.81 [d e]		

Exceeded the following concentration thresholds set by Directive 2008/50/EC (**Table S1**): [a] it is assumed that the site was in China from reading the paper, however the location wasn't stated.
[b] annual average upper assessment of $PM_{2.5}$; [c] annual average lower assessment of $PM_{2.5}$; [d] 24 hour average upper assessment of PM_{10}; [e] 24 hour average lower assessment of PM_{10}; *Arithmetic mean. Abbreviations: number of samples (n).

The study by Azarmi and Kumar (2016) took place over seven days and involved measuring concentrations in a variety of locations near to the demolition of a building, including static sampling sites; inside a static portable office; inside an excavator and also mobile sampling around the site (**Table 10**). Both the downwind and one of the mobile samplers showed levels of PM_{10} that exceeded the 50 µg m^{-3} limit, as well as the 24 hour upper and lower limits. The levels in the excavator were 6.5 times higher than the fixed outdoor sampler exceeding the 50 µg m^{-3} threshold by nine times. Even more concerning were the concentrations at the temporary site office that reached levels of more than 14 times the threshold limit during a period of intense demolition. This finding is of particular interest, because speculatively, office environments are often considered relatively safe spaces on construction and demolition sites and respiratory protection equipment is rarely worn inside. Azarmi and Kumar (2016) showed that the concentrations were higher inside the office than anywhere else on the site, inferring a potential need for engineering controls and procedures to prevent the ingress of PM into the buildings.

The relative contribution of demolition activities compared to construction and excavation activities was investigated by Arocho et al. (2014) who monitored air concentrations around two road resurfacing projects in the US (**Figure 15**). The study showed a significant contribution from the demolition phase; accounting for 35% and 45% of PM in the two studies. While these data are highly specific to two projects in a US context, they provide a useful indication of emissions that can be used by health and safety risk planners to mitigate potentially harmful concentrations of atmospheric matter produced by their projects.

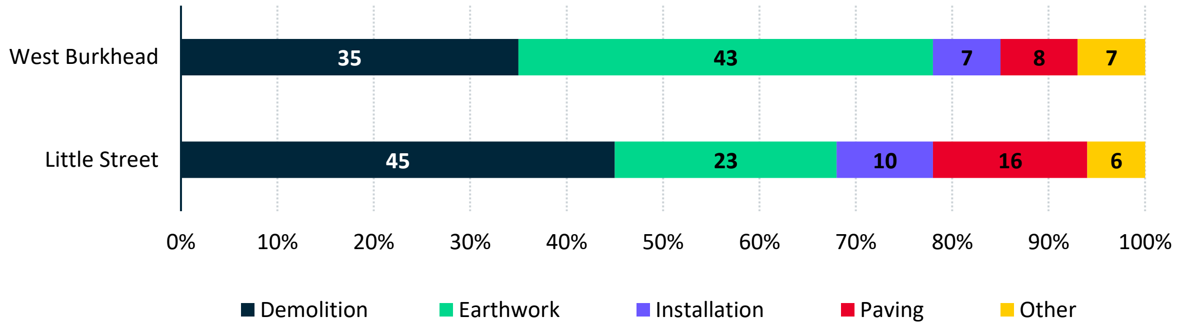


Figure 15: Apportionment of PM emissions by project phase for two roadway reconstruction projects in the USA; after Arocho et al. (2014).

To assist future occupational safety planners further with the proactive management of risk, several authors have derived emissions factors for PMs emitted from various construction and demolition processes; data that are surprisingly scarce in the literature (Azarmi and Kumar, 2016). Both Kumar and Morawska (2014) and Kumar et al. (2012) reported particle count from simulated concrete recycling and demolition processes respectively. The data are not presented here, but the studies focus on ‘ultra-fine’ particles which the authors assert may pose significant health and safety hazards, and are a likely subject of further research.

Azarmi and Kumar (2016) provided more accessible emissions factors for PM_{10}, $PM_{2.5}$ and $PM_{1.0}$ based on their observations of the UK demolition site (reported in **Table 10**), providing indicative values on the basis of µg PM per floor space demolished per second (**Table 11**).

Table 11: Emissions factors (EF) for particulate matter (PM) generated by demolition activities (µg m^{-2} s^{-1}); after Azarmi and Kumar (2016).

	EF_{PM10}	**$EF_{PM2.5}$**	**$EF_{PM1.0}$**
Day 1	34.67±17.09	16.85±3.07	4.38±0.03
Day 2	36.05±8.15	17.52±4.32	4.56±1.07
Average	35.36±12.72	17.19±3.69	4.47±0.54

Abbreviations: particulate matter < 10 µm (PM_{10}); particulate matter < 2.5 µm ($PM_{2.5}$); particulate matter < 0.1 µm ($PM_{0.1}$); emission factor (EF).

Few studies have carried out chemical characterisation of PM from demolition activities. Jiang et al. (2018) analysed dusts in Zhengzhou, China, and compared the geological and chemical profile with road dust, soil dust, and cement dust. By mass, the mean particle size across all samples was similar with approximately 10% (wt.) of the particles below 2.5 µm in all four samples. By particle count, the ≤1 µm was dominant, with 90% of all samples consisting of these ultrafine particles. Organic carbon (OC) <10 µm represented between approximately 5% and 12% of the mass, with concentrations of crustal elements and tens of elements detected.

Two studies used particle emission characterisation to calculate occupational and public health risk. Normohammadi et al. (2016) used the concentrations of silica identified in dusts sampled in Tehran to calculate lifetime excess cancer cases from occupational exposure over 45 years. The study found that the concentrations identified in **Table 9** would result in an average of 50 excess cancer deaths per 1,000 workers exposed (**Table 12**). The study also calculated that the cumulative effect of silica exposure to workers in the study over 45 years would result in a further 22.64 deaths per 1,000 people due to silicosis (data not shown) based on a cohort study of silicosis mortality by t Mannetje et al. (2002).

Table 12: Excess lifetime cancer deaths per 1,000 workers; after Normohammadi et al. (2016).

Area	**No. of samples**	**GM (μg m^{-3})**	**Excess lifetime risk of mortality from lung cancer (deaths per 1,000 workers)**
South	15	158	60
East	15	156	59
West	15	85	32
Centre	15	143	54
Total	60	132	50

Assumes 45 years of exposure at concentration specified. Abbreviations: geometric mean (GM); number of samples (n).

Brown et al. (2015) identified PTEs in PM from demolition activities to calculate the risk to adults and children living nearby from selected elements (**Table 13**). The analysis showed that the risk to children was >1 for aluminium and chromium.

Table 13: Hazard index (HI) calculated for residents living near to demolition activities at a site in London, UK; after Brown et al. (2015).

Element	**HI - adults**	**HI - children**
Al	0.711	1.132
Ba	0.005	0.039
Cr	0.528	1.079
Cu	0.009	0.062
Pb	0.039	0.099
Ni	0.004	0.033
V	0.015	0.103
Zn	0.004	0.024

This section has summarised relatively scant data on the risks associated with dust generated by demolition activities. These data should be used by future researchers as a basis to develop a more detailed understanding of the risks resulting from dust generated by demolition activities. This is work that should be carried out as there is clearly an indication of risk to both the health of workers and of the surrounding population.

3.6. Substances from previous use of industrial premises

The previous two sections have summarised evidence for emissions produced during the physical handling and processing of construction and demolition waste, relating to the actual materials used to construct buildings. However, there are also substances that arise from the previous use of the buildings. This section briefly summarises two of these, pesticides and radioactivity that have contaminated sites and require consideration to protect the health of workers carrying out demolition activities.

The first study, by Duggan et al. (1974) is outside the temporal scope of this review; being published in 1974. However, it is included here as an example of potential hazards as a consequence of substances arising in demolition waste as a result of previous use, rather than as part of the material fabric of the building. Duggan et al. (1974) sampled air at two facilities that had previously been used for radium luminising (production of luminous products) and a thorium extraction from monazite. Each factory contained radioactive dust as detailed in **Table 14** and rather than clean the dust, the demolition operation involved breaking up and removing the entire concrete floor in each building.

Table 14: Radioactive surface contamination in two United Kingdom (UK) industrial buildings undergoing demolition; after Duggan et al. (1974).

Context	**Substance**	**Units**	**Apparent contamination per cm^{-2}**
Former radium luminising building	Radioactive surface contamination	3.7 Bq ^{226}Ra cm^{-2}	7.4 Bq of β-ray emitters 7.4 Bq of α-ray emitters
Former thorium factory		3.7 Bq ^{232}Th cm^{-2}	3.7 Bq of β-ray emitters

Abbreviations: becquerels (Bq)

As the concrete was agitated, much of the radioactive material became aerosolised, exposing the unprotected workers. The air concentrations were determined using personal and static air samplers as detailed in **Table 15**. A stark difference was noted between the two plants that is explained by a defective jack-hammer being used in the Thorium extraction plant. Although the authors cite this as being ‘unfortunate’, it is a factor that may have reduced the probability of ill health in the workers over the proceeding decades. Duggan et al. (1974) conceded that had the jack-hammer been fully operable, the demolition workers may have required radiological supervision following the activity.

Table 15: Concentrations of radioactive elements during demolition of two United Kingdom (UK) facilities that had previously processed radioactive materials; after Duggan et al. (1974).

Facility	**Activity context**	**Dust loading (mg m^{-3})**	**Concentration (Bq m^{-3})**	**Specific activity (Bq g^{-1})**
		38	0.555	14.43
	At start of hammering	41	0.481	11.84
		160	0.999	6.29
		160	2.22	14.06
	During hammering	130	2.22	17.02
		100	4.44	44.4
		400	3.219	8.14
	During hammering	390	3.219	8.14
		14	0.185	13.32
		80	0.296	3.7
		75	0.999	13.32
Radium luminising facility	Shovelling	50	0.666	13.32
		2	0.407	20.35
		1-5	0-0.29	19.61
		1-5	0-0.29	19.61
		3	0.074-0.333	35.89
		4-5	0.111-0.296	31.08
	During hammering, outside	3-5	1.11	31.82
		12	1.776	148
		11	1.998	181.3
		11	0.777	70.3
		6	0.777	129.5
		14	1.295	92.5
Thorium extraction	During hammering, inside	17	1.739	103.6

Two studies investigated concentrations of pesticides at disused manufacturing facilities in South-western Sweden (Van Praagh and Modin, 2016) and Northern China (Huang et al., 2016) (**Table 16**). Van Praagh and Modin (2016) found that although the concentrations of phenoxy acids, chlorophenols and chlorocresols were higher than Swedish soil guidelines for residential and industrial properties, they were far below the concentrations necessary to be classed as hazardous waste. Leaching from the concrete occurred at a rate greater than inorganic substances and therefore the recycling of this concrete should be discouraged according to the study.

Table 16: Pesticide concentrations in media at former pesticide manufacturing facilities.

Ref.	Geog.	Waste analysed	n	Substance	Mean conc.	Low	High	SGV res.*	SGV ind.*
Van Praagh and Modin (2016)	SWE	Crushed concrete debris	4	Σ Phenoxy acids (PA)	8.5				
				Σ Chlorophenols (CP)	11.1			0.5	3
				Σ Chlorocresoles (CC)	10.7			1.5	5
				Σ PA, CP, CC	30.3				
Huang et al. (2016)	CHN	Concrete coatings Brick Wood Detritus	32	0,0,0-Triethyl-phosphorothioate	288.5	UD	2,764		
				0,0'-Diethyl dithiophosphate	3,254	47.1	18,749		
				Phorate	16,868	112.9	82,327		
				Parathion	6,521	UD	67,807		
				Terbufos	170	UD	1,933		
				Ethion	53.3	UD	585.2		
				Chlorpyrifos	167.5	UD	1,919		
				Sulfotepp	80.8	UD	383.9		
				Cholrmephos	29	UD	692.1		
				Phorate sulfone	111.3	UD	3,163		
				Cypermethrin (Pyrethroid)	179.4	UD	3,155		

[a] Organophosphorus and pyrethroid; * soil guideline values (SGV) from Swedish guidelines for residential (res.) and industrial (ind.) premises reported by Van Praagh and Modin (2016); abbreviations: number of samples (n); geographical context (geog.); concentration (conc.).

Huang et al. (2016) analysed construction and demolition waste from a disused organophosphorus and pyrethroid pesticide production facility that had been closed for a decade. The study indicated that many of the concentrations were high and extremely severe, however the findings were not placed in context with other studies as it is challenging to do so because of the specificity of products.

3.7. Risk characterisation for handling and physical processing of construction and demolition waste

The semi quantitative risk characterisation for the handling and physical processing of CDW is shown in **Table 17**. The highest risk was scored for asbestos exposure to workers in LIMICs. While the use of asbestos has been focused in HICs throughout the last century, consumption continues in LIMICs and the lack of stringency for protective equipment and safe systems of work indicates a much higher risk for workers in these countries. Workers in HICs were also scored high in this category as asbestos is still ubiquitous throughout the built environment and the probability of exposure is still considered high in several studies reviewed. HICS are not ‘over the hump’ yet.

The risk of physical accident in LIMICs is also scored medium high as there is evidence for a much higher accident rate and it is assumed that safe systems of work are generally less stringent and access to resources to reduce accidents less available.

Particulate matter is also an important hazard that should not be overlooked though it scored medium low in all categories. One potentially overlooked risk is exposure to people working in portable offices who were exposed to extremely high levels of PM from demolition activities in one study. This is important because workers in offices are less likely to wear protective equipment as it is often assumed that they work in a safe area.

The risks from substances resulting from the previous use of a building have not been risk assessed. These were included to indicate the harm but there is little evidence to suggest the prevalence of hazards or risks, though further investigation of this theme may be warranted.

Table 17: Risk characterisation summary for handling and physical processing (non-thermal) of construction and demolition waste (CDW).

Haz.	Pathway	Receptor	Geog.	Evidence and justification for risk assessment	Uncertainty (aleatoric and epistemic)	Receptor vulnerability	L	S	R	Global receptor context
Physical accident	CDW handling	Construction and demolition workers	EUR	• Eurostat (2020) provides some basic data on accidents involving 'bulk waste' under the NACE (economic) activity category for 'construction and demolition' indicating 6.14 accidents and 0.02 fatalities per 100,000 workers per annum.	• Scant evidence from submissions to Eurostat with considerable underreporting due to method of data collection (Eurostat, 2019). • Accidents or near misses that do not result in significant injury are not included in the statistics (European Commission, 2009). • Most states do not or inconsistently report Phase III level of detail (Eurostat, 2010).	• In HICs workers are increasingly protected through safe systems of work, however there is evidence from Japan(Maeda et al., 2003; Takahashi, 2019) that good health and safety culture is not synonymous with HIC status and may be cultural.	na	na	na	HIC LIMIC
Physical accident	Demolition activities	Demolition workers	JPN, EUR, AUS, TUR, GBR	• Evidence indicates fatalities in the demolition sector represent between 0.71 (European Commission, 2009) (EUR) and 7.5% (Maeda et al., 2003) (JPN) as a proportion of injuries from all sectors and accidents represent 0.16% in the EU only. For accidents and fatalities combined, data from AUS (Zaharuddin et al., 2009) indicate demolition represents 0.4% as a proportion of injuries from all sectors. • As a proportion of all construction and demolition, activities, fatalities range from 6.5% in JPN (Takahashi, 2019), 3.8% in TUR (Gürcanli and Müngen, 2013) and 1.09% in EUR (European Commission, 2009). • Injury rate as a proportion of all construction and demolition activities range from 3.9% in TUR (Gürcanli and Müngen, 2013) to 1.23% in EUR (European Commission, 2009).	• Very limited global data, limited to JPN and EUR. • Scant evidence from submissions to Eurostat with considerable underreporting due to method of data collection (Eurostat, 2019). • Accidents or near misses that do not result in significant injury are not included in the statistics (European Commission, 2009). • Most states do not or inconsistently report Phase III level of detail (Eurostat, 2010). • Challenging to put accident and fatality data into context as not reported as a proportion of workforce.	• In HICs workers are increasingly protected through safe systems of work, however there is evidence from Japan (Maeda et al., 2003; Takahashi, 2019) that good health and safety culture is not synonymous with HIC status and may be cultural.	2 3	4 4	**8** **12**	HIC LIMIC
Asbestos	Construction and demolition activities/inhalation	Construction and demolition workers	Global	• Though production and consumption have decreased over recent decades, huge quantities remain in the use phase, meaning that asbestos will remain a hazard for many decades to come. Though Brazil has now ceased production (Flanagan, 2020), Russia, China and Kazakhstan continue and consumption of cement bonded chrysotile continues in 39 countries in 2017 (National Minerals Information Center, 2018). • Strong data on mesothelioma deaths, however other diseases are estimates (Driscoll et al., 2005; Odgerel et	• Considerable work has been carried out to estimate death as risk based on more than 100 cohort studies (Concha-Barrientos et al., 2004) and a considerable body of evidence is being compiled all the time. • Few studies have estimated non-mesothelioma deaths which are often challenging to attribute (Furuya et al., 2018b) and therefore there is some uncertainty until further estimates have been carried out.	• While workers in HICs theoretically have safer systems of work and better access to PPE, HICs have much greater historical consumption of asbestos synonymous with their level of construction activity during the 20th century.	3	4	**12**	HIC
						• Workers in LIMICs may be less aware of the potential hazards posed by asbestos and have less access to	4	4	**16**	LIMIC

Haz.	Pathway	Receptor	Geog.	Evidence and justification for risk assessment	Uncertainty (aleatoric and epistemic)	Receptor vulnerability	L	S	R	Global receptor context
		Population		al., 2017; Vanya et al., 2011; World Health Organization, 2019). • 125 million estimated to be exposed (Spasiano and Pirozzi, 2017) and fatalities from all sources estimated at approximately 90,000 (Henderson and Leigh, 2012); 112,000 (Furuya et al., 2018b); 255,000 of which 233,000 are occupational (Furuya et al., 2018b).		PPE and safe systems of work in comparison to HICs. • Asbestos consumption continues unabated in many LIMICs. • Countries such as India continue to permit unabated consumption of asbestos and it has been estimated that half of all asbestos related deaths will occur in the country in the coming decades (Jadhav and Gawde, 2019).	1	4	**4**	HIC LIMIC
Other PM	Construction and demolition activities/inhalation	Construction and demolition workers	IRN, GBR, DEU, CHN	• Variable concentrations detected by studies depending on activity that was often not reported in enough detail to make a generalised assessment of risk. • High concentrations detected at some sites in Iran (Normohammadi et al., 2016), but much lower in GBR (Stacey et al., 2011). • Possible under-assessed risk in non-operational areas of construction and demolition sites such as offices which showed very high concentrations during intense demolition activity (Azarmi and Kumar, 2016). • Also evidence that PM levels return to normal soon after intense demolition / blast demolition (Liu et al., 2019; Wagner et al., 2017). • Quantified risk unacceptable and for exposure to Al (1.132) and Cr (1.079) by children in one study (Brown et al., 2015) but below 1 for all other elements and below 1 for adults for all elements. • Evidence (Arocho et al., 2014) that considerable proportion of emissions in road reconstruction are attributable to the demolition phase in comparison to the whole project.	• Data generalisable but PM emission from demolition activities are process dependent and therefore spot sampling may not be applicable to all activities.	• In HICs workers are increasingly protected through safe systems of work, however there is evidence from Japan (Maeda et al., 2003; Takahashi, 2019) that good health and safety culture is not synonymous with HIC status and may be cultural.	2	3	**6**	HIC
						• Both formal and informal workers often operate without respiratory protective equipment.	3	3	**9**	LIMIC
		Population				• Adults and children have no choice to avoid exposure if they live near construction and demolition activities.	2	3	**6**	HIC LIMIC
						• Children have no choice to avoid exposure if they live around construction and demolition activities.	3	3	**9**	HIC LIMIC

Abbreviations: Likelihood (L); severity (S); risk (R); personal protective equipment (PPE); low income and middle income countries; high income countries (HIC); particulate matter (PM); European Union (EU).

4. Challenge 2: Land disposal of construction and demolition waste (CDW)

4.1. Context

The majority of CDW by mass is composed of biologically inert materials such as ceramics, plastics, and metals. Although inert to biota, some of these materials contain substances that can migrate to the surface and into surrounding media such as water or soil. For instance, polybrominated diphenyl ethers (PBDEs) that have been added to plastics to retard combustion are known to migrate from their host polymer to the surface from where they can be washed away by rainwater and into the surrounding land, ground or surface water. Biological materials may also exhibit similar migration properties, and in addition, have the potential to decompose, releasing gasses, chemical and biological residues that are created while being consumed by micro-biota. This section covers the evidence that relates to emissions of substances into the environment from the disposal of CDW on land, exploring the pathways that result in these substances interacting with environmental and human receptors as illustrated in the conceptual diagram in **Figure 16**.

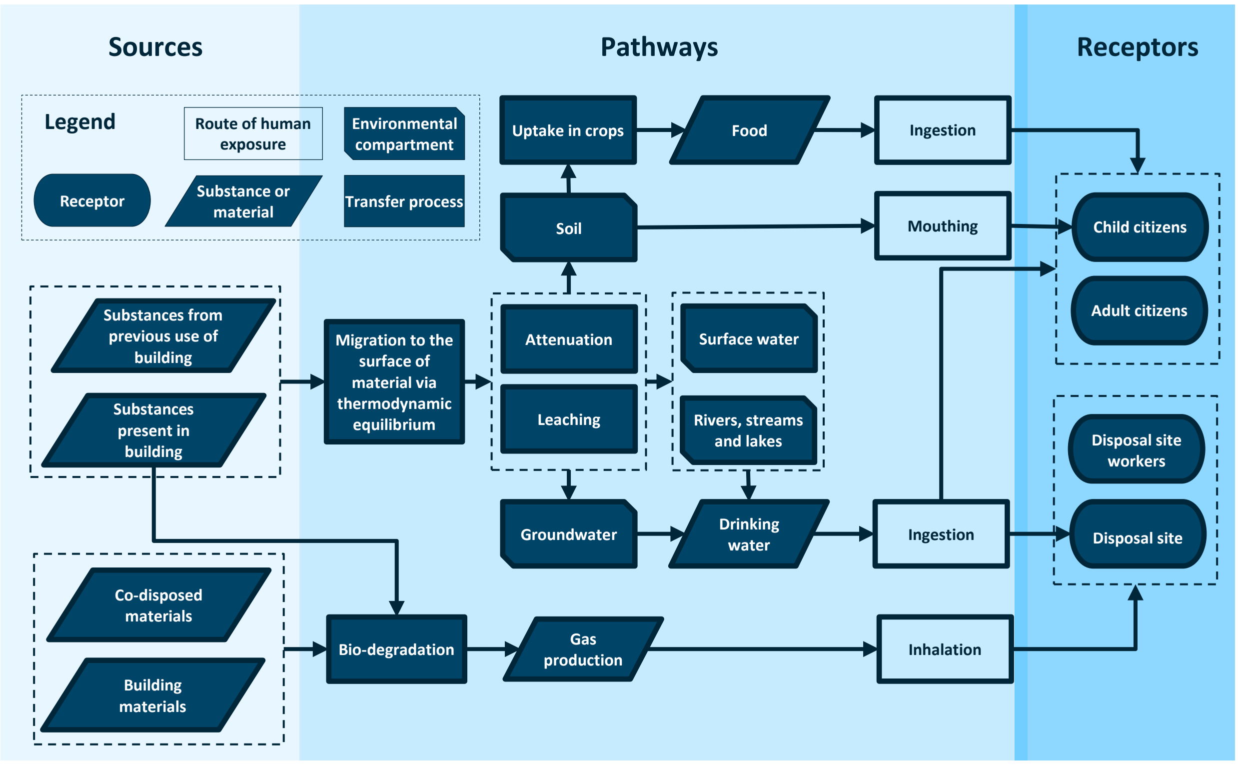


Figure 16: Hazard exposure conceptual model (source–pathway–receptor) associated with disposal of construction and demolition waste (CDW) on land.

4.2. Leachate from CDW

Understanding of the characteristics of leachate from CDW when disposed of on land is important to determine the risk of exposure to environmental receptors. Leachate from CDW in HICs is often controlled under strict legislation, and collected and treated on-site to prevent it escaping into the surrounding land and water (European Union, 1999; United States Environmental Protection Agency, 2000). However in LIMICs, especially scenarios where open dumps are the main disposal method, leachate is often not controlled at all and may be at risk of interacting with sensitive receptors in the vicinity or further afield through water transport.

Studies of leachate are either field based, or simulated in the laboratory, the latter of which is often carried out to determine whether waste is suitable for disposal prior to actually doing so. López and Lobo (2014) sampled leachate at a CDW Spanish landfill site over a five year period that accepted mainly wood (31.5%), aggregates (28%), fine inert material (14.5%), plastics (6.7%), and inert building material (5%) along with many other materials produced as a consequence of construction and demolition activities. Concentrations of most substances in the leachate were mostly within limits for inert waste set by the Directive 1999/31/EC (European Union, 2002) (Landfill Directive) for waste acceptance (**Table 18**). While the Directive limits are intended to establish waste acceptance and are not designed for comparison with field analysis, they provide a useful comparison alongside other primary research for reference. Some elements showed higher concentrations than those set in the Directive. For instance, Pb was historically used in paints, coatings, and is still used in flashing and caulks. Mean concentrations of Pb were much higher than the levels in studies by Townsend et al., Weber et al., and Melendez, 6.5 times higher than the Directive limit but lower than the United States Environmental Protection Agency (USEPA) study.

Table 18: Leachate quality from field samples collected from CDW landfill sites; field sample test from primary research by López and Lobo (2014) alongside compared values from other studies reported by the same author.

		López and Lobo (2014)		**USEPA (1995)***		**Melendez (1996)***		**Townsend et al. (2000)* & Weber et al. (2002)***		**European Union (2002)**
		Field samples		**Field samples**		**Field samples. Range from lit rev. C&D leachate.**		**Field samples**		**Directive 1999/31/EC**
Parameter	**Units**	**Mean**	**Range**	**Mean**	**Range**	**Mean**	**Range**	**Mean**	**Range**	**(L/S ratio 0.1)**
pH		7.5	6.8-8.3		6.2-8	6.95	4.45-8	6.9	6.1-7.9	
DO	mg L^{-1}	1.0	0.3-2.1					0.5	0.06-1.58	
Conductivity	mS cm^{-1}	8.3	5.8-11			-1.67			1.1-3.1	
ORP	mV	-89	-407/392						<-200	
Total COD	mg L^{-1}	1,571	775-4,641	11,200		755			115-700	
Dissolved COD	mg L^{-1}	1,407	586-4,190							
Total BOD$_5$	mg L^{-1}	227	70-500	320		87				
Dissolved BOD$_5$	mg L^{-1}	99	20-150							
Dissolved TOC	mg L^{-1}	404	120-1,185	1,080		307				30,000
Alkalinity	mg CaCO$_3$ L^{-1}	3,189	1,800-4,170	6,520		965	938.2-6,520	530	210-960	
NH$_4$_N	mg L^{-1}	401	92-765	305		13			<1-4.1	
Dissolved TN	mg L^{-1}	463	182-844							
Sulphates	mg L^{-1}	405	133-1,038	2,700[†]		254	11.7-1,700[†]	880	310-1,370	1,500
TS	mg L^{-1}	4,939	3,756-577							
TDS	mg L^{-1}	4,860	3,412-576	8,400		2263	990-8,400	2,120	970-3,310	
TVS	mg L^{-1}	1,619	1,208-247		170-380					
VSS	mg L^{-1}	75	5-781	43,000						
As	mg L^{-1}	0.233[†]	0.048-0.724[†]	0.12[†]		0.0123	0.0014-0.0773[†]	0.0438	<0.01-0.148[†]	0.06
Ca	mg L^{-1}	150	28-608	600		270	90-600	470	225-690	
Cd	mg L^{-1}	0.027[†]	<0.002-0.182[†]	2.05[†]		0.0319[†]		ND	ND	0.02
Cr	mg L^{-1}	0.105[†]	0.005-0.25[†]	0.25[†]		0.25[†]		0.0178	0.006-0.0749	0.1
Cu	mg L^{-1}	0.028	<0.001-0.087	0.62[†]		0.0203	0.005-0.620	0.092	0.0056-1.74[†]	0.6
Hg	mg L^{-1}	0.0014	<0.002-0.0043[†]	0.009[†]		0.009[†]		ND	ND	0.002
Na	mg L^{-1}	495	206-834	1,510		163	11-1290	42.8	18.8-100.3	
Ni	mg L^{-1}	0.0059	<0.003-0.152[†]	0.17[†]		0.02	0.030-0.170[†]	ND	ND	0.12
Pb	mg L^{-1}	0.987[†]	0.043-3.119[†]	2.13[†]		0.0088	0.0049-2.13[†]	0.0041	<0.001-0.0141	0.15
Zn	mg L^{-1}	0.276	0.021-0.735	8.63[†]		0.657		0.433	<0.1-1.731[†]	1.2

* Reported secondary source by López and Lobo (2014); [†] exceeded waste acceptance criteria limit specified in Directive 1999/31/EC (European Union, 2002) for inert landfill waste abbreviations: liquid solid ratio (L/S ratio); number of samples (n); construction and demolition (C&D); not detected (ND); dissolved oxygen (DO); redox potential (ORP), total organic carbon (TOC), ammonia nitrogen (NH$_4$-N), total solids (TS), total volatile solids (TVS), total suspended solids (TSS); volatile suspended solids (VSS); biochemical oxygen demand (BOD$_5$); chemical oxygen demand (COD); total nitrogen (TN); liquid to solid (L/S).

Concentrations of As and Cd were also high in comparison to the other sites (**Table 18**), and to the levels set by Directive 1999/31/EC (European Union, 2002), the former of which has been used historically in wood treatments. Alkalinity was within the 7.4-8.3 range as befits this type of material where dissolution of carbonates present in the CDW takes place. Ammoniacal-nitrogen (NH_4-N) levels were generally higher than the other studies compared, likely because of the very high levels of wood waste being accepted at the site.

In the lab based samples, virtually all of the concentrations were well within limits set by Directive 1999/31/EC (European Union, 2002) (**Table 19**). An exception is the levels of Pb determined by Devia and Suryo (2017) which were more than four times greater in some samples. The sampling took place in Indonesia and the author attributes the high levels to paint on chip plaster. Research by Saca et al. (2017) of waste obtained from a demolished steel plant investigated biologically inert CDW such as concrete, bricks and ceramics, which are materials that are unlikely to contain large quantities of hazardous materials. In all cases, the concentrations determined by Saca et al. (2017) were low. Unsurprisingly, the concrete batches showed higher pH due to carbonate dissolution, whereas the brick waste was neutral. Sulphate concentrations were variable and not congruent with the material type. The likely source of sulphate ions is gypsum plasterboard and therefore it is likely that the concentrations relate to material adhered to the surface or otherwise included in the samples from a demolished factory.

Whereas the characteristics presented in **Table 19** refer to data obtained from percolation tests, two other tests are common for determining leachate over six or twenty four hours using a liquid to solid ratios (L/S) of 2 L kg^{-1} and 10 L kg^{-1} respectively. Saca et al. (2017) performed these tests on demolition waste from a steel plant in addition to those whose results are presented in **Table 19**. As with the other tests, the concentrations of substances assessed by both Puthussery et al. (2017) and Saca et al. (2017) were well below limits set by Directive 1999/31/EC (European Union, 2002) (**Table 20**). One exception is chlorides, which were slightly higher in one test, indicating that the material may not be suitable for recycling as the chloride ions can threaten the stability of structures by leading to corrosion of steel reinforcing materials. The phenol index was also higher in four of the samples and Saca et al. (2017) postulated that these concentrations were related to the previous use of the building where phenolic compounds are used in steel production.

Table 19: Chemical properties determined from simulated leachate tests on sampled of CDW.

		Wang et al. (2012)*		Devia and Suryo (2017)		Saca et al. (2017)						European Union (2002)
		CDW		Demolition waste <10 years	Demolition waste >10 years	Concrete 1	Concrete 2	Bricks 1	Bricks 2	Mixture 1 [a]	Mixture 2 [a]	Directive 1999/31/EC (L/S ratio 0.1)
Parameter	**Units**	**Mean**	**Range**	**Range**	**Range**							
pH		6.4	6.1-6.9			10.84	8	7.45	7.18	12.34	10.18	
Alkalinity	mg CaCO$_3$ L^{-1}		75-725									
Sulphates	mg L^{-1}			191.6-240	150.4-220.3	123.46	575.3	486.44	723	49.38	303	1,500
Chloride	mg L^{-1}			24-30	20.5-55	4.25	4.96	42.25	13.47	3.55	3.55	460
Fluoride	mg L^{-1}			1.1-1.5	2.4-2.75[†]	<0.1	<0.1	<0.1	0.37	1.25	0.37	2.5
Phenol index						1.2	<0.1	<0.1	<0.1	0.31[†]	<0.1	0.3
TDS	mg L^{-1}		873-2010									
As	mg L^{-1}	<0.004				0.01	0.01	0.02	0.01	0.005	0.013	0.06
Ba	mg L^{-1}					0.03	0.11	0.17	0.07	0.059	0.059	4
Ca	mg L^{-1}	274										
Cd	mg L^{-1}					<0.001	<0.001	<0.001	0.001	<0.001	<0.001	0.02
Cr	mg L^{-1}					0.1	0.01	0.003	0.004	0.09	0.1	0.1
Cu	mg L^{-1}			0.12-0.2	0.2-0.35	0.3	0.2	0.07	0.19	0.157	0.085	0.6
Hg	mg L^{-1}					0.00005	0.00045	0.00005	<0.00005	0.00032	0.00005	0.002
Mb	mg L^{-1}					0.03	0.04	0.05	0.05	0.027	0.065	0.2
Na	mg L^{-1}		21-37									
Ni	mg L^{-1}					0.03	0.01	0.01	0.02	0.028	0.012	0.12
Pb	mg L^{-1}			0.52[†]-0.65[†]	0.42[†]-0.6[†]	0.005	0.007	0.003	0.01	0.005	0.005	0.15
Se	mg L^{-1}					0.006	0.005	0.01	0.01	0.006	0.009	0.04
Zn	mg L^{-1}			0.47-0.55	0.8-0.87	0.03	0.05	0.05	0.04	0.039	0.03	1.2

* Reported secondary source by López and Lobo (2014); [†] exceeded waste acceptance criteria limit specified in Directive 1999/31/EC (European Union, 2002) for inert landfill waste; [a] mixture of concrete, bricks, tiles and ceramics; abbreviations: number of samples (n); total dissolved solids (TDS); liquid to solid ratio (L/S).

Table 20: Characteristics of leachate from batch tests on various CDW media units are mg kg^{-1}, except pH and phenol index which are dimensionless.

	Puthussery et al. (2017)		**Saca et al. (2017)**												**European Union (2002)**	
	CDW		**Concrete 1**		**Concrete 2**		**Bricks 1**		**Bricks 2**		**Mixture 1**		**Mixture 2**		**Directive 1999/31/EC limit**	
	L/S=2	**L/S=10**	**L/S=2**	**L/S=10**	**L/S=2**	**L/S=10**	**L/S=2**	**L/S=10**	**L/S=2**	**L/S=10**	**L/S=2**	**L/S=10**	**L/S=2**	**L/S=10**	**L/S=2**	**L/S=10**
pH			11.82	11.64	8.45	8.53	8.28	8.48	8.04	8.18	11.87	12.02	10.49	10.24		
Fluoride			0.2	1	2	5.9	2.1	3.7	2.4	5.9	0.7	1	3.6	9.9	4	10
Chloride			4.2	5	4.2	14	85.2	85	27	5	7	5	1	14	550	800
Sulphate			344	626	454	543	190	255	462	517	142	375	593 †	612	560	1,000
Phenol index			2.2 †	3.7 †	0.1	1	0.2	1.5 †	0.2	1	0.7	7.3 †	1.1 †	5.9 †	0.5	1
As	0.01	0.003	0.06	0.02	0.01	0.05	0.05	0.16	0.01	0.08	0.01	<0.01	0.03	0.16	0.4	2
Ba	0.29	0.051	0.06	0.25	0.06	0.17	0.06	0.1 1	0.07	0.3	0.114	0.45	0.052	0.2	30	100
Cd	0.01	0	0.002	<0.01	<0.002	<0.01	<0.002	<0.01	<0.002	<0.01	<0.002	<0.01	<0.002	0.01	0.6	1
Cr	0.03	0.013	0.2	0.3	0.004	0.04	0.01	0.03	0.01	0.07	0.2	0.48	0.11	0.2	4	10
Cu	0.19	0.039	0.4	1	0.1	0.7	0.19	0.75	0.27	0.78	0.198	0.95	0.2	0.57	25	50
Hg	0.26	0.004	0.0001	<0.0005	<0.0001	<0.0005	<0.0001	<0.0005	<0.0001	<0.0005	0.00068	0.00002	<0.0001	0.0005	0.05	0.2
Mo	0.05	0.002	0.07	0.14	0.04	0.05	0.04	0.08	0.03	0.05	0.05	0.12	0.09	0.12	5	10
Ni	0.07	0.033	0.04	0.08	0.01	0.03	0.03	0.05	0.01	0.03	0.068	0.08	0.02	0.04	5	10
Pb	0.12	0.079	0.004	0.04	0.006	0.02	0.01	0.03	0.01	0.06	0.016	0.02	0.008	0.05	5	10
Sb	0.01	0.002													0.2	0.7
Se	0.01	0.001	0.006	<0.01	<0.002	<0.01	0.01	0.02	<0.002	<0.01	0.014	<0.01	0.008	0.01	0.3	0.5
Zn	0.46	0.303	0.06	0.26	0.05	0.34	0.06	0.21	0.08	0.52	0.104	0.39	0.09	0.56	25	50

† Exceeded waste acceptance criteria limit specified in Directive 1999/31/EC (European Union, 2002) for inert landfill waste: abbreviations: liquid solid ratio (L/S). Abbreviations: number of samples (n); liquid to solid ratio (L/S).

In summary, the concentrations of elements and other parameters identified in both the field sampling (**Table 18**) and the lab sampling (**Table 19** and **Table 20**) were low in most cases compared to the limits set by Directive 1999/31/EC (European Union, 2002) and also other sites. However, only studies of surrounding soil, surface and underground waste can determine the potential exposure to receptors in proximity to land disposal. Furthermore, the limits set by Directive 1999/31/EC relate to well managed European landfills that have undergone careful site selection and risks assessment to determine the risk of leachate contamination to the surrounding area and groundwater sources. In the context of LIMICs where such rigour may not have been applied, CDW may pose a more significant risk to the environment and health of the local populous. Further studies should focus on understanding the impact of CDW on environmental compartments in LIMICs to determine the credibility of these risks.

4.3. Wood

Wood used in construction is often treated with biocidal agents to improve its properties with substances such as fungicides, preservatives, creosote, paint, varnish, oils, glues, resins, and stains (Environment Agency, 2017). A large number of biocides have been used historically, several of which contain potentially hazardous and carcinogenic ingredients, such as pentachlorophenol (PCP), an organic chlorinated compound (Freeman et al., 2006) creosote, a tarry black substance containing a complex mix of polycyclic aromatic hydrocarbons (Freeman et al., 2006); and chromated copper arsenate (CCA), a highly effective, waterborne biocide (Morrell, 2006).

Preservatives in timber are released through several mechanisms that involve: biodegradation of the wood itself; transformation of the wood, and/or preservatives by biological and thermal activity; and desorption by thermodynamic equilibrium (Schiopu and Tiruta-Barna, 2012). Once they have reached the surface of the wood, they may be volatilised, leached into surrounding liquids or attenuated into soil. Many studies into the environmental and health impacts of treated wood focus on the release and exposure of preservatives during the use phase, whereas there is comparatively scant information on the after-use phase (Schiopu and Tiruta-Barna, 2012).

Koyano et al. (2019) analysed samples of demolition and recycled timber for the presence of four wood preservatives that are now known to be persistent organic pollutants, comparing concentrations to limits suggested by the Basel Convention Secretariat (**Table 21**). Although the Basel Convention concerns the transboundary movements of waste, the Secretariat publishes guidelines that defines whether waste has been managed responsibly, so called 'environmentally sound management' (Secretariat of the Basel Convention, nd). To assist with determining whether waste contains concentrations of persistent organic pollutants (POPs), it publishes a threshold below which the content is considered 'low' and hence different treatment practices may be applied. These low POP content limits provide a useful benchmark for determining the potentially hazardous concentrations of waste. As shown in **Table 21,** Koyano et al. (2019) found low levels of POP wood treatments in all samples of wood compared to the Basel Convention limits of: chlordanes (CHLs) 50 mg kg^{-1} (Secretariat of the Basel Convention, 2017c); PCP 100 mg kg^{-1} (Secretariat of the Basel Convention, 2017a); and polychloronaphthalenes (PCNs) 10 mg kg^{-1} (Secretariat of the Basel Convention, 2017b). Of course, the samples analysed by Koyano are highly specific to one area in Japan and further research would be required to determine whether these concentrations are representative of other contexts.

Table 21: Concentrations of elements, polybrominated diphenyl ethers, and selected wood preservatives (mg kg^{-1} dry wt.).

Ref.	**Geog.**	**Waste media analysed**	**n**	**Substance**	**Mean**	**Range**	**SD**
Koyano et al. (2019)	JPN	Recycled timber	45	Chlordanes (CHLs)	<0.01	<0.01-0.86	0.13
				Pentachlorophenol (PCP)	0.025	<0.01-3.0	0.5
				Pentachloroanisole (PCA)	<0.01	<0.01-1.1	0.18
				Polychloronaphthalenes (PCNs)	0.033	0.0012-2.6	0.43
		Demolition timber	55	Chlordanes (CHLs)	<0.01	<0.01-15	2.3
				Pentachlorophenol (PCP)	<0.01	<0.01-0.20	0.026
				Pentachloroanisole (PCA)	<0.01	<0.01-0.043	0.0057
				Polychloronaphthalenes (PCNs)	0.003	0.00049-0.036	0.011
Duan et al. (2016)	CHN	Wood from landfill	1	polybrominated diphenyl ether (PBDE)	0.000541		
Carpenter et al. (2013)	USA	CDW wood	n/a	Arsenic	37.04		
				Boron	0.27		
				Cadmium	0.65		
				Chromium	55.13		
				Copper	3,227.42		
				Mercury	0.13		
				Nickel	0.18		
				Lead	259.10		
				Antimony	0.03		
				Selenium	BDL		
				Zinc	2.88		

Abbreviations: number of samples (n); standard deviation (SD); construction and demolition waste (CDW).

Two other authors determined concentrations of potentially hazardous substances (**Table 21**). Duan et al. (2016) measured concentrations of brominated flame retardants in a variety of building materials, one of which was wood. Levels identified were six orders of magnitude lower than the Basel Convention's recommended Low POP Content of 1,000 mg kg^{-1} (for sum of hexa-brominated diphenyl ether (hexa-BDE), hepta-BDE, penta-BDE and tetra-BDE). Carpenter et al. (2013) reported concentrations of various elements in CDW wood from a variety of literature sources, however no commentary is provided as these levels were reported as emission factors.

Gaskin et al. (2005) carried out leaching tests on engineered timber mulch to determine the concentrations of substances that might leach into and potentially contaminate land. The comparison with non-treated varieties showed little difference and levels of all substances were low enough to conclude that engineered timber studies is entirely suitable to be used as mulch.

Table 22: Rainfall runoff chemical characteristics (mg L^{-1}) from simulated 64 mm storm leaching wooden mulch; after Gaskin et al. (2005) USA.

Waste media analysed				**2002**		**2003**		**TCLP regulatory level**
Category	**Composition**	**n**	**Substance**	**Mean**	**SD**	**Mean**	**SD**	
Engineered timber	60% OSB, 20% plywood, 10% I-joist, 5% laminated veneer lumber, and 5% southern yellow pine gluelam timbers		Barium	0.295				5
		1	Pentachlorophenol	ND				100
			Total phosphorus	0.21	0.017	<0.18		
			Total nitrogen	8.19	0.53	0.92	0.54	
		3	BOD	154.9	7.0	9.26	6.03	
Residential mix	30% EWP (in proportions listed above), 45% dimension lumber (in proportions listed above), and 25% finger-jointed studs.		Barium	0.299				5
		1	Pentachlorophenol	0.83				100
			Total phosphorus	0.13	0.047	<0.18		
			Total nitrogen	2.57	0.40	0.92	0.16	
		3	BOD	273.5		8.28	3.37	
Dimension Lumber	100% Dimension Lumber		Total phosphorus	0.21	0.15	<0.18		
			Total nitrogen	0.50	0.30	0.64	0.036	
		3	BOD	209.8	67.5	29.66	36.46	

Abbreviations: toxicity characteristic leaching procedure (TCLP); number of samples (n); oriented strand board (OSB); biochemical oxygen demand (BOD); engineered wood products (EWP).

Jambeck et al. (2008) studied the leachability of As, Cr and Cu from CDW containing 10% (wt.) timber treated with chromated copper arsenate preservative (**Table 23**). The study found that though the concentrations of Cu were not different to the control, that Cr and As levels were significantly ($\propto = 0.05$, $p < 0.001$) higher, indicating the need for vigilance in CDW landfills where leachate is not captured for treatment and where attenuation may risk contaminating sensitive receptors.

Table 23: Element content and leachability of 10% chromated copper arsenate (CCA) treated wood by mass in construction and demolition (C&D) debris (leaching column); after Jambeck et al. (2008).

Basis	**Parameter**	**Units**	**As**	**Cr**	**Cu**
Content	New CCA-treated wood	mg kg^{-1}	1,390 ± 20.0	814 ± 52.4	1,450 ± 68.3
	Waste CCA-treated wood		1,960 ± 27.7	1,340 ± 54.0	2,550 ± 48.0
Leachate concentration	Min	mg L^{-1}	1.09	0.3	<0.004
	Max		4.25	2.1	0.07
	Total		2.26	1.34	0.007
	Proportion leached		1.14%	0.57%	0.006%

Abbreviations: chromated copper arsenate (CCA)

4.4. Gypsum

Calcium sulphate dihydrate, otherwise known as ‘gypsum,’ is a soft mineral used in fertiliser, plaster and drywall plasterboard. Global mine production has grown steadily from approximately 10 million tonnes in 1940 to 160 million tonnes in 2010 and this sustained growth rate is expected to continue in the near future alongside global population growth (Asakura, 2013; US Geological Survey, 2020).

As it is used to coat internal walls in many constructions, gypsum is liberally distributed throughout demolition waste where it exists as fragments and dust between 17%and 27% of the mass of CDW (Townsend et al., 2000). Once it has been mixed, it is challenging to separate, and although some novel methods of separation have been suggested (Montero et al., 2010), manual separation is often the only effective method (Asakura, 2013).

In situ, plasterboard (drywall) and rendered plaster are generally stable, and exist in buildings for many hundreds of years. However in landfills or dumpsites, sulphate ions are leached from the gypsum when they become solubilised, and in combination with carbon (organic matter), water and a lack of oxygen (anaerobic environment) the conditions are created to allow sulphate reducing bacteria to flourish and produce hydrogen sulphide (H_2S) (Townsend et al., 2000).

H_2S is colourless, smells of rotten eggs, and can be hazardous to human health if inhaled at sufficient quantity. H_2S can cause: eye and lung irritation (20 to 200 ppm); pulmonary oedema (250 to 500 ppm); serious damage to eyes, unconsciousness, amnesia and death after four to eight hours (500 ppm) (Guidotti, 1996). The concentrations necessary to cause a fatality have been reported at 1,000 ppm (Asakura, 2013; Guidotti, 1996) and 2,000 ppm (Townsend et al., 2000) and there are incidences where landfill operators have been killed after being overcome with H_2S fumes (Asakura, 2013). The Health and Safety Executive (2020a) in the UK, sets an eight-hour time-weighted average workplace exposure limit of 5 ppm and a 15 minute exposure limit of 10 ppm.

Townsend et al. (2000) published a major non-academic report that investigated H_2S production form drywall gypsum plasterboard in landfills in the US. This spurred two academic studies by Lee et al. (2006) and Yang et al. (2006), who determined concentrations of H_2S generated from CDW leachate samples in field and simulated studies CDW samples in the laboratory respectively (**Table 24**). The subsurface probes and landfill gas samples in the field studies observed average concentrations that breached the UK HSE long-term workplace exposure limits at nine of the ten sites investigated, and the short-term exposure limit at seven. The average ambient concentrations were generally low in the study by Lee et al., indicating generally low risk to workers at the site with the exception of two sites where concentrations exceeded the limit of detection (>50 ppm) for the ambient sampling equipment. Both the sites that showed a very high limit disposed of fines from CDW recycling plants, which are known to contain higher than average concentrations of gypsum drywall fragments that are generally more friable and easily fall through the grate openings of ballistic separation equipment.

Table 24: Concentrations of hydrogen sulphide (H_2S) produced by construction and demolition waste (CDW) in field sampled and simulated experiments.

Ref	Geog.	Sample media	Components	n*	Mean	Med	Min	Max
Lee et al. (2006)	USA	LF gas from sub-surface probes or gas wells	CDW	19	$26^{\dagger\ddagger}$	0.013	BDL	$470^{\dagger\ddagger}$
			CDW	77	$8.1^{\dagger}$	0.007	BDL	$920^{\dagger\ddagger}$
			CDW	8	$30^{\dagger\ddagger}$	$25^{\dagger\ddagger}$	0.013	$12{,}000^{\dagger\ddagger}$
			CDW	25	$2{,}110^{\dagger\ddagger}$	$1{,}800^{\dagger\ddagger}$	BDL	$7{,}000^{\dagger\ddagger}$
			CDW	62	$36^{\dagger\ddagger}$	0.02	BDL	$2{,}500^{\dagger\ddagger}$
			Class III	16	$5.9^{\dagger}$	0.004	BDL	$49^{\dagger\ddagger}$
			CDW	19	0.007	0.005	BDL	0.64
			Class III	20	$151^{\dagger\ddagger}$	0.025	BDL	$3{,}300^{\dagger\ddagger}$
			CDW ^{e}	22	$1{,}200^{\dagger\ddagger}$	$23^{\dagger\ddagger}$	BDL	$11{,}000^{\dagger\ddagger}$
			CDW ^{e}	26	$26^{\dagger\ddagger}$	0.35	BDL	$530^{\dagger\ddagger}$
			Total	294	$660^{\dagger\ddagger}$	0.023	BDL	$12{,}000^{\dagger\ddagger}$
		Ambient air at surface	CDW	5	0.042	-		0.39
			CDW	18	0.003	-		0.11
			CDW	5	0.12	0.05		0.39
			CDW	24	0.19	0.007		2.4
			CDW	41	0.039	0.004		0.6
			Class III	17	0.008	0.004		0.12
			CDW	2	0.15	-		3.5
			Class III	6	0.037	-		0.27
			CDW ^{e}	23	4	0.61		$>50^{\dagger\ddagger}$

			CDW [e]	21	2.7	0.008		>50[†‡]
Yang et al. (2006)	USA	Simulation	Wood, drywall, concrete [a]	56	0.277		BDL	1.6
				62	0.2		BDL	1.03
				64	0.15		BDL	0.67
			Drywall, wood [b]	73	14,075[†‡]		BDL	63,000[†‡]
				74	11,155[†‡]		0.003	48,000[†‡]
				73	21,636[†‡]		BDL	47,000[†‡]
			Drywall [c]	73	24,389[†‡]		BDL	50,000[†‡]
			Wood, concrete [d]	37	0.13		BDL	1.5

[†] Exceeds long-term (eight hour) exposure limit set by UK Health and Safety Executive (2020a) of 5 ppm; [‡] exceeds short-term (15 min) exposure limit set by UK Health and Safety Executive (2020a) of 10 ppm; [e] these sites accept residues from CDW recycling facilities; class III facilities accept combined CDW, large non-putrescible items such as furniture and yard waste. Abbreviations: number of samples (n); landfill (LF); below detection limit (BDL); geographical context (Geog.); construction and demolition waste (CDW).

The gas samples generated from simulated CDW studied by Yang et al. (2006) showed very high concentrations of H_2S in four of the eight samples investigated. The four samples that included concrete showed much lower overall decomposition, and subsequent studies (Xu et al., 2011) have indicated that the concrete has an inhibiting effect on H_2S production due to its alkalinity. Sulphate reducing bacteria require a source of carbon, and despite the wood content in the concrete sample, H_2S production remained low. The samples that did not contain concrete produced high concentrations of H_2S including the purely drywall sample, which obtained enough carbon from the paper lining (typically 10% of the drywall mass) (Yang et al., 2006).

Modern, well managed landfill operators deposit gypsum in separate cells and capture and manage the landfill gas generated. Although no evidence was forthcoming, it is conceivable that CDW disposal practices in LIMICs are less rigorous, and that an increasing quantity of gypsum may be co-disposed with MSW in the future. As some landfill site and dumpsites in LIMICs are not restricted effectively from public access, H_2S generation could pose an increasing threat to human health and even cause further fatalities if management practices are not improved.

4.5. Hexabromocyclododecane (HBCD)

As one of the most widely used brominated flame retardants, hexabromocyclododecane (HBCD), is mainly used in expanded polystyrene insulation, an increasingly prevalent component of CDW (Nie et al., 2015). In 2011 production was 31,000 tonnes worldwide; however, it has decreased in recent years as its persistence in the natural environment and potentially harmful health effects on humans and animals have become established and alternatives developed to perform the same function. HBCD is listed in Annex A of the Stockholm Convention (Secretariat of the Stockholm Convention, nd), which means that parties to the convention must take steps to eliminate it from production and consumption; as well as Annex C, which obliges parties to control unintended release of the substance into the environment. As HBCD has been used in insulating material, it is likely to be in use for many decades and will therefore continue to arise in CDW.

Similarly to HBCD, PBDEs include congeners that are persistent organic pollutants and cause harm to fauna. Duan et al. (2016) sampled CDW collected from a recycling facility in China to determine HBCD and PBDE concentrations, finding the highest in samples of polyurethane foam and sponge for both compounds compared to other samples by orders of magnitude (**Table 25**). Drage et al. (2018) sampled expanded polystyrene (EPS) and extruded polystyrene (XPS) insulation found in construction waste in Ireland, finding high concentrations of HBCD in the XPS sample and extremely high concentrations in the EPS sample.

Table 25: Concentrations of selected brominated flame retardants, and polychlorinated biphenyls (PCBs) in construction nd demolition waste (CDW) (mg kg^{-1} total solids).

Ref	Geog.	Sample media	Components	n*	Mean	Med	Min	Max
Duan et al. (2016)	CHN	PUR foam insulating layer	HBCD	1	0.1666			
		PUR foam floor mat		1	0.1105			
		Furniture		1	0.03			
		PUR foam and sponge		1	7.039			
		Remainder sample		1	0.0077			
		PUR foam insulating layer	PBDE	1	0.2187			
		PUR foam floor mat		1	0.14994			
		PUR foam and sponge		1	79.766			
		Remainder of sample		1	0.00059			
Drage et al. (2018)	IRL	Construction and demolition EPS	ΣHBCD	62	2,100	100	<0.0003	10,000
			ΣPBDEs		<0.0003	<0.0003	<0.0003	<0.0003
			BDE-209		<0.0008	<0.0008	<0.0008	<0.0008
		Construction and demolition XPS	ΣHBCD		27	19	<0.0003	94
			ΣPBDEs		<0.0003	<0.0003	<0.0003	<0.0003
			BDE-209		<0.0008	<0.0008	<0.0008	<0.0008
Butera et al. (2014)	DNK	CDW from recycling facility	ΣPCBs	33	17			

Abbreviations: number of samples (n); construction nd demolition waste (CDW); expanded polystyrene (EPS) and extruded polystyrene (XPS); polyurethane (PUR); hexabromocyclododecane (HBCD); brominated diphenyl ethers (BDE); polychlorinated biphenyls (PCB); polybrominated diphenyl ethers (PBDE).

While concentrations of brominated flame retardants and PCBs in leachate and groundwater were not identified in proximity to CDW activities in this study, the concentrations identified in **Table 25** provide an indication that these substances exist in considerable quantity. As Nie et al. (2015) point out, the prevalence of these substances and their persistence in the value chain means that considerable attention will need to be paid toward managing these products safely in the future, particularly when it comes to land disposal. Furthermore, assuming the recycling of CDW becomes more common in the coming decades, there will be a greater need to identify products containing PCDDs, HBCDs, PBDEs and PCBs and divert them to other forms of treatment for complete destruction.

4.6. Risk characterisation for land disposal of construction and demolition waste

The risk assessment in **Table 26** indicates generally low to medium risks from CDW when disposed of on land. In general, CDW is composed of biologically inert material. Some exceptions are the inclusion of gypsum plasterboard that can produce hydrogen sulphide gas when co-disposed with small amounts of biological material; providing a source of carbon for sulphate reducing bacteria to consume and produce the gas. Some wood preservatives may also pose a risk and one author cautions vigilance in scenarios where CDW is disposed in unlined and unmonitored landfills where it is assumed that the contents are generally inert and pose little threat to the surrounding environment. This is particularly important for LIMICs where less stringent governance and monitoring may be implemented. HBCD was not assessed as it was considered negligible based on the evidence.

Table 26: Risk characterisation summary for land disposal of construction and demolition waste (CDW).

Material	**Haz.**	**Pathway**	**Receptor**	**Geog.**	**Evidence and justification for risk assessment**	**Uncertainty (aleatoric and epistemic)**	**Receptor vulnerability**	**L**	**S**	**R**	**Global receptor context**
CDW general	Misc. substances in an properties of CDW	Leachate, groundwater, land	Drinking water/ population	USA, SPN, IND	• Several studies (Devia and Suryo, 2017; López and Lobo, 2014; Puthussery et al., 2017; Saca et al., 2017) determined characteristics of CDW itself as well as leachate produced from CDW in landfill finding generally low levels of potentially hazardous substances in comparison to limits set by Directive 1999/31/EC (European Union, 2002).	• Although evidence is presented of the levels of various substances in leachate, no data was found that indicates the concentrations in environmental compartments close to CDW disposal sites.	• Inert landfills often have less secure liners as they are assumed to contain less hazardous material, in LIMICs they may have no liner at all or exist as open dumpsites. In these cases, local environmental receptors may be more vulnerable to exposure from potentially hazardous substances in leachate from disposed CDW.	1	2	2	LIMIC
CDW wood	Wood preservatives	Leachate, groundwater, land	Drinking water/ population	USA, CHN, JPN	• Preservative (POP) concentrations determined in samples of wood in one study in JPN (Koyano et al., 2019) to be very low; PBDE concentrations extremely low (Duan et al., 2016) and element concentrations ‘unremarkable’ (Carpenter et al., 2013). • Study of leachate from wood chip mulch (Gaskin et al., 2005) made with treated timer indicated very low risk of transmission of hazardous substances into surrounding area • Study of leachate from chromated copper arsenate treated wood (Jambeck et al., 2008) indicates cause for concern if landfill leachate not treated or risk of attenuation to nearby sensitive receptors.	• Limited data but indication of little cause for concern from wood leachate		2	3	6	LIMIC
CDW gypsum	Hydrogen sulphide gas	Atmosphere/ inhalation	Landfill/ dumpsite workers (formal)	USA	• Several studies determined H_2S production in simulated studies (Yang et al., 2006) as well as in real word concentrations of landfill gas (Lee et al., 2006), finding potentially very high concentrations in the simulated and landfill gas studies. • Examples exist where landfill workers have died when overcome with fumes from excessive concentrations of H_2S in the air, though ambient concentrations in one study were determined to be little cause for concern (Lee et al., 2006).	• The theoretical basis exists for H_2S production but the one available study of ambient concentrations reported them to be low. Further study is necessary to determine the credibility of the threat posed by H_2S in CDW landfill specifically.	• Many HICs have banned co-disposal of gypsum plasterboard.	1	3	3	HIC LIMIC
			Landfill/ dumpsite workers (informal)				• Informal workers operate without respiratory protective equipment and may be unaware of the potential hazard from H_2S production. • Speculatively, in LIMICs, co-disposal of gypsum with organic material may be more likely	3	4	12	LIMIC

Abbreviations: Likelihood (L); severity (S); risk (R); low income and middle income countries; high income countries (HIC); hydrogen sulphide (H_2S); persistent organic pollutants (POP); construction and demolition waste (CDW); polybrominated diphenyl ethers (PBDE).

5. Challenge 3: Thermal deconstruction and processing of construction and demolition waste (CDW)

5.1. Context

Several thermal processes take place on construction and demolition sites. Materials may be combusted in the open (open burning) as a means of waste disposal, resulting in uncontrolled emissions of substances within materials and also those that are formed and transformed when substances and materials interact during combustion and various temperatures. Other thermal processes involve more incidental emission of substances. For instance steelwork on a surface coated in lead paint, or paint de-coating with a heat gun. These processes, the emissions that result and the pathways through which these emissions may reach receptors are illustrated in the conceptual diagram in **Figure 17**.

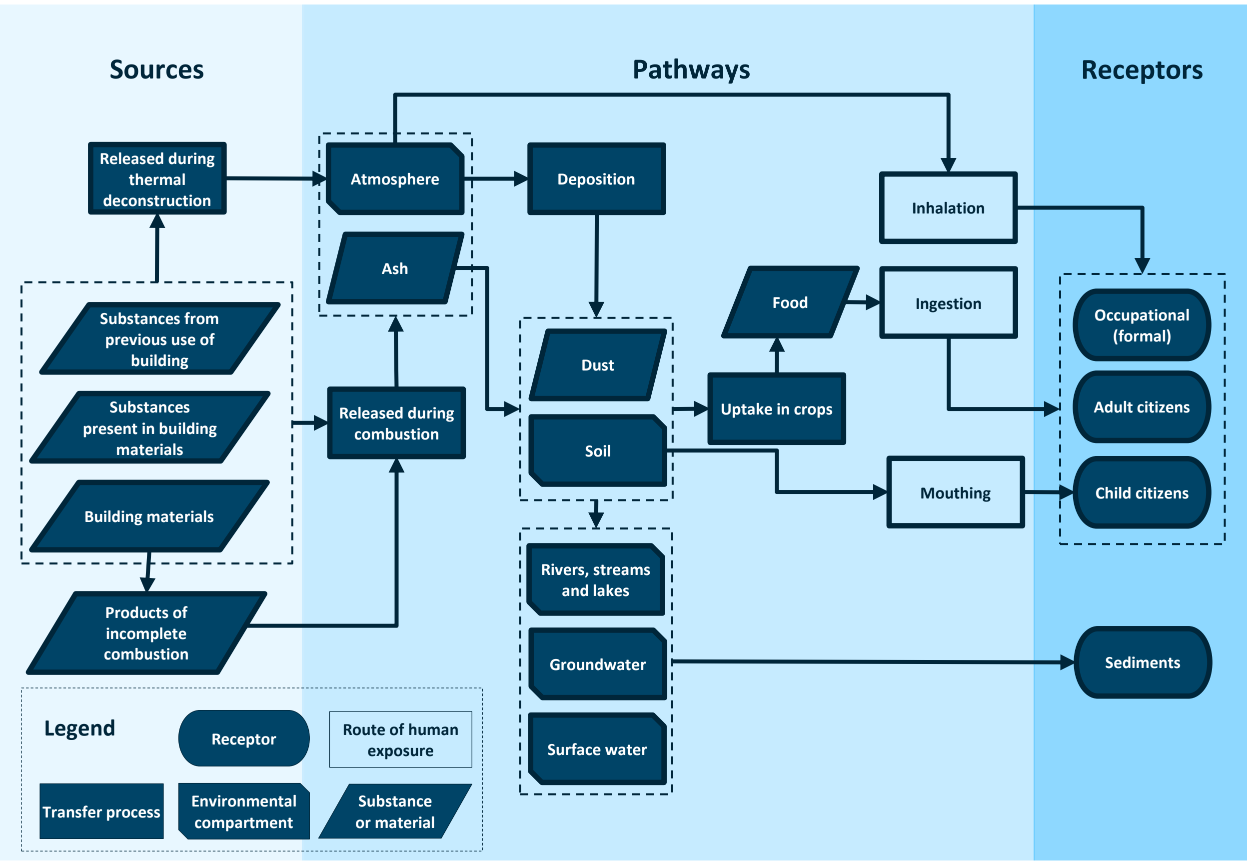


Figure 17: Hazard exposure conceptual model (source–pathway–receptor) associated with thermal deconstruction and processing of construction and demolition waste (CDW).

5.2. Lead release during deconstruction activities

The dangers of lead (Pb) exposure are well established and there is evidence that the potential hazards from Pb have been known for thousands of years (Scholz et al., 2002). In CDW, Pb occurs in soldered plumbing, but mainly in paints and coatings where Pb has been added to accelerate drying, increase durability, maintain a fresh appearance and resist moisture. Though Pb is still used in road markings, its potential hazardousness has seen the substance phased out of use in recent decades, however it still exists almost ubiquitously throughout the built environment. For instance, Turner and Solman (2016) analysed paint sampled (n=272) from multiple public buildings, road markings, street furniture, children's playgrounds, and residential buildings in Plymouth, UK, finding it was present in 221 (81%) of the samples with a mean concentration of 29,300 μg g^{-1} and a median of 4,180 μg g^{-1}. In 1998, Jacobs (1998) reported that in the US, more than 90,000 bridges were painted in lead-based coatings and approximately 83% of residential homes constructed before 1980.

These findings indicate the prevalence of Pb almost everywhere people live, however there is some evidence that it is still being used. For instance Gottesfeld et al. (2013) analysed 61 samples of paint in Cameroon and found that 66% contained concentrations of Pb that exceeded United States Environmental Protection Agency (USEPA) 90 ppm total Pb with a median content of 2,150 across the samples (range: <21-500,000 ppm).

While there is considerable awareness of the dangers of Pb in HICs, and in many LIMICs, construction and demolition workers in LIMICs may have less awareness and have limited access to safe systems of work and protective equipment to protect them from the potential hazards posed by Pb when it is heated and volatilised during deconstruction activities. The Health and Safety Executive (2009) in the UK, defines a ceiling workplace exposure limit 150 µg m^{-3} ('lead other than lead alkyls').

Jacobs (1998) reported a range of Pb concentrations in workplaces in the US from secondary sources, showing a large range of concentrations reported (**Table 27**), many of which exceeded the HSE occupational exposure ceiling limit of 150 µg m^{-3}. Scholz et al. (2002) also found similarly high limits in a study of paint workers who removed Pb paint during refurbishment activities. In another study by Lange and Thomulka (2000) much lower concentrations were identified in a study of workers who implemented US OSHA procedures in their work, indicating that they were effective at reducing their exposure.

Table 27: Concentrations of Pb measured in air proximate to deconstruction workers (µg m^{-3}).

Ref	Geog.	Activity context	Receptors	n	% n	Mean	Range
					14%	<1	
					18%	1-99	
					10.7%	100-200†	
		Wrecking and demolition [a]	Demolition workers	178	57.3%	>200†	
			Torch burner				220†-6,000†
		Bridge rehabilitation [b]	Hammering and drilling				40-360†
			Torch burner				110-1,200†
			Burner helper			330†	
			Torch burner				180†-1,800†
		Bridge demolition [b]	Rivet removal				500†-930†
		Paint removal from boiler [b]	Blaster				640†-1,400†
		Power plant demolition [b]	Torch burner				2,100†-22,400†
			Welder				2,200†-4,200†
			Blaster				1,070†-10,400†
		Bridge repair [b]	Burner				840-4,900†
			Blaster				4-540
			Groundsman				20-640
		Paint removal from bridge [b]	Blaster				2-730
		Bridge demolition [b]	Burners				600-4,000†
			Blaster				3,690†-29,400†
Jacobs (1998)	USA	Paint removal from bridge [b]	Groundsman				5-6,720
			Heat gun	6		2.3	<1 (n.d.) - 5
			Wet sanding	3		3.3	<1 (n.d.) - 7
			Open flame burning	5		9.8	<4 (n.d.) - 20
			HEPA-exhausted power sanding	7		33	4 - 60
			Dry scraping	18		71	<4 - 230
			Dry manual sanding	9		420†	29 – 1,200†
			Uncontrolled power sanding	10		580†	65 – 3,400†
			HEPA-exhausted power sanding	7		1,600†	
			Dry scraping	17		1,100†	
			Dry sanding	9		6,700†	
Scholz et al. (2002)	USA	Residential and commercial painting	Uncontrolled power sanding	10		14,000†	
				5		379.6†	194-571† (122.1)
			No wet methods for cutting	36		31.9	1.3-119 (11.0)
			No wet methods for burning	5		27.1	8.2-39.5 (13.5)
			Wet methods for cutting	8		7.8	4.7-10.6 (1.7)
			No wet methods for cleaning	1		60.8	
Lange and Thomulka (2000)	USA	Burning and cutting of pipes and removal (demolition) of walls that were painted	Total for all samples	57		61.1	1.3-571† (29.4)

† exceeds HSE limit of 150 µg m^{-3} for Pb concentration in atmosphere; abbreviations: number of samples (n); high efficiency particulate or arrestance (HEPA); geographical context (geog.).

Blood concentrations of workers involved in deconstruction activities were determined by several authors. Fischbein et al. (1978) found concentrations of Pb in the blood of steel deconstruction workers to be higher in some cases than the HSE maximum limit set at 600 µg

L^{-1} blood. Centers for Disease Control and Prevention (1989) found very high concentrations in the blood of workers deconstructing a steel bridge, noting that the paintwork on the bridge contained 30% Pb (wt.). Four of the workers in that study had to undergo chelation therapy to recover from the experience.

Table 28: Concentrations of elements in blood of workers engaged in deconstruction

Ref	Geog.	Activity context	Receptors	n	Mean (µg L^{-1})	Range
Fischbein et al. (1978)	USA	Deconstruction of elevated steel subway	Demolition workers	11	460	320-710[†]
Centers for Disease Control and Prevention (1989)	USA	Deconstruction of steel bridge	Demolition workers	5	780[†]	
					670[†]	
					580[†]	
					740[†]	
					1,600[†]	
Jacobs (1998)	USA	Lead based abatement work	Demolition workers	1		40-150
				1		30-180
				1		30-100
				1		40-180
				1		40-<100
				1		50-60
				1		20-<100
				1		50-60
				1		100-290
				1		50-100

[†] exceeds HSE limit of 600 µg L^{-1} for Pb concentration in blood; abbreviations: number of samples (n); geographical context (geog.).

It is noteworthy that most of the studies reviewed in this section relate to HIC examples from several decades ago. Workplace safety has improved considerably in HICs since these studies took place and awareness of the dangers of Pb at work has increased to the level where many workers have safety systems of work in place to protect them from harmful exposure. However in LIMICs, as with many hazards, such safety measures may not have been implemented with the same stringency, therefore resulting in ongoing and considerable risk to those engaged in thermal deconstruction of steel structures and in the removal of paint.

5.3. Combustion of CDW

The combustible fraction of CDW is a potential source of fuel, which in LIMICs may be utilised by those engaged in demolition or construction activities. If fuel isn't required, then alongside dumping and storage, combustion is a common disposal option (Nie et al., 2015) as it can rapidly reduce the volume and mass of waste, discharging the problem to the atmosphere. The prevalence of the activity isn't well reported, but surveys of Nigerian construction workers indicate 2.9% (n=243) (Ogunmakinde et al., 2019), and 16% (n=75) (Wahab and Lawal, 2011) of construction practitioners engaged in open burning activities as a method of disposal. Furthermore, construction wood that is sold for reuse as suggested by Dania et al. (2007) is often burned as fuel, though the prevalence was not stated.

Combustible components of CDW include: wood, plastics, foam insulation, plastics, yard waste. Emissions from open burning of waste have been modelled extensively by Wiedinmyer et al. (2014) and (Kodros et al., 2016).

Lemieux et al. (2004) stated that open burning of CDW is likely to be a prevalent activity but suggested that there is little evidence to support its prevalence or impact. Instead, they suggested a study by Carroll (2001) that characterises polychlorinated dibenzo-p-dioxins (PCDD) and polychlorinated dibenzofuran (PCDF) (hereafter dioxins and related compounds – DRCs) emissions from house fires as the composition of the material has some congruence with CDW. Carroll (2001) provided a comprehensive review of emission factors for various wood products, demolition and construction wastes and plastics used in construction such as polyvinyl chloride (PVC) piping (**Table 29**). PVC is used increasingly on construction sites and a priori data suggests that it may occur increasingly in demolished buildings as its use becomes more prevalent. The chlorine content in PVC means that production of DRCs is considerably higher (for example, 3,500 µg I-TEQ t^{-1} in soot phase) than other combustible components of CDW (for example, waste wood 26-173 µg I-TEQ t^{-1} in vapour phase).

Table 29: PCDD/F emissions factors for selected products used in CDW; after Carroll (2001).

Secondary ref.	**Sample**	**Phase**	**Emission factors (µg I-TEQ t^{-1})**
	Soft PVC		230
	Hard PVC		3,500
Theisen et al. (1989)	Fibres		600
Ikeguchi and Tanaka (1999)	Electrical wire tube		1,032
	PVC resin		100
Vikelsoe and Johansen (2000)	PVC resin		3
Merk et al. (1995), Merk (2000)	PVC/wood	Soot	750-2,250
Schatowitz et al. (1994)	Waste wood		26-173
	Construction waste		92
Ikeguchi and Tanaka (1999), Ikeguchi (2000)	Demolition waste	Air	26
	Beech		0.44-0.50
	Chips, chipboard		0.007-0.15
Schatowitz et al. (1994)	Waste wood		0.7-29
Schramm et al. (1998)	Treated wood pieces, boards	Vapour	15-40

Secondary ref.	Sample	Phase	Emission factors (μg I-TEQ t^{-1})
	Treated wood pieces, beams		2.4-6.6
	Blocks, plywood, residues		3.5-11
			4.9-7.0
Kolenda et al. (1993)	Chopped wood briquettes		1.4-6.3
Launhardt et al. (1996)	Beech, conifer		0.035-0.13

Abbreviations polychlorinated dibenzo-p-dioxins and polychlorinated dibenzo-p-furans (PCDD/F); polyvinyl chloride (PVC); toxic equivalency (I-TEQ)

When wood that has been treated with preservatives is combusted, the potential exists for some chemical species to be produced in addition to those already created because of combustion of the wood itself. For instance, PCP, an organochlorinated compound used in many pressure treated timber products since the late 1950s contained DRCs formed at the time of production (**Table 30**).

Table 30: Concentrations of DRCs in selected wood products treated with pentachlorophenol (PCP); after Swedish Environmental Protection Agency (2009).

Product	TEQ ng g^{-1}
Ky-5 treated wood	38
Wood used in agricultural application	0.016-315
Sawmill waste landfill	0.067
Utility pole, freshly treated, 1996	3.1
Utility pole, freshly treated, 1999	6.8
Utility pole after 1 years' use	15
Utility pole after 4 years' use	14
Utility pole after 11 years’ use	6.3
Utility pole after 24 years' use	7.7
Utility pole after 34 years' use	0.71

Abbreviations: toxic equivalency (TEQ)

All chlorinated hydrocarbons have the potential to produce DRCs when combusted, including untreated timber. If combustion is controlled, for instance in modern incinerators, dioxin production is limited by maintaining optimum temperatures to reduce formation and increase the potential for destruction. Emissions cleaning technology is able to capture the majority of DRCs before the remaining (circa 1%) are released to the atmosphere where they are diluted into the environment. However in open burning, no such controls exist, and although temperatures in some parts of the fire may be sufficient (for example, >850°C) (Wielgosiński, 2011) to reduce formation, other parts will facilitate conditions ideal for DRC formation and release (Tame et al., 2007).

CCA is another important wood preservative that entered the global market in the 1940s and became the most globally prevalent preservative used in wood treatment during the 1970s (Wasson et al., 2005). The high content of three potentially toxic elements Cr, Cu and As results in their emission into ash and air during combustion. Wasson et al. (2005) characterised emissions from combustion of wood treated with several CCA formulations, finding very large concentrations of As, Cr and Cu in the fly ash (**Table 31**).

Table 31: Concentrations of elements in soot from combustion of chromium copper arsenate (CCA) treated timber; after Wasson et al. (2005).

Element	**Formulation 1**	**Formulation 2**	**Formulation 3**
As	116,500	111,350	129,300
Ca	200	7,600	3,510
Cl	110	270	190
Cr	980	29,500	12,000
Cu	1,060	17,800	6,710
K	740	2,810	1,730
Na	60	1,240	1,050
P	70	340	140
S	740	1,160	480
Unidentified	838,000	757,000	791,100

Emission factors for As, Cr and Cu were also calculated by Wasson et al. (2005) and are presented in **Table 32,** however it is noteworthy that the emissions of DRCs reported in the same study were ‘unremarkable’ with mean concentrations of 1.7 ng TEQ kg^{-1}. This indicates that the CCA treatment doesn’t significantly contribute to DRC formation.

Table 32: Emission factors for Cr, As and Cu from chromium copper arsenate (CCA) treated timber (mg kg^{-1} CCA treated wood); after Wasson et al. (2005).

	As	**Cr**	**Cu**
Sample 1	188	22	9.8
Sample 2	218	14.9	13.4
Sample 3	237	8.4	8.7

In general, data on the open burning of CDW are extremely limited. It is a recommendation of this report that considerable additional work is carried out to determine the prevalence of this activity and also to determine the relative emissions of different material composition to assist with the improved compilation of a global inventory.

5.4. Risk characterisation for thermal deconstruction and processing of construction and demolition waste

The semi-quantitative risk assessment for thermal deconstruction and processing activities is shown in **Table 33**. Very high scores were attributed to the risk to both construction and demolition workers in LIMICs as well as the population who may be exposed to the activities. There is still limited information in this area on the prevalence of CDW open burning and more data are urgently needed to assess the magnitude of the threat to human health.

Exposure to lead was scored low in HICs mainly because the dangers are well established and safe systems of work have been in place, often for many decades. In LIMICs the score was medium high as although the dangers are known, the governance, enforcement and access to resources required to reduce exposure may not be in place; acknowledging that no evidence was found to determine direct lead exposure from CDW in LIMICs in this study.

Table 33: Risk characterisation summary for thermal deconstruction and processing of construction and demolition waste (CDW).

Haz.	Pathway	Receptor	Geog.	Evidence and justification for risk assessment	Uncertainty (aleatoric and epistemic)	Receptor vulnerability	L	S	R	Global receptor context
Pb	Thermal deconstruction of steel structures and removal of paint	Deconstruction workers	USA	• Pb exists in coatings throughout the built environment (Jacobs, 1998; Turner and Solman, 2016) and without adequate precautions could pose risk to deconstruction workers for many decades to come (Scholz et al., 2002). • The evidence for aerosolisation of Pb from thermal deconstruction of steelwork and paint removal is strong (Jacobs, 1998; Scholz et al., 2002), as is the effectiveness of safe systems of work at reducing atmospheric concentrations (Lange and Thomulka, 2000). • A clear link between thermal deconstruction activities and blood Pb levels exists and therefore it is clear that adequate precautions should be taken.	• All the studies (Jacobs, 1998; Lange and Thomulka, 2000; Scholz et al., 2002) were in the USA and several decades old. No data was found to determine risk in LIMICs other than Pb is still being used in paint in one LIMIC – Cameroon (Gottesfeld et al., 2013).	• HICs are likely to have safe systems of work in place having evidenced the potential dangers over many decades.	1	4	**4**	HIC
						• Workers in LIMICs are likely to have less stringent safe systems of work and less access to PPE to protect them from Pb exposure.	3	4	**12**	LIMIC
Multiple substances	Open burning of CDW	Construction and demolition workers	NGA, global, USA	• Several papers evidenced that open burning is used to dispose of CDW (Nie et al., 2015; Ogunmakinde et al., 2019; Wahab and Lawal, 2011) or that it is used as fuel (Dania et al., 2007) • Risk of dioxin production is high, particularly from the combustion of PVC but also from wood sources (Carroll, 2001; Kodros et al., 2016; Lemieux et al., 2004; Wiedinmyer et al., 2014). • Emissions from CCA treated wood characterised (Wasson et al., 2005), noting that DRC formation was limited but levels of Cr, Cu, and As were very high.	• The data for CDW specifically are limited and more work is needed in this area.	• Both formal and informal workers operate without respiratory protective equipment.	4	4	**16**	LIMIC
		Population				• Adults and children are unable to avoid exposure if they live around e-waste open burning activities.	4	4	**16**	

Abbreviations: Likelihood (L); severity (S); risk (R); low income and middle income countries (LIMIC); high income countries (HIC); hydrogen sulphide (H_2S); persistent organic pollutants (POP); construction and demolition waste (CDW); dioxins and related compounds (DRC); chromated copper arsenate (CCA); polyvinyl chloride (PVC); personal protective equipment (PPE).

6. Conclusions

As we have shown in this systematic review, some construction and demolition processes result in the transformation and physical movement of materials and substances in CDW, thus creating pathways through which human can be exposed to harm to approximately 200 million formal and informal workers worldwide (Mella and Savage, 2018). Data to indicate how many of those work with waste is not available, and speculatively may never become so due to the lack of prioritisation for this metric. Yet many of the CDW related high risk hazard-pathway-receptor combinations identified here involve the aerosolisation of particles and substances, or involve accidents, all of which affect the entire construction and demolition workforce, regardless of their direct or specialist involvement with waste.

Asbestos, a longstanding, potentially lethal, and prolific material, continues to cause the occupational deaths of approximately 90,000-250,000 people every year. Although the majority of these occur in HICs where historical use of the material has been concentrated, the use of asbestos in LIMICs has continued in the last several decades; chrysotile has yet to be banned in 39 countries that consumed 1.1 Mt in 2017. Whereas Russia produces just over half of it, India and China consume approximately half, and India's apparent ignorance of the potential hazards means that almost half of the 1.25 million deaths anticipated from asbestos in the coming years are expected to occur on the subcontinent. The substantial stocks of asbestos that exist throughout the global built environment mean that exposure to asbestos will continue to be a significant cause of death and ill-health over the coming decades, as engineered structures reach their end of life, often demolished by unprotected and untrained informal workers across LIMICs.

There is a surprising lack of data to indicate the number of injuries and fatalities specifically on demolition sites, given that these workplaces are intuitively high-risk, especially for informal workers in LIMICs. Acknowledging this lack of evidence, we have tentatively assigned and highlighted a medium to high level of risk of physical injury for demolition workers in LIMICs with a recommendation that the strength of knowledge is considerably improved in these contexts.

A similar lack of data exists to evidence the scale of open burning that takes place on construction and demolition sites across the world. Whereas only a small proportion (wt.) of

CDW materials are combustible, several substances of concern may be released in open, uncontrolled fires that is thought to be used as a common method of disposal in countries where MSW mismanagement is reported to be high. Given the prevalence of PVC in CDW the hazards associated with exposure to DRCs from open burning may be as yet, an increasing cause for concern. However, until the activity prevalence can be determined, it is challenging to assess the magnitude of these emissions, and hence, potential harm to human health.

The general quality of studies reviewed here was mixed, ranging from several complex and ambitious global burden of disease studies on asbestos through to insufficiently methodologically documented studies in LIMICs; some of these case studies which lacked sufficient context to be generalisable across wider socio-economic conditions. This lack of robust research into solid waste and human health in countries where risks are likely to be higher, can be expected to encourage the continuation of elevated risk practices. Given the very large number of workers involved in the construction sector, the high level of informality, and the very large quantities of waste involved, it is strongly recommended that further research into CDW in LIMICs is carried out to address and mitigate the level of potential harm caused by the mismanagement of these materials.

CRediT author statement

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

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References

Arocho, I., Rasdorf, W. and Hummer, J. (2014). *Methodology to Forecast the Emissions from Construction Equipment for a Transportation Construction Project*.

Asakura, H. (2013). Removing gypsum from construction and demolition waste (C&DW) In F. Pacheco-Torgal et al. (eds.) *Handbook of Recycled Concrete and Demolition Waste* (479-499): Woodhead Publishing.

Azarmi, F. and Kumar, P. (2016). Ambient exposure to coarse and fine particle emissions from building demolition. *Atmospheric Environment*, 137, 62-79.

Balaras, C.A., Gaglia, A.G., Georgopoulou, E., Mirasgedis, S., Sarafidis, Y., Lalas, D.P.J.B. and environment (2007). European residential buildings and empirical assessment of the Hellenic building stock, energy consumption, emissions and potential energy savings. 42(3), 1298-1314.

Brown, A., Barrett, J.E.S., Robinson, H. and Potgieter-Vermaak, S. (2015). Risk assessment of exposure to particulate output of a demolition site. *Environmental Geochemistry and Health*, 37(4), 675-687.

Burki, T. (2010). Health experts concerned over India's asbestos industry. *The Lancet*, 375(9715), 626-627.

Burns, C.J., LaKind, J.S., Mattison, D.R., Alcala, C.S., Branch, F., Castillo, J., Clark, A., Clougherty, J.E., Darney, S.P., Erickson, H., Goodman, M., Greiner, M., Jurek, A.M., Miller, A., Rooney, A.A. and Zidek, A. (2019). A matrix for bridging the epidemiology and risk assessment gap. *Global Epidemiology*, 1, 100005.

Butera, S., Christensen, T.H. and Astrup, T.F. (2014). Composition and leaching of construction and demolition waste: Inorganic elements and organic compounds. *Journal of Hazardous Materials*, 276, 302-311.

Carpenter, A., Jambeck, J.R., Gardner, K. and Weitz, K. (2013). Life Cycle Assessment of End-of-Life Management Options for Construction and Demolition Debris. *Journal of Industrial Ecology*, 17(3), 396-406.

Carroll, W.F. (2001). The relative contribution of wood and poly(vinyl chloride) to emissions of PCDD and PCDF from house fires. *Chemosphere*, 45(8), 1173-1180.

Centers for Disease Control and Prevention (1989). Lead Poisoning in Bridge Demolition Workers - Massachusetts *Morbidity and Mortality Weekly Report (MMWR)*, 687-688, 693-694). Washington DC, USA: Centers for Disease Control and Prevention (CDC).

Chen, W., Liu, Y., Wang, H., Hnizdo, E., Sun, Y., Su, L., Zhang, X., Weng, S., Bochmann, F., Hearl, F.J., Chen, J. and Wu, T. (2012). Long-term exposure to silica dust and risk of total and cause-specific mortality in Chinese workers: a cohort study. *PLOS Medicine*, 9(4), e1001206-e1001206.

Concha-Barrientos, M., Nelson, D.I., Driscoll, T., Steenland, N.K., Punnett, L., Fingerhut, M.A., Prüss-Üstün, A., Leigh, J., Tak, S. and Corvalan, C. (2004). Selected occupational risk factors In M. Ezzati et al. (eds.) *Comparative Quantification of Health Risks Global and Regional Burden of Disease Attributable to Selected Major Risk Factors* (1651-1801): World Health Organization.

Cook, E., Velis, C.A. and Derks, M. (2020). Plastic waste processing: A systematic review of risks to occupational and public health from legacy substances and extrusion. *engrXiv*, 10.31224/osf.io/yxb5u.

Cooper, C., Booth, A., Varley-Campbell, J., Britten, N. and Garside, R. (2018). Defining the process to literature searching in systematic reviews: a literature review of guidance and supporting studies. *BMC Medical Research Methodology*, 18(1), 85.

Dania, A.A., Kehinde, J.O. and Bala, K. (2007). A study of construction material waste management practices by construction firms in Nigeria. *PRoBE 2007. The Third Scottish Conference for Postgraduate Researchers of the Built and Natural Environment*, https://www.irb.fraunhofer.de/CIBlibrary/search-quick-result-list.jsp?A&idSuche=CIB+DC10782, 121-129. Glasgow Caledonian University.

Devia, Y.P. and Suryo, E.A. (2017). Leachate of Demolition Waste In J. W. Park et al. (eds.) *6th International Conference of Euro Asia Civil Engineering Forum*. Seoul, South Korea: E D P Sciences,.

Dodson, R.F. and Hammar, S.P. (2012). *Asbestos: Risk Assessment, Epidemiology, and Health Effects*. Boca Raton, USA: Taylor & Francis Group.

Drage, D.S., Sharkey, M., Abdallah, M.A.E., Berresheim, H. and Harrad, S. (2018). Brominated flame retardants in Irish waste polymers: Concentrations, legislative compliance, and treatment options. *Science of The Total Environment*, 625, 1535-1543.

Driscoll, T., Nelson, D.I., Steenland, K., Leigh, J., Concha-Barrientos, M., Fingerhut, M. and Prüss-Ustün, A. (2005). The global burden of disease due to occupational carcinogens. *American journal of industrial medicine*, 48(6), 419-431.

Duan, H., Yu, D., Zuo, J., Yang, B., Zhang, Y. and Niu, Y. (2016). Characterization of brominated flame retardants in construction and demolition waste components: HBCD and PBDEs. *Science of The Total Environment*, 572, 77-85.

Duggan, M.J., James, A.C. and Allen, S.G. (1974). The inhalation hazard to workers engaged in the demolition of buildings contaminated with radioactivity. *The Annals of Occupational Hygiene*, 17(1), 15-22.

Environment Agency (2017). Waste Wood: quick guide 43_17. Retrieved from: https://biomass-suppliers-list.service.gov.uk/Content/Documents/2017%2003%2006%20Waste%20Wood%2043_17%20-%20EA%20guidance.pdf.

Ertaş, H. and Erdoğan, A.S. (2017). An Analysis of Occupational Accidents in Demolition Work. *Civil Engineering and Architecture*, Vol. 5(2), 37 - 51.

European Commission (2006). Population statistics. Luxembourg: Office for Official Publications of the European Communities. Retrieved from: https://ec.europa.eu/eurostat/documents/3217494/5685052/KS-EH-06-001-EN.PDF/1e141477-9235-44bb-a24b-a55454c2bc42?version=1.0.

European Commission (2009). Causes and circumstances of accidents at work in the EU. Belgium: European Commission Directorate-General for Employment: Social Affairs and Equal Opportunities F4 unit. Retrieved from: https://ec.europa.eu/eurostat/documents/53621/53703/Full-Publication%5BEN%5D-WO.pdf/6e90be02-c41e-43d6-87d4-68a4a7899ad1.

European Union (1999). Council Directive 1999/31/EC of 26 April 1999 on the landfill of waste. The Council of the European Union. Retrieved from: https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:31999L0031:EN:HTML.

European Union (2002). Council Decision of 19 December 2002 establishing criteria and procedures for the acceptance of waste at landfills pursuant to Article 16 of and Annex II to Directive 1999/31/EC *L11, p.27-49*.

European Union (2008a). Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on ambient air quality and cleaner air for Europe *L152, P. 169-212*.

European Union (2008b). Regulation (EC) No 1338/2008 of The European Parliament and of The Council of 16 December 2008 on Community statistics on public health and health and safety at work. Off. J. Eur. Union. Retrieved from: https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:32008R1338.

European Union (2009). Directive (EU) 2017/2398 of the European Parliament and of the Council of 12 December 2017 amending Directive 2004/37/EC on the protection of workers from the risks related to exposure to carcinogens or mutagens at work (Text with EEA relevance). Off. J. Eur. Union. Retrieved from: https://eur-lex.europa.eu/eli/dir/2017/2398/oj.

Eurostat (2010) *Accidents at work (ESAW) - until 2007 (hsw_acc7_work): Reference Metadata in Euro SDMX Metadata Structure (ESMS).* Retreived from https://ec.europa.eu/eurostat/cache/metadata/en/hsw_acc7_work_esms.htm.

Eurostat (2019) *Accidents at work statistics* Retreived from https://ec.europa.eu/eurostat/statistics-explained/index.php/Accidents_at_work_statistics#Accidents_2010_to_2017_.E2.80.94_absolute_changes_in_incidence_rates.

Eurostat (2020) *Your Key to European Statistics.* Retreived from https://ec.europa.eu/eurostat.

Evans, L. (2014). Traffic fatality reductions: United States compared with 25 other countries. *American Journal of Public Health*, 104(8), 1501-1507.

Ferronato, N. and Torretta, V. (2019). Waste Mismanagement in Developing Countries: A Review of Global Issues. 16(6), 1060.

Fischbein, A., Daum, S.M., Davidow, B., Slavin, G., Alvares, A.P., Sassa, S., Anderson, K.E., Kappas, A., Eisinger, J., Blumberg, W.E., Winicow, E.H. and Selikoff, I.J. (1978). Lead hazard among ironworkers. Dismantling lead-painted elevated subway line in New York City. *New York State Journal of Medicine*, 78(8), 1250-1259.

Flanagan, D.M. (2020). U.S. Geological Survey, Mineral Commodity Summaries: Asbestos. U. S. G. Survey. Retrieved from: https://pubs.usgs.gov/periodicals/mcs2020/mcs2020-asbestos.pdf.

Font, A., Baker, T., Mudway, I.S., Purdie, E., Dunster, C. and Fuller, G.W. (2014). Degradation in urban air quality from construction activity and increased traffic arising from a road widening scheme. *Science of The Total Environment*, 497-498, 123-132.

Frank, A.L. (2006). The history of the extraction and use of asbestos *Asbestos–Risk Assessment, Epidemiology, and Health Effects* (1-7): Taylor and Francis Group.

Frank, A.L. and Joshi, T. (2014). The global spread of asbestos. 80(4), 257-262.

Freeman, M.H., Nicholas, D.D. and Schultz, T.P. (2006). Nonarsenical Wood Protection: Alternatives for Chromated Copper Arsenate, Creosote and Pentachlorophenol In T. G. Townsend and H. Solo-Gabriele (eds.) *Environmental Impacts of Treated Wood*. Boca Raton, USA: Taylor & Francis.

Fuller, G.W. and Green, D. (2004). The impact of local fugitive PM10 from building works and road works on the assessment of the European Union Limit Value. *Atmospheric Environment*, 38(30), 4993-5002.

Furuya, S., Chimed-Ochir, O., Takahashi, K., David, A. and Takala, J. (2018a). Global Asbestos Disaster. 15(5), 1000.

Furuya, S., Chimed-Ochir, O., Takahashi, K., David, A. and Takala, J. (2018b). Global Asbestos Disaster. *International Journal of Environmental Research and Public Health*, 15(5), 1000.

Gaskin, J.W., Risse, L.M., Kastner, J.R. and McLaurin, W.J. (2005). Evaluating onsite beneficial reuse of ground engineered wood wastes from residential construction. *Transactions of the American Society of Agricultural Engineers*, 48(5), 1731-1738.

Ginga, C.P., Ongpeng, J.M.C. and Daly, M.K.M. (2020). Circular economy on construction and demolition waste: A literature review on material recovery and production. *Materials*, 13(13), 1-18.

Gottesfeld, P., Kuepouo, G., Tetsopgang, S. and Durand, K. (2013). Lead Concentrations and Labeling of New Paint in Cameroon. *Journal of Occupational and Environmental Hygiene*, 10(5), 243-249.

Guidotti, T.L. (1996). Hydrogen Sulphide. *Occupational Medicine*, 46(5), 367-371.

Gürcanli, G.E. and Müngen, U. (2013). Analysis of Construction Accidents in Turkey and Responsible Parties. *Industrial Health*, 51(6), 581-595.

Health and Safety Executive (2009) *The control of lead at work regulations 1998.* Retreived from https://www.hse.gov.uk/foi/internalops/ocs/200-299/298_15.htm#para-7.

Health and Safety Executive (2020a). EH40/2005 Workplace exposure limits: Containing the list of workplace exposure limits for use with the Control of Substances Hazardous to Health Regulations 2002 (as amended) UK: TSO (The Stationery Office). Retrieved from: https://www.hse.gov.uk/pUbns/priced/eh40.pdf.

Health and Safety Executive (2020b) *Information and services.* Retreived from https://www.hse.gov.uk/.

Henderson, D.W. and Leigh, J. (2012). The History of Asbestos Utilization and Recognition of Asbestos-Induced Diseases In R. F. Dodson and S. P. Hammar (eds.) *Asbestos: Risk Assessment, Epidemiology, and Health Effects*. Boca Raton, USA: Taylor & Francis Group.

Huang, S., Zhao, X., Sun, Y., Ma, J., Gao, X., Xie, T., Xu, D., Yu, Y. and Zhao, Y. (2016). Spatial distribution of organic pollutants in industrial construction and demolition waste and their mutual interaction on an abandoned pesticide manufacturing plant. *Environ Sci Process Impacts*, 18(4), 482-492.

Hunter, P.R., Payment, P., Ashbolt, N. and Bartram, J. (2003). Assessment of risk *Assessing microbial safety of drinking water: Improving approaches and methods* (79-109). Paris, France: Organisation for Economic Cooperation and Development and World Health Organisation.

IARC Working Group on the Evaluation of Carcinogenic Risks to Humans (2012). Arsenic, Metals, Fibres, and Dusts: IARC Monographs on the Evaluation of Carcinogenic Risks to Humans Volume 100C. Lyon, France. Retrieved from: https://publications.iarc.fr/120.

International Chrysotile Association (nd) *For environmental occupational health safe and responsible use: Products.* Retreived from https://chrysotileassociation.com/chrysotile/products/default.php.

International Labour Organization (2020a) *Cases of fatal occupational injury by economic activity: Annual.* International Labour Organization, Retreived from https://www.ilo.org/ilostat-files/Documents/Excel/INDICATOR/INJ_FATL_ECO_NB_A_EN.xlsx.

International Labour Organization (2020b) *Cases of non-fatal occupational injury by economic activity | Annual.* International Labour Organization, Retreived from https://www.ilo.org/ilostat-files/Documents/Excel/INDICATOR/INJ_NFTL_ECO_NB_A_EN.xlsx.

International Labour Organization (2020c) *ILOSTAT: The leading source of labour statistics.* Retreived from https://ilostat.ilo.org/.

Jacobs, D.E. (1998). Occupational exposures to lead-based paint in structural steel demolition and residential renovation work. *International Journal of Environment and Pollution*, 9(1), 126-139.

Jadhav, A.V. and Gawde, N.C. (2019). Current Asbestos Exposure and Future Need for Palliative Care in India. *Indian journal of palliative care*, 25(4), 587-591.

Jambeck, J.R., Townsend, T.G. and Solo-Gabriele, H.M. (2008). Landfill Disposal of CCA-Treated Wood with Construction and Demolition (C&D) Debris: Arsenic, Chromium, and Copper Concentrations in Leachate. *Environmental Science & Technology*, 42(15), 5740-5745.

Jewell, C., Flanagan, R. and Cattell, K. (2005). The Effects of the Informal Sector on Construction. *Construction Research Congress 2005 : Broadening Perspectives . 2005*, doi:10.1061/40754(183)78.

Jiang, N., Dong, Z., Xu, Y., Yu, F., Yin, S., Zhang, R. and Tang, X. (2018). Characterization of PM10 and PM2.5 Source Profiles of Fugitive Dust in Zhengzhou, China. *Aerosol and Air Quality Research*, 18(2), 314-329.

Kaya, G.K., Ward, J.R. and Clarkson, P.J. (2018). A framework to support risk assessment in hospitals. *International Journal for Quality in Health Care*, 31(5), 393-401.

Kazan-Allen, L. (2019a) *Chronology of Asbestos Bans and Restrictions* Retreived from http://www.ibasecretariat.org/chron_ban_list.php.

Kazan-Allen, L. (2019b) *Current Asbestos Bans: National Asbestos Bans.* Retreived from http://www.ibasecretariat.org/alpha_ban_list.php.

Kodros, J.K., Wiedinmyer, C., Ford, B., Cucinotta, R., Gan, R., Magzamen, S. and Pierce, J.R. (2016). Global burden of mortalities due to chronic exposure to ambient PM2.5 from open combustion of domestic waste. *Environmental Research Letters*, 11(12), 124022.

Koyano, S., Ueno, D., Yamamoto, T. and Kajiwara, N. (2019). Concentrations of POPs based wood preservatives in waste timber from demolished buildings and its recycled products in Japan. *Waste Management*, 85, 445-451.

Kumar, P. and Morawska, L. (2014). Recycling concrete: An undiscovered source of ultrafine particles. *Atmospheric Environment*, 90, 51-58.

Kumar, P., Mulheron, M. and Som, C. (2012). Release of ultrafine particles from three simulated building processes. *Journal of nanoparticle research*, 14(4), 771.

Lange, J.H. and Thomulka, K.W. (2000). Effectiveness of Engineering Controls for Airborne Lead Exposure during Renovation/Demolition of a Commercial Building. *Indoor and Built Environment*, 9(3-4), 207-215.

Lee, S., Xu, Q., Booth, M., Townsend, T.G., Chadik, P. and Bitton, G. (2006). Reduced sulfur compounds in gas from construction and demolition debris landfills. *Waste Management*, 26(5), 526-533.

Lemieux, P.M., Lutes, C.C. and Santoianni, D.A. (2004). Emissions of organic air toxics from open burning: a comprehensive review. *Progress in Energy and Combustion Science*, 30(1), 1-32.

Leung, C.C., Yu, I.T.S. and Chen, W. (2012). Silicosis. *The Lancet*, 379(9830), 2008-2018.

Li, J., Dong, Q., Yu, K. and Liu, L. (2014). Asbestos and asbestos waste management in the Asian-Pacific region: trends, challenges and solutions. *Journal of Cleaner Production*, 81, 218-226.

Liu, W., Tang, P.T., Li, K. and Jiang, T. (2019). Demolition dust formation, diffusion mechanism and monitoring quantitative research on demolition of existing buildings. *Applied Ecology and Environmental Research*, 17(6), 14543-14559.

López, A. and Lobo, A. (2014). Emissions of C&D refuse in landfills: A European case. *Waste Management*, 34(8), 1446-1454.

Maeda, H., Fujita, M.Q., Zhu, B.-L., Quan, L., Kamikodai, Y., Tsuda, K. and Taniguchi, M. (2003). Labor-related fatalities in forensic postmortem investigations during the past 6 years in the southern half of Osaka city and surrounding areas. *Legal Medicine*, 5, S325-S327.

Mella, A. and Savage, M. (2018). Construction Sector Employment in Low-Income Countries. Infrastructure and Cities for Economic Development (ICED). Retrieved from: http://icedfacility.org/wp-content/uploads/2018/08/Report_Construction-Sector-Employment-in-LICs_Final.pdf.

Moher, D., Liberati, A., Tetzlaff, J., Altman, D.G. and The Prisma Group (2009). Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. *PLOS Medicine*, 6(7), e1000097.

Montero, A., Tojo, Y., Matsuo, T., Matsuto, T., Yamada, M., Asakura, H. and Ono, Y. (2010). Gypsum and organic matter distribution in a mixed construction and demolition waste sorting process and their possible removal from outputs. *Journal of Hazardous Materials*, 175(1), 747-753.

Morrell, J.J. (2006). Chromated Copper Arsenate as a Wood Preservative In T. G. Townsend and H. Solo-Gabriele (eds.) *Environmental Impacts of Treated Wood*. Boca Raton, USA: Taylor & Francis.

National Minerals Information Center (2018). Asbestos Statistics and Information: Minerals Yearbook: Advance Data Release of the 2018 Annual Tables In National Minerals Information Center (ed.).

National Minerals Information Center (2020). Asbestos Statistics and Information: Minerals Yearbook In National Minerals Information Center (ed.).

Nie, Z., Yang, Z., Fang, Y., Yang, Y., Tang, Z., Wang, X., Die, Q., Gao, X., Zhang, F., Wang, Q. and Huang, Q. (2015). Environmental risks of HBCDD from construction and demolition waste: a contemporary and future issue. *Environmental Science and Pollution Research*, 22(21), 17249-17252.

Normohammadi, M., Kakooei, H., Omidi, L., Yari, S. and Alimi, R. (2016). Risk Assessment of Exposure to Silica Dust in Building Demolition Sites. *Safety and Health at Work*, 7(3), 251-255.

Odgerel, C.O., Takahashi, K., Sorahan, T., Driscoll, T., Fitzmaurice, C., Yoko, O.M., Sawanyawisuth, K., Furuya, S., Tanaka, F., Horie, S., Zandwijk, N.V. and Takala, J. (2017). Estimation of the global burden of mesothelioma deaths from incomplete national mortality data. *Occupational and Environmental Medicine*, 74(12), 851-858.

Ogunmakinde, O., Sher, W. and Maund, K. (2019). An Assessment of Material Waste Disposal Methods in the Nigerian Construction Industry. *Recycling*, 4, 13.

Ogunseitan, O.A. (2015). The asbestos paradox: global gaps in the translational science of disease prevention: SciELO Public Health.

Puthussery, J.V., Kumar, R. and Garg, A. (2017). Evaluation of recycled concrete aggregates for their suitability in construction activities: An experimental study. *Waste Management*, 60, 270-276.

Saca, N., Dimache, A., Radu, L.R. and Iancu, I. (2017). Leaching behavior of some demolition wastes. *Journal of Material Cycles and Waste Management*, 19(2), 623-630.

Schiopu, N. and Tiruta-Barna, L. (2012). Wood preservatives In F. Pacheco-Torgal et al. (eds.) *Toxicity of building materials*. Cambridge, UK: Woodhead Publishing Limited.

Scholz, P.F., Materna, B.L., Harrington, D. and Uratsu, C. (2002). Residential and commercial painters' exposure to lead during surface preparation. *American Industrial Hygiene Association Journal*, 63(1), 22-28.

Secretariat of the Basel Convention (2017a). Technical guidelines on the environmentally sound management of wastes consisting of, containing or contaminated with pentachlorophenol and its salts and esters (PCP). Geneva: United Nations Environment Programme. Retrieved from: http://www.basel.int/Implementation/TechnicalMatters/DevelopmentofTechnicalGuidelines/TechnicalGuidelines/tabid/8025/Default.aspx.

Secretariat of the Basel Convention (2017b). Technical guidelines on the environmentally sound management of wastes consisting of, containing or contaminated with polychlorinated biphenyls, polychlorinated terphenyls, polychlorinated naphthalenes or polybrominated biphenyls including hexabromobiphenyl (PCBs, PCTs, PCNs or PBBs, including HBB). Geneva: United Nations Environment Programme. Retrieved from: http://www.basel.int/Portals/4/download.aspx?d=UNEP-CHW.13-6-Add.4-Rev.1.English.pdf.

Secretariat of the Basel Convention (2017c). Technical guidelines: technical guidelines on the environmentally sound management of wastes consisting of, containing or contaminated with the pesticides aldrin, alpha hexachlorocyclohexane, beta hexachlorocyclohexane, chlordane, chlordecone, dieldrin, endrin, heptachlor, hexachlorobenzene, hexachlorobutadiene, lindane, mirex, pentachlorobenzene, pentachlorophenol and its salts, perfluorooctane sulfonic acid, technical endosulfan and its related isomers or toxaphene or with hexachlorobenzene as an industrial chemical (POP Pesticides). Geneva: United Nations Environment Programme. Retrieved from: http://www.basel.int/Portals/4/download.aspx?d=UNEP-CHW.13-6-Add.6-Rev.1.English.pdf.

Secretariat of the Basel Convention (nd) *Framework for the environmentally sound management of hazardous wastes and other wastes.* Retreived from http://www.basel.int/Implementation/CountryLedInitiative/EnvironmentallySoundManagement/ESMFramework/tabid/3616/Default.aspx.

Secretariat of the Stockholm Convention (nd) *Hexabromocyclododecane.* Retreived from http://chm.pops.int/Implementation/Alternatives/AlternativestoPOPs/ChemicalslistedinAnnexA/HBCD/tabid/5861/Default.aspx.

Siegel, L.S. (1991). As the Asbestos Crumbles: A Look at New Evidentiary Issues in Asbestos-Related Property Damage Litigations Note. *Hofstra Law Review*, 20(4), 1139-1172.

Sirrs, C. (2016). Accidents and Apathy: The Construction of the 'Robens Philosophy' of Occupational Safety and Health Regulation in Britain, 1961–1974. *Social History of Medicine*, 29(1), 66-88.

Spasiano, D. and Pirozzi, F. (2017). Treatments of asbestos containing wastes. 204, 82-91.

Stacey, P., Thorpe, A. and Roberts, P. (2011). Levels of respirable dust and respirable crystalline silica at construction sites. Report No. RR878. UK: Health and Safety Executive. Retrieved from: https://www.hse.gov.uk/research/rrpdf/rr878.pdf.

Stayner, L., Welch, L.S. and Lemen, R. (2013). The worldwide pandemic of asbestos-related diseases. *Annu Rev Public Health*, 34, 205-216.

Swedish Environmental Protection Agency (2009). The role of pentachlorophenol treated wood for emissions of dioxins into the environment. Stockholm, Sweden: Swedish Environmental Protection Agency. Retrieved from: https://www.naturvardsverket.se/Documents/publikationer/978-91-620-5935-4.pdf?pid=3534.

t Mannetje, A., Steenland, K., Attfield, M., Boffetta, P., Checkoway, H., DeKlerk, N. and Koskela, R.S. (2002). Exposure-response analysis and risk assessment for silica and silicosis mortality in a pooled analysis of six cohorts. *Occupational and Environmental Medicine*, 59(11), 723.

Takahashi, H. (2019). An investigation of fatal accidents in demolition work of buildings *ISEC 2019 - 10th International Structural Engineering and Construction Conference*.

Tame, N.W., Dlugogorski, B.Z. and Kennedy, E.M. (2007). Formation of dioxins and furans during combustion of treated wood. *Progress in Energy and Combustion Science*, 33(4), 384-408.

The Air Quality Standards Regulations (2010). The Air Quality Standards Regulations 2010. Retrieved from: http://www.legislation.gov.uk/uksi/2010/1001/contents/made.

The World Bank (2020) *World Bank Open Data: Free and open access to global development data.* Retreived from https://data.worldbank.org/.

The World Bank (nd) *World Bank Country and Lending Groups.* Retrieved from https://datahelpdesk.worldbank.org/knowledgebase/articles/906519-world-bank-country-and-lending-groups.

Townsend, T., Chadik, P., Bitton, G., Booth, M., Lee, S. and Yang, K.J.G., FL: State University System of Florida (2000). Gypsum drywall impact on odor production at landfills: Science and control strategies.

Turner, A. and Solman, K.R. (2016). Lead in exterior paints from the urban and suburban environs of Plymouth, south west England. *Science of The Total Environment*, 547, 132-136.

United States Environmental Protection Agency (2000). Effluent Limitations Guidelines, Pretreatment Standards, and New Source Performance Standards for the Landfills Point Source Category. Retrieved from: https://www.federalregister.gov/documents/2000/01/19/00-1037/effluent-limitations-guidelines-pretreatment-standards-and-new-source-performance-standards-for-the.

US Geological Survey (2020). Mineral commodity summaries 2020. Reston, USA: US Geological Survey. Retrieved from: https://pubs.er.usgs.gov/publication/mcs2020.

Van Praagh, M. and Modin, H. (2016). Leaching of chloride, sulphate, heavy metals, dissolved organic carbon and phenolic organic pesticides from contaminated concrete. *Waste Management*, 56, 352-358.

Vanya, D., Ken, T., Eun-Kee, P., Giang, V.L., Toshiyuki, H. and Tom, S. (2011). Global mesothelioma deaths reported to the World Health Organization between 1994 and 2008. *Bulletin of the World Health Organization*, 89, 716-724C.

Virta, R.L. (2006). Worldwide Asbestos Supply and Consumption Trends from 1900 through 2003. U.S. Geological Survey. Retrieved from: https://pubs.usgs.gov/circ/2006/1298/c1298.pdf.

Wagner, A.C., Bergen, A., Brilke, S., Bühner, B., Ebert, M., Haunold, W., Heinritzi, M., Herzog, S., Jacobi, S., Kürten, A., Piel, F., Ramme, A., Weber, D., Weinbruch, S. and Curtius, J. (2017). Characterization of Aerosol Particles Produced by a Skyscraper Demolition by Blasting. *Journal of Aerosol Science*, 112, 11-18.

Wahab, A.B. and Lawal, A.F. (2011). An evaluation of waste control measures in construction industry in Nigeria. *African Journal of Environmental Science and Technology*, 5(3), 246-254.

Wasson, S.J., Linak, W.P., Gullett, B.K., King, C.J., Touati, A., Huggins, F.E., Chen, Y., Shah, N. and Huffman, G.P. (2005). Emissions of chromium, copper, arsenic, and PCDDs/Fs from open burning of CCA-treated wood. *Environ Sci Technol*, 39(22), 8865-8876.

Wiedinmyer, C., Yokelson, R.J. and Gullett, B.K. (2014). Global Emissions of Trace Gases, Particulate Matter, and Hazardous Air Pollutants from Open Burning of Domestic Waste. *Environmental Science & Technology*, 48(16), 9523-9530.

Wielgosiński, G. (2011). The Reduction of Dioxin Emissions from the Processes of Heat and Power Generation. *Journal of the Air & Waste Management Association*, 61(5), 511-526.

World Health Organization (1999). Hazard Prevention and Control in the Work Environment: Airborne Dust. Geneva: World Health Organization. Retrieved from: https://apps.who.int/iris/bitstream/handle/10665/66147/WHO_SDE_OEH_99.14.pdf?sequence=1&isAllowed=y&ua=1.

World Health Organization (2012). Rapid Risk Assessment of Acute Public Health Events. Report No. WHO/HSE/GAR/ARO/2012.1. Geneva, Switzerland: World Health Organization. Retrieved from: https://www.who.int/csr/resources/publications/HSE_GAR_ARO_2012_1/en/.

World Health Organization (2019) *Download the raw data files of the WHO Mortality Database*. World Health Organization, Retreived from https://www.who.int/healthinfo/statistics/mortality_rawdata/en/.

World Health Organization (2020) *World Health Data Platform*. Retreived from https://www.who.int/data.

Xu, Q., Townsend, T. and Bitton, G. (2011). Inhibition of hydrogen sulfide generation from disposed gypsum drywall using chemical inhibitors. *Journal of Hazardous Materials*, 191(1), 204-211.

Yang, K., Xu, Q., Townsend, T.G., Chadik, P., Bitton, G. and Booth, M. (2006). Hydrogen sulfide generation in simulated construction and demolition debris landfills: impact of waste composition. *J Air Waste Manag Assoc*, 56(8), 1130-1138.

Zaharuddin, W., Paraskevas, I. and Liu, C. (2009). Accident avoidance importance for building demolition *CIB W099 Working Commission on Construction Safety and Health (2009 : Melbourne, Victoria)*, http://hdl.handle.net/10536/DRO/DU:30029283 9-14. RMIT University