frontiers | Frontiers in Sustainability

REVIEW
published: 30 June 2022
doi: 10.3389/frsus.2022.924926

Construction and Demolition Waste Management: A Systematic Scoping Review of Risks to Occupational and Public Health

Ed Cook, Costas A. Velis and Leon Black*

School of Civil Engineering, University of Leeds, Leeds, United Kingdom

Despite the relatively benign characteristics of construction and demolition waste, its mismanagement can result in considerable harm to human health for 200 million workers and those who live and work in proximity to construction and demolition activities. The high number of workers classified as informal, results in a large unregulated and vulnerable workforce at a high risk of exposure to hazards. We focused a systematic scoping review (PRISMA-ScR) on evidence associating construction and demolition waste with hazards and risks in low- and middle-income countries. We reviewed more than 3,000 publications, narrowed to 49 key sources. 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 construction and demolition waste is disposed of by open burning in many low- and middle-income countries, including increasing quantities of high chloride-content PVC; risking exposure to dioxins and related compounds. A long-standing and well-known hazard, asbestos, continues to represent a health threat throughout the world, claiming 250,000 lives per annum despite being banned in most countries. In the coming decades, it is anticipated that more than half of all deaths from asbestos will take place in India, where it is still sold. Comparatively, the highest risks from construction and demolition waste exist in low- and middle-income countries where attention to risk mitigation and control is needed.

Keywords: solid waste (MSW), informal recycling sector (IRS), circular economy, hazardous waste, accidents and causes, construction and demolition waste, occupational and public health and safety, open burning of solid waste

Edited by:
Maria Alzira Pimenta Dinis,
Fernando Pessoa University, Portugal

Reviewed by:
Lubaba Sadaf,
National University of Sciences and Technology (NUST), Pakistan
Zujaja Wahaj,
National University of Sciences and Technology, Pakistan

***Correspondence:**
Costas A. Velis
c.velis@leeds.ac.uk

Specialty section:
This article was submitted to Waste Management, a section of the journal Frontiers in Sustainability

Received: *20 April 2022*
Accepted: *13 May 2022*
Published: *30 June 2022*

Citation:
Cook E, Velis CA and Black L (2022) Construction and Demolition Waste Management: A Systematic Scoping Review of Risks to Occupational and Public Health. Front. Sustain. 3:924926. doi: 10.3389/frsus.2022.924926

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 toward total solid waste generation (estimated 36% wt.) (Wilson et al., 2015). Partly, this can be explained because many of the constituents of CDW are comparatively benign. CDW is characterized (on a weight basis) by comparatively 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 (**Supplementary Section S.5.2**). Because it is often generated during commercial (non-domestic) activities, any negative effects on the environment or public health emerge away from the public eye.

CDW is defined as the material generated during: construction of new buildings; renovation of old structures; partial deconstruction of buildings; and during full 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 (HICs), CDW has been managed with increasing resource recovery and wider 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). Globally, this trend 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, ∼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).

A posteriori evidence suggests that 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. 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 Erdogan (2017), who investigated accident data in the UK and Australia; and by Gürcanli and Müngen (2013), who carried out a similar study analyzing prosecution records in Turkey. Several recent efforts that are partly related to the safety topic include Chen et al. (2021), who carried out analysis of the environmental effects of CDW; and Molla et al. (2021), who investigated chemicals of concern in CDW. A large body of evidence also exists regarding the occupational and public health implications of the management of specific CDW components; the most prominent being asbestos, which has claimed many thousands of lives since its commercialization in the early 20th century and which is expected to continue to do so for several more decades (Driscoll et al., 2005; Odgerel et al., 2017; Furuya et al., 2018; Stevulova et al., 2020). However, there are no reviews on CDW management and its safety in the public domain that is disaggregated from the wider topic of construction and demolition.

In response to this 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**). We bring together, for the first time, a wide range of literature, indicating occupational and public health risks from CDW. The review is organized 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 link identified safety challenges with practiced CDW management 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 activities within the sector. The focus is on LIMICs, where well-resourced, independent environmental regulation is not always guaranteed. However, the dearth of research in LIMICs means that many of the papers reviewed are taken from the HIC context. We exclude the management of CDW from disasters, war and conflict, as these very specific sub-cases warrant a specialist review (shown outside the CDW system boundary in **Supplementary Figure S5**). In addition, we do not address risks from the wider construction activities, but focus only on those that relate to CDW itself. The preprint of this paper is available at https://doi.org/10.31224/osf.io/5tpbz (Cook and Velis, 2022).

METHODS

Systematic Review

We carried out a systematic scoping review following PRISMA-ScR guidelines (Peters et al., 2020) and using the preferred reporting items listed by Tricco et al. (2018) (**Supplementary Section S2**) 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?

Abbreviations: BDE, brominated diphenyl ether; BDL, below detection limit; CCA, chromated copper arsenate; CDW, construction and demolition waste; conc., concentration; DRCs, dioxins and related compounds; H_2S, hydrogen sulfide; HBCD, hexabromocyclododecane; HBCD, hexabromocyclododecane; HI, hazard index; HIC, high income countries; HSE, Health and Safety Executive; ind., industrial; L/S, liquid to solid ratio; LIC, low income countries; LIMIC, low income and middle income countries; LMC, lower middle income countries; MSW, municipal solid waste; Mt, million metric tons; n, number of samples; PBDEs, polybrominated diphenyl ethers; PCB, polychlorinated biphenyls; PM, particulate matter; $PM_{0.1}$, particulate matter $<0.1\,\mu m$; PM_{10}, particulate matter $<10\,\mu m$; $PM_{2.5}$, particulate matter $<2.5\,\mu m$; POP, persistent organic pollutants; PPE, personal protective equipment; ppm, parts per million; PUR, polyurethane; PVC, polyvinyl chloride; res., residential; RQ, research question; SGV, soil guideline values; t, metric tons (1,000 kg); 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; wt., weight (i.e., on a weight reporting basis).

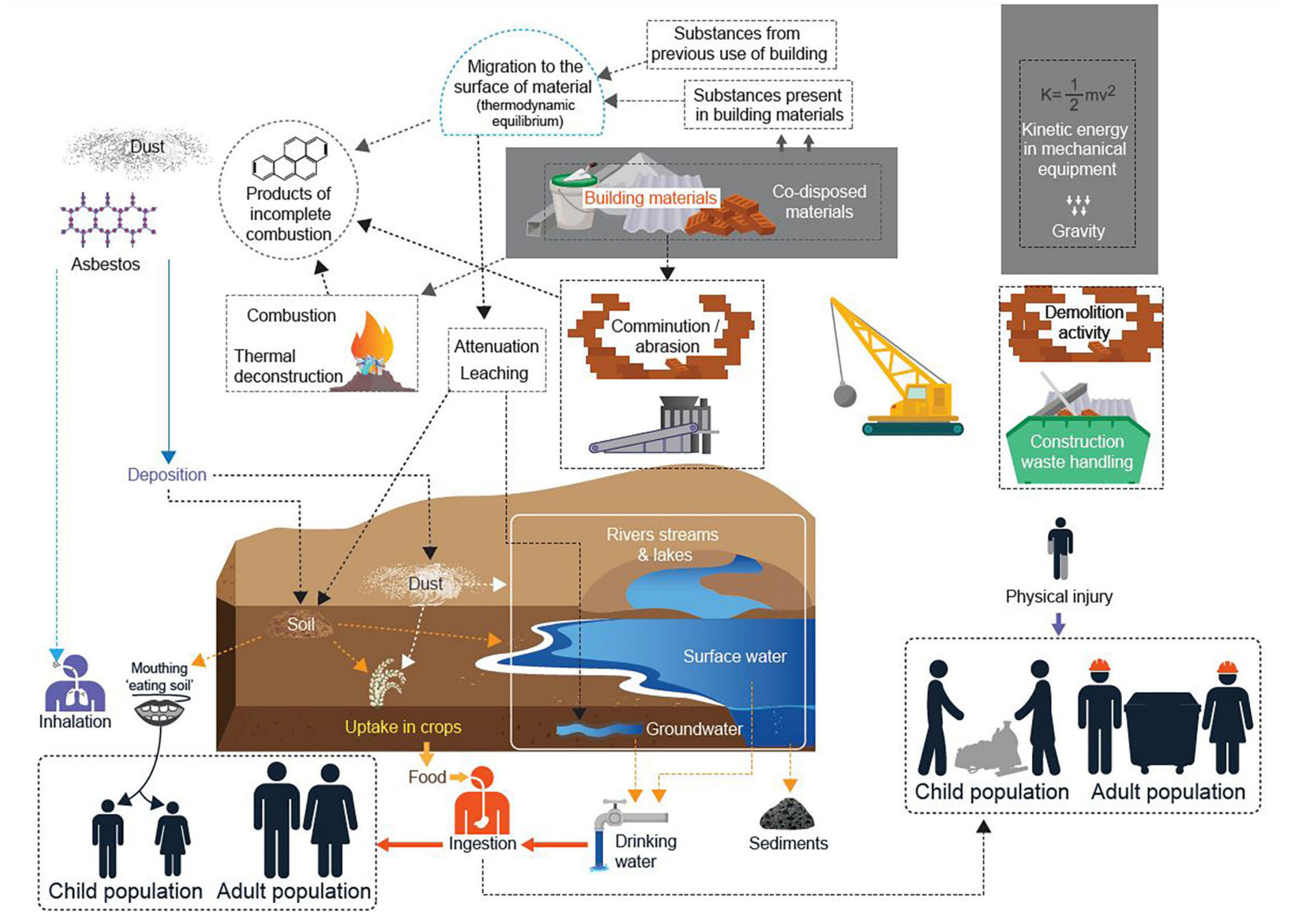

FIGURE 1 | Summary of the main hazards associated with construction and demolition waste (CDW) and the pathways through which they may result in exposure to receptors.

One-at-a-time sensitivity analysis (Hamby, 1995) was used to optimize Boolean search terms (**Supplementary Section S.3.1**) in order to retrieve the maximum number of relevant articles, whilst reducing the non-relevant from Scopus, Web of Science and Google Scholar. Sources were selected for inclusion according to the criteria in **Supplementary Section S.3.2** (**Supplementary Table S2**). 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 Health Safety Executive (2020b), International Labour Organization (2020b), The World Bank (2020), World Health Organization (2020), (HSE). A summary of the results of search decisions is illustrated in **Supplementary Section S.3.3** (**Supplementary Figure S1**) and geographical provenance of the first author's affiliated institution is shown in **Supplementary Section S.3.4** (**Supplementary Figure S2**).

Risk Based Approach

A semi-quantitative risk assessment process detailed in **Supplementary Section S.3.5** (**Supplementary Table S4**) was used to characterize risks associated with CDW based on an approach adapted from Hunter et al. (2003), World Health Organization (2012), Kaya et al. (2018) and Burns et al. (2019); the adaptation was first described by Cook et al. (2020) and elaborated by Velis and Cook (2021). 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 1**). Each hazard-pathway-receptor combination was indicatively assigned a risk score based on the likelihood of it occurring and potential severity to different receptors (**Supplementary Section S.3.5** and **Supplementary Table S5**). Scores were assessed separately for HICs and LIMICs. This process was not intended to quantitatively assess risk, but to indicate and rank the relative risks to prioritize future research agenda; the combined and ranked results are shown in **Supplementary Section S.4** (**Supplementary Table S6**).

CHALLENGE 1: HANDLING AND PHYSICAL PROCESSING OF CONSTRUCTION AND DEMOLITION WASTE

Context

The hazard-pathway-receptor (H-P-R) linkages necessary for potential hazards to be actualized on construction and demolition sites as a consequence of handling and physical processing are shown in **Supplementary Figure S6**. 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.

Accidents Involving Construction and Demolition Waste

According to data from 2016, 20% of all workplace fatalities occurred in the construction and demolition sector (International Labour Organization, 2020a) which has been reported to employ 8.6% of all workers (Mella and Savage, 2018).

Eurostat (2020) reports accidents requiring more than 3 days absence from work (hereafter ">3 day accidents") and fatalities for European Union member states (European Union, 2008b). Very little change was reported for the number of accidents and fatalities between 2014 and 2017, with ∼3,000 >3 day accidents per 100,000 people and around 5-6 fatalities reported for the construction related NACE economic categories (**Supplementary Figure S7A**). Accidents and fatalities involving CDW are not well reported. Though not obliged to do so (European Commission, 2009), some member states provide more granular, "Phase III" information for "bulk waste" (no definition is provided for this term) (Eurostat, 2010). As shown in **Supplementary Figure S7B**, ∼5 were reported each year between 2014 and 2017 and no fatalities were reported in 2016 or 2017.

Accidents or near misses that do not result in significant injury are not included in the statistics (European Commission, 2009) and it is likely that many accidents go unreported (Eurostat, 2019), for instance by self-employed people; uninsured people (in states where the data originate from the insurance industry); and public sector, mining and fishing workers, who may be covered under specific insurance schemes that do not necessarily submit data (European Commission, 2009). It is also 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.

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 Erdogan, 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 (Zaharuddin et al., 2009; Ertaş and Erdogan, 2017; Takahashi, 2019). 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 1**). European Commission (2009) reported a specific Phase III sub-category of "Demolition" for the EU15 in 2005. As a proportion of injuries from all sectors, it indicated 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). In the EU15, the demolition sector reported 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 reported by Maeda et al. (2003) who observed fatalities to be higher than European Commission (2009) by a factor of 10 in a single city in Japan between 1996 and 2001. 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, other studies (Evans, 2014) have suggested that fatality data are unlikely to be under-reported 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.

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 2**). Whereas, the proportions of fatalities and >3 day injuries by the European Commission (2009) in **Table 2** are broadly proportional to those reported in **Table 1**, the overall proportion of accidents and fatalities from demolition reported by Zaharuddin et al. (2009) are nearly six times higher. The Zaharuddin et al. (2009) 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 Erdogan (2017), indicating the accident rate has halved.

The data reported by Takahashi (2019) of demolition fatalities over a 5 year period in Japan (**Table 2**), have some similarity with the data reported by Maeda et al. (2003) for Osaka, Japan (**Table 1**), in that the fatality rate of the sector is ∼6 times higher than the European Commission and nearly twice the proportion reported by Gürcanli and Müngen (2013) in their study of eye-witness court testimonies in Turkey. For instance, recent analysis by Shim et al. (2022) of risk on construction sites in Japan showed the fatality rate to be almost six times great than the UK.

Takahashi (2019) 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,

TABLE 1 | Injuries and fatalities from demolition activities as a proportion of injuries and fatalities from all sectors.

Reference	Geog.	Secondary source / data type		*n*	Time-frame	Proportion of all fatalities	Proportion of all injuries	Proportion of all injuries and fatalities
Maeda et al. (2003)	JPN, Osaka	City forensic post-mortem data	Fatalities	67	1996–2001	7.5%		
European Commission (2009)	EUR	European Statistics on Accidents at Work	Fatalities	2,307	2003–2005^{a}	0.71%	0.16%	0.16%
			Injuries	1,709,648	2005			
			Total	1,711,955				
Zaharuddin et al. (2009)	AUS	Australian Safety and Compensation Council	Total	14,869	2002–2004			0.4%

^{a}*Sample originally reported over 3 years, therefore divided by three in this table. N, number of samples; Geog., geographical context.*

the testimony by Takahashi (2019) ought to provide the basis for further investigation of attitudes toward safety in specific cultures. Japan is an 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. There is one suggestion that the strict hierarchy in Japan is a hindrance to health and safety implementation (Shoji and Egawa, 2006). 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.

In studies from both the USA (Ertaş and Erdogan, 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 2**). Zaharuddin et al. (2009) reported a similar proportion for demolition workers in the UK, with ∼53% of fatal and non-fatal accidents being caused by collapse and 28% caused by a fall. Whereas, the data for these four accident types shows some congruence, other accident types reported in **Table 2** are less consistent, making the data challenging to compare.

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 that period (**Supplementary Table S9**). 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 ∼21 fatalities per year between 2010 and 2014 (Takahashi, 2019) (**Table 2**).

Gürcanli and Müngen (2013) cautioned that official Turkish statistics are unreliable indicators of accidents because they only report injuries and fatalities for which a conviction was successful. Moreover, they noted that Turkey 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. 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 harmonized global system of reporting, without which cost-effective interventions cannot be targeted where most needed.

Asbestos

Asbestos is the generalized term used to describe a group of six main types (**Supplementary Table S10**) 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., 2018).

After it was first commercially extracted in Quebec in 1876 (Henderson and Leigh, 2012), asbestos production rose sharply following the Second World War, reaching its peak in 1980 (**Supplementary Figure S8**), after which concerns over its safety resulted in successive bans of specific asbestos applications and materials across Europe and in the US (Kazan-Allen, 2019a); although there is still no outright asbestos ban in the US (Arachi et al., 2021). 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. According to Flanagan (2020), reliable data on global asbestos production and consumption have not been published since 2017 when Russia supplied nearly two thirds of the 1.1 Mt consumed worldwide, while Brazil produced around 12% (**Supplementary Figure S9**). But there is an apparent continuing downward trend in production, and in 2020 Brazil closed its last mine extracting asbestos.

Asbestos was still consumed in 39 countries in 2017, with India, China and Russia representing over 60% of global consumption (**Supplementary Figure S10**). Although the data since 2010 indicates a general reduction in consumption in Russia and China, continued use is apparent in India (**Supplementary Figure S11**), 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. Other applications continue, including: insulating protective equipment for fire-fighting and brakes for automobiles (Frank, 2006; Henderson and Leigh, 2012; Ogunseitan, 2015).

TABLE 2 | Injuries and fatalities from demolition activities.

Basis	Reference	Geog.	Secondary source/data type	Receptor/activity		n	Time-frame	Fatalities		Non-fatal injuries		Total	
								No.	Proportion of all fatalities	No.	Proportion of all injuries	No.	Proportion of all injuries and fatalities
As proportion of injuries and fatalities from construction and demolition combined	Gürcanli and Müngen, 2013	TUR	Eye-witness accounts from court records		Fatalities	788	1972–2008	30	3.8%	14	3.9%	44	3.8%
					Injuries	361							
					Total	1,149							
	Ertaş and Erdogan, 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—European Statistics on Accidents at Work		Fatalities	1,464	2003–2005[c]	16	1.09%	2,786	1.23%	2,802	1.23%
					Injuries	226,835	2005						
					Total	227,323							
	Takahashi, 2019	JPN	n/a		Fatalities	1,646	2010–2014	107	6.5%				
As proportion of injuries and fatalities from demolition activities	Ertaş and Erdogan, 2017	USA	Occupational Safety and Health Administration	Collapse of building			1984–2012	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%
				Total demolition				383	100.00%	270	100.00%	653	100.00%

(Continued)

TABLE 2 | Continued

Basis	Reference	Geog.	Secondary source/data type	Receptor/activity	*n*	Time-frame	Fatalities		Non-fatal injuries		Total	
							No.	**Proportion of all fatalities**	**No.**	**Proportion of all injuries**	**No.**	**Proportion of all injuries and fatalities**
	Zaharuddin et al., 2009	GBR	HSE (2008)	Falls		1997–2005					13	27.66%
				Transport							5	10.64%
				Collapse							25	53.19%
				Struck-by							2	4.26%
				Miscellaneous							2	4.26%
				Total demolition							47	100.00%
	Takahashi, 2019	JPN	Japan (Ministry of Health, Labor and Welfare 2018)	Fall		2010–2014	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%				
				Total demolition			107	100%				

[a] *Cuts/scratches/jamming/hitting/puncturing/manual handling.*

[b] *Direct descriptions are shown and assumed translations are suggested in brackets.*

[c] *Sample originally reported over 3 years, therefore divided by three in this table. n, Number of samples; no., number observed/reported; Geog., geographical context; HSE, Health and Safety Executive.*

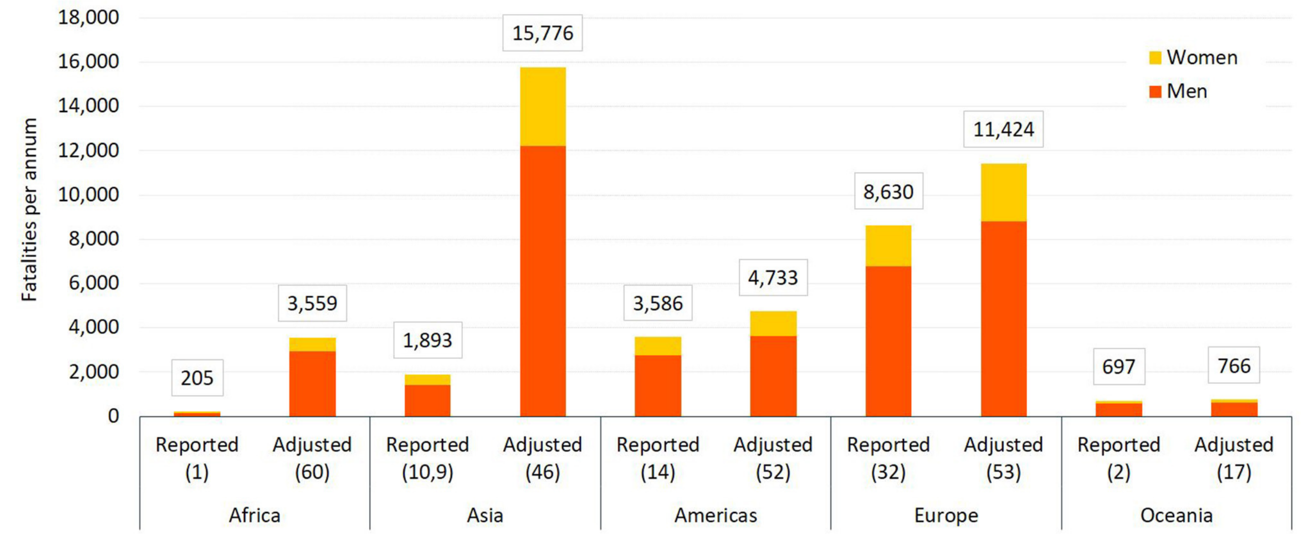

FIGURE 2 | Global mesothelioma deaths region reported to the World Health Organization (2019) alongside adjusted data calculated by Odgerel et al. (2017). Numbers in boxes at the top of bars represent the total of fatalities per category. Numbers in brackets represent the number of countries reporting deaths within each region.

Asbestos fibers are mineral and do not volatilize so they only represent a hazard when they have been weathered or otherwise abraded from the material after which solid particles can easily aerosolize (i.e., 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 estimates that ∼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 World Health Organization (2019) Mortality Database provides a record of reported cases of mesothelioma from countries that submit data. Delgermaa et al. (2011) analyzed 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 **Supplementary Table S11**, 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). Moreover, the median latency (period from exposure to death) for mesothelioma has been estimated at nearly 23 years (Frost, 2013) which means that many cases will not arise in countries with lower life expectancy.

Taking the arithmetic mean of the global deaths reported between 2001 and 2008 (**Supplementary Table S11**), 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 World Health Organization (2019) Mortality Database to model deaths from mesothelioma in the countries that either did not 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 2** the continental adjusted data are compared with the reported data, revealing huge underreporting in Asia and Africa.

As with the reported data, the proportion of people dying from mesothelioma in the estimated (adjusted) data who were women was ∼23%, a likely reflection of the number of men working in construction compared to women worldwide (**Figure 2**). When stratified by the World Bank income category for countries (The World Bank, (nd)), the differences between the reported deaths and modeled deaths are stark (**Supplementary Figure S12**), with virtually all reporting taking place in HICs and almost none in lower middle income countries (LMCs) or low income countries (LICs).

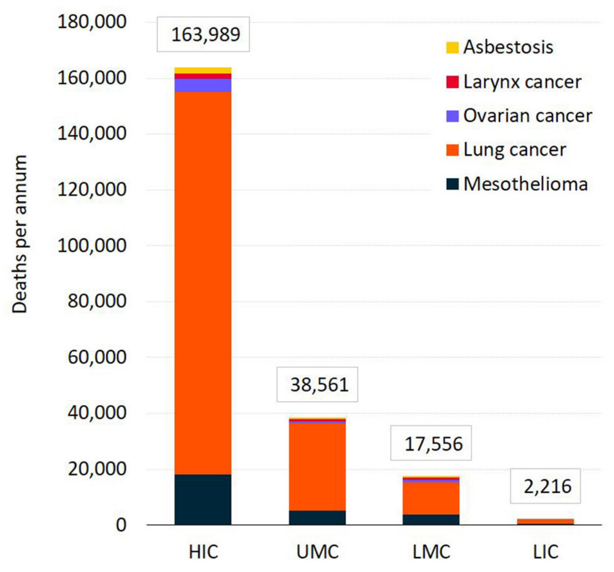

FIGURE 3 | Global deaths from all diseases as a result of occupational exposure to asbestos; data from Furuya et al. (2018). Numbers in boxes at the top of bars represent the total of deaths per category. HIC, high-income country; UMC, upper-middle-income country; LMC, lower-middle-income country; LIC, low-income country.

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 (Henderson and Leigh, 2012; Furuya et al., 2018). Estimates by Furuya et al. (2018) (**Figure 3**) 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 ∼2,000 in each of UMCs and LMCs, and <300 in LICs.

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. (2018) indicated that the current death rate from asbestos may continue in future, at least at the same rate, acknowledging that the lack of data in LIMICs makes these kind of predictions highly uncertain.

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 (Frank and Joshi, 2014), especially as life expectancy increases (Singh and Ladusingh, 2013) and exposed populations survive the latency period for mesothelioma (Frost, 2013). 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).

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 of over 80 sites across the city by Fuller and Green (2004) between 1999 and 2001 found that construction and demolition activities contributed to mean daily concentrations of $>50\ \mu g.m^{-3}$ 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 PM, the scope is narrowed further to focus on emissions that arise when materials, such as ceramics, undergo mechanical attrition and aerosolisation. Here, we will discuss "dust", defined variously as PM that is <75 or $<100\ \mu m$ 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 (a sub-category of dust) in and around demolition sites (**Table 3**). 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. (2011) were higher during demolition activities, they were still far below the recently imposed absolute limit of $100\ \mu g.m^{-3}$ stipulated in Directive (EU) 2017/2398 (European Union, 2009).

The The Air Quality Standards Regulations (2010) in the UK, require that PM $<10\ \mu m$ (PM_{10}) concentrations must not exceed 50 $\mu g.m^{-3}$ more than 35 times per year or an annual mean of 40 $\mu g.m^{-3}$. 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 $\mu g.m^{-3}$, for block cutting and demolition (**Table 3**). However, the majority were below the 50 $\mu g.m^{-3}$ 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 (2010), 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 ∼100 and 200 times higher, respectively, than those observed by Stacey et al. (2011) (**Table 3**). All the mean concentrations identified by Normohammadi et al. exceeded the absolute limit of 100 $\mu g.m^{-3}$ 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 3**), with many concentrations exceeding the threshold concentrations in Directive 2008/50/EC (European Union, 2008a) (**Supplementary Table S8**). Liu et al. (2019) measured concentrations of PM_{10} and PM $<2.5\,\mu m$ ($PM_{2.5}$) during and following the demolition of a teaching building, finding elevated levels of both particle size profiles during the demolition process. 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 $\mu g.m^{-3}$. 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 min, meaning that the daily average concentration only slightly exceeded the 24 h lower threshold (25 $\mu g.m^{-3}$) for PM_{10} stated in the Directive 2008/50/EC.

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 3**). Both the downwind and one of the mobile samplers showed levels of PM_{10} that exceeded the 50 $\mu g.m^{-3}$ limit, as well as the 24 h upper and lower assessment thresholds. The levels in the excavator were 6.5 times higher than the fixed outdoor sampler exceeding the 50 $\mu g.m^{-3}$ 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. Speculatively, office environments are often considered relatively safe spaces on construction and demolition sites and respiratory protection equipment was rarely worn inside prior to the SARS-CoV-2 pandemic. 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 or procedures to prevent the ingress of PM or to ventilate 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 (**Supplementary Figure S13**). 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.

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 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 3**), providing indicative values on the basis of μg PM per floor space demolished per second (**Supplementary Table S12**).

Two studies used particle emission characterization 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 (**Supplementary Table S13**). The study found that the concentrations identified in **Table 3** would result in an average of 50 excess cancer deaths per 1,000 workers exposed. 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).

High alkalinity of PM is also likely to be a source of risk to the health of people exposed to airborne dust from CDW according to Landrigan Philip et al. (2004) who associated high pH in dusts from the World Trade Center collapse with increased risk of asthma, persistent cough and bronchial hyper-reactivity. Both Chen and Thurston (2002) and McGee John et al. (2003) observed high alkalinity in World Trade Center collapse dusts as a consequence of concrete and gypsum content, reporting pH>10 and pH 8.9–10.0 (aqueous extracts of $PM_{2.5}$), respectively. noted that alkalinity decreased with particle size, to the degree that $PM_{2.5}$ were generally neutral. Research into the impact of PM from CDW primarily focusses on the finer, respirable fractions, larger inhalable fractions tend to receive less attention (Lippmann et al., 2015). In a critical review of the health effects of dust from the disaster, Lippmann et al. (2015) argued that the massive load of highly alkaline dusts caused extensive damage to epithelial cell

TABLE 3 | Concentrations of particulate matter (PM) in air around construction and demolition activities (μg.m^{-3}).

Reference	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
		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		
		Center		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
		Center		15		14,680	11,460	20,790
		Total		60		13,370	5,000	28,000
Liu et al. (2019)	CHN[f]	Demolition	PM$_{2.5}$	296		94.409[bc]	10.18	432.3[bc]
			PM$_{10}$			156.521[de]	49.36[de]	495.4[de]
		After demolition	PM$_{2.5}$	112		59.511[bc]	10.01	189.24[bc]
			PM$_{10}$			92.881[de]	28.91	202.2[de]
Wagner et al. (2017)	DEU	During skyscraper blast demolition (15 min)	PM$_{10}$					844.9[de]
		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[bc]
			PM$_{10}$			162.7[de]	24.4	440[de]
		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[de]	17.9	75.8[de]
		Inside excavator cabin	PM$_1$			75		699
			PM$_{2.5}$			109[bc]		12[c], 401[bc]
			PM$_{10}$			455[de]		54[e], 124[de]
		Inside temporary site office (normal)	PM$_1$			8		26
			PM$_{2.5}$			16[c]		6
			PM$_{10}$			90[de]		2,566[de]
		Inside temporary site office (during intense demolition)	PM$_1$			56		338
			PM$_{2.5}$			144[bc]		114[bc]
			PM$_{10}$			720[de]		549[de];124[de]

(Continued)

TABLE 3 | Continued

Reference	Geog.	Activity context	Substance	*n*	Median	Mean^a	Min	Max
		Fixed outdoor downwind of demolition activity	PM_1			15.66		
			$PM_{2.5}$			60.19^{bc}		
			PM_{10}			123.81^{de}		

*[*] Time weighted average; [a] arithmetic mean; exceeded the following concentration thresholds set by Directive 2008/50/EC (**Supplementary Table S4**): [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}; [f] it is assumed that the site was in China from reading the paper, however the location was not stated. n, number of samples; geog., geographical context; CEN, European Standards Organization; ISO, International Organization for Standardization.*

function in exposed individuals, resulting in both pulmonary and gastroesophageal damage.

Substances From Previous Use of Industrial Premises

The previous two sections summarize 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 summarizes two examples where waste from two demolished manufacturing facilities in South-western Sweden (Van Praagh and Modin, 2016) and Northern China (Huang et al., 2016) has been contaminated with pesticides at a time when possibly the occupiers were ignorant of the risks and for which such legacy contamination remains a challenge for those undertaking clean-up work (**Table 4**).

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.

Huang et al. (2016) analyzed construction and demolition waste from a disused pesticide production facility in northern China that had been closed for a decade (**Table 4**). The study identified 11 organophosphorus compounds and Cypermethrin, a type of pyrethroid insecticide. Several of the organophosphorus pesticides were found in extremely high concentrations amongst the CDW. For instance, the arithmetic mean concentration of Phorate was 16,868 $mg.kg^{-1}$ CDW and for Parathion it was 6,521 $mg.kg^{-1}$ CDW. The level of potential human exposure to both of these agents is dependent on the human activity in those areas but given their potential toxicity the risk of lethal human exposure is potentially high. Phorate bio concentrates in the human body (Chawla et al., 2018) and the median lethal dose (LD_{50}) for oral ingestion is 2–4 $mg.kg^{-1}$ mammalian body weight (Dar et al., 2022). Parathion has a median lethal dose (LD_{50}) for oral ingestion of ∼2–4 $mg.kg^{-1}$ mammalian body weight (PubChem, 1998) and has been used in chemical warfare (Soltaninejad and Shadnia, 2014).

CHALLENGE 2: LAND DISPOSAL OF CONSTRUCTION AND DEMOLITION WASTE

Context

The majority of CDW by mass is composed of materials that are engineered to be biologically inert (for the timescales considered) such as ceramics, plastics, and metals (**Section S.5.2**). Although most of these materials are comparatively harmless to biota, some plastics contain substances that can migrate to the surface and into surrounding media such as water or soil (Molla et al., 2021). 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 (Duan et al., 2016). Biological matter (primarily timber) also exists in CDW and has the potential to decompose, releasing gasses, chemical and biological residues that are created while being consumed by micro-biota (Vodyanitskii, 2016). Though CDW is classified as "inert" in many geographical jurisdictions (Butti et al., 2018), or as having a low potential impact on the environment (Cerminara and Cossu, 2018), in reality, as we show here, it includes heterogeneously distributed components (materials and substances) that may result in harmful emissions under certain conditions.

Leachate From Construction and Demolition Waste

Leachate from landfill sites has been regulated in many HICs, for at least the last 50 years, for instance the Deposit of Poisonous Waste Act (1972) in the UK prohibited waste being deposited on land where it is 'liable to give rise to an environmental hazard'. More recent legislation includes specific thresholds for monthly surface discharge of leachate according to its physico-chemical properties (European Union, 1999; United States Environmental Protection Agency, 2000), and contemporary sanitary landfills incorporate sophisticated leachate capture and treatment (Christensen et al., 2011). 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 (Wilson et al., 2015).

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

TABLE 4 | Pesticide concentrations in media at former pesticide manufacturing facilities.

Reference	Geog.	Waste analyzed	*n*	Substance	Mean conc.	Low	High	SGV res.*	SGV ind.*
					(mg.kg^{-1} dry matter CDW)			(mg.kg^{-1} dry matter soil)	
Van Praagh and Modin (2016)	SWE	Crushed concrete debris	4	ΣPhenoxy acids	8.5				
				ΣChlorophenols	11.1			0.5	3
				ΣChlorocresoles	10.7			1.5	5
				ΣPhenoxy acids, Chlorophenols, Chlorocresoles	30.3				
Huang et al. (2016)	CHN	Concrete coatings; bricks; 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		

**Soil guideline values (SGV) from Swedish guidelines for residential (res.) and industrial (ind.) premises reported by Van Praagh and Modin (2016). n, number of samples; geog., geographical context; conc., concentration.*

so. López and Lobo (2014) sampled leachate at a CDW Spanish landfill site over a 5 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 acceptance set by Directive 1999/31/EC (European Union, 2002) (Landfill Directive) (**Table 5**). 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.

Concentrations of As and Cd were also high in comparison to the other sites (**Table 5**) 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 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 laboratory based samples, virtually all of the concentrations were well within limits set by Directive 1999/31/EC (European Union, 2002) (**Supplementary Table S14**). 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. Sulfate concentrations were variable and not congruent with the material type. The likely source of sulfate 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 **Supplementary Table S14** refer to data obtained from percolation tests, two other tests are common for determining leachate over 6 or 24 h using a liquid to solid ratios (L/S) of 2 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 **Supplementary Table S14**.

The concentrations of substances assessed by both Puthussery et al. (2017) and Saca et al. (2017) were also well below limits set by Directive 1999/31/EC (European Union, 2002)

TABLE 5 | 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.

Parameter	Units	López and Lobo (2014)		USEPA (1995)*		Melendez (1996)*		Townsend et al. (2000)* and 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
		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	
Dissolved oxygen	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	
Redox potential	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 total organic carbon	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	
Ammonia nitrogen	mg.L^{-1}	401	92–765	305		13			<1–4.1	
Dissolved total nitrogen	mg.L^{-1}	463	182–844							
Sulfates	mg.L^{-1}	405	133–1,038	2,700†		254	11.7–1,700†	880	310–1,370	1,500
Total solids	mg.L^{-1}	4,939	3,756–577							
Total dissolved solids	mg.L^{-1}	4,860	3,412–576	8,400		2263	990–8,400	2,120	970–3,310	
Total volatile solids	mg.L^{-1}	1,619	1,208–247		170–380					
Volatile suspended solids	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. L/S ratio, liquid solid ratio; n, number of samples; C&D, construction and demolition; ND, not detected; BOD$_5$, biochemical oxygen demand; COD, chemical oxygen demand; TN, total nitrogen; L/S, liquid to solid.

(**Supplementary Table S15**). 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.

In summary, the concentrations of elements and other parameters identified in both the field sampling (**Table 5**) and the lab sampling (**Supplementary Tables S14, S15**) 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 rigor 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.

Wood

Wood used in construction is often treated with biocidal agents 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, 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 volatilized, 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) analyzed 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 6**). 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. Koyano et al. (2019) found low levels of POP wood treatments in all samples of wood compared to the Basel Convention limits of: chlordanes 50 $mg.kg^{-1}$ (Secretariat of the Basel Convention, 2017c); pentachlorophenol 100 $mg.kg^{-1}$ (Secretariat of the Basel Convention, 2017a); and polychloronaphthalenes 10 $mg.kg^{-1}$ (Secretariat of the Basel Convention, 2017b). Of course, the samples analyzed 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.

Two other authors determined concentrations of potentially hazardous substances (**Table 6**). Duan et al. (2016) observed concentrations of brominated flame retardants 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-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.

Leaching tests of engineered timber mulch carried out by Gaskin et al. (2005) showed little difference compared to non-treated varieties and levels of all substances were low enough to conclude that engineered timber studies is entirely suitable to be used as mulch. Jambeck et al. (2008) studied the leachability of As, Cr and Cu from CDW containing 10% (wt.) timber treated with chromated copper arsenate preservative (**Supplementary Table S17**). The study found that though the concentrations of Cu were not different to the control, that Cr and As levels were significantly (α=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.

Gypsum

Calcium sulfate dihydrate, otherwise known as "gypsum," is a soft mineral used in fertilizer, Portland cement, plaster and drywall plasterboard (Colman et al., 2020). Global mine production has grown steadily from ∼10 million tons in 1940 to 160 million tons in 2010 and this sustained growth rate is expected to continue in the near future alongside global population growth (Asakura, 2013; U. S. Geological Survey, 2020). In demolished buildings where it has been used to coat internal walls, gypsum is often liberally distributed throughout the waste, existing as fragments and dust between 17 and 27% (wt.) of CDW (Townsend et al., 2000). Once it has been mixed, it is challenging to separate and if the concrete is to be recycled to The British Standards Institution (BS 8500-2:2015+A2:2019) for instance, the gypsum content must be reduced to <1% (wt.) with an acid soluble sulfate content <0.8%. Often this is done *via* a comminution and size screening process or manual separation (Asakura, 2013) and some novel methods have also been suggested (Montero et al., 2010), but source separation is often the most economical

TABLE 6 | Concentrations of elements, polybrominated diphenyl ethers, and selected wood preservatives (mg.kg^{-1} dry wt.).

Reference	Geog.	Waste media analyzed	*n*	Substance	Mean	Range	Standard deviation
Koyano et al. (2019)	JPN	Recycled timber	45	Chlordanes	<0.01	<0.01–0.86	0.13
				Pentachlorophenol	0.025	<0.01–3.0	0.5
				Pentachloroanisole	<0.01	<0.01–1.1	0.18
				Polychloronaphthalenes	0.033	0.0012–2.6	0.43
		Demolition timber	55	Chlordanes	<0.01	<0.01–15	2.3
				Pentachlorophenol	<0.01	<0.01–0.20	0.026
				Pentachloroanisole	<0.01	<0.01–0.043	0.0057
				Polychloronaphthalenes	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		

n, number of samples; CDW, construction and demolition waste.

method (Rodríguez-Quijano et al., 2015; Jiménez-Rivero and García-Navarro, 2017).

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

H_2S is colorless, 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 edema (250 to 500 ppm); serious damage to eyes, unconsciousness, amnesia and death after 4–8 h (500 ppm) (Guidotti, 1996). The concentrations necessary to cause a fatality have been reported at 1,000 ppm (Guidotti, 1996; Asakura, 2013) 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 (Kitazaki et al., 2014). The Health Safety Executive (2020a) in the UK, sets an 8-h time-weighted average workplace exposure limit of 5 ppm and a 15 min exposure limit of 10 ppm.

In a non-academic report, Townsend et al. (2000) investigated H_2S production from 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 7**). 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 10 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.

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. Sulfate 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.

TABLE 7 | Concentrations of hydrogen sulfide (H_2S) produced by construction and demolition waste (CDW) in field sampled and simulated experiments.

Reference	Geog.	Sample media	Components	*n**	Mean	Med	Min	Max
Lee et al. (2006)	USA	Landfill gas from sub-surface probes or gas wells	CDW	19	26[†‡]	0.013	BDL	470[†‡]
			CDW	77	8.1[†]	0.007	BDL	920[†‡]
			CDW	8	30[†‡]	25[†‡]	0.013	12,000[†‡]
			CDW	25	2,110[†‡]	1,800[†‡]	BDL	7,000[†‡]
			CDW	62	36[†‡]	0.02	BDL	2,500[†‡]
			Class III	16	5.9[†]	0.004	BDL	49[†‡]
			CDW	19	0.007	0.005	BDL	0.64
			Class III	20	151[†‡]	0.025	BDL	3,300[†‡]
			CDW[a]	22	1,200[†‡]	23[†‡]	BDL	11,000[†‡]
			CDW[a]	26	26[†‡]	0.35	BDL	530[†‡]
			Total	294	660[†‡]	0.023	BDL	12,000[†‡]
		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[a]	23	4	0.61		>50[†‡]
			CDW[a]	21	2.7	0.008		>50[†‡]
Yang et al. (2006)	USA	Simulation	Wood, drywall, concrete	56	0.277		BDL	1.6
				62	0.2		BDL	1.03
				64	0.15		BDL	0.67
			Drywall, wood	73	14,075[†‡]		BDL	63,000[†‡]
				74	11,155[†‡]		0.003	48,000[†‡]
			Drywall	73	21,636[†‡]		BDL	47,000[†‡]
				73	24,389[†‡]		BDL	50,000[†‡]
			Wood, concrete	37	0.13		BDL	1.5

[†] *Exceeds long-term (8 h) exposure limit set by UK Health Safety Executive (2020a) of 5 ppm.*

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

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.

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 at 31,000 tons 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 8**). Drage et al. (2018) sampled expanded polystyrene and extruded polystyrene insulation found in construction waste in Ireland, finding high concentrations of HBCD in the extruded

TABLE 8 | Concentrations of selected brominated flame retardants, and polychlorinated biphenyls (PCBs) in construction and demolition waste (CDW) (mg.kg^{-1} total solids).

Reference	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 expanded polystyrene	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 extruded polystyrene	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			

n, number of samples; CDW, construction and demolition waste; PUR, polyurethane; HBCD, hexabromocyclododecane; BDE, brominated diphenyl ethers; PCB, polychlorinated biphenyls; PBDE, polybrominated diphenyl ethers.

polystyrene sample and extremely high concentrations in the expanded polystyrene sample.

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 8** provide an indication that these substances exist in considerable quantity. As Nie et al. (2015) highlighted, 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 polychlorinated dibenzo-p-dioxins, HBCDs, PBDEs and PCBs and divert them to other forms of treatment for complete destruction.

CHALLENGE 3: THERMAL DECONSTRUCTION, OPEN BURNING AND THERMAL PROCESSING OF CONSTRUCTION AND DEMOLITION WASTE

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 **Supplementary Figure S14**.

Lead Release During Deconstruction Activities

The dangers of lead (Pb) exposure 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) analyzed 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 $\mu g.g^{-1}$ and a median of 4,180 $\mu g.g^{-1}$. In 1998, Jacobs (1998) reported that in the US, more than 90,000 bridges were painted in lead-based coatings and ∼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 in contemporary construction. For instance Gottesfeld et al. (2013) analyzed 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 exposure 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 specifically protective equipment to protect them from the potential hazards posed by Pb when it is heated and volatilized during deconstruction activities.

Jacobs (1998) reported a range of Pb concentrations in workplaces in the US from secondary sources, showing a large range of concentrations reported (**Table 9**), many of which exceeded the Health Safety Executive (2009) occupational exposure ceiling limit of 150 $\mu g.m^{-3}$ ("lead other than lead alkyls"). 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 Occupational Safety and Health Administration procedures in their work, indicating that they were effective at reducing their exposure.

Blood concentrations of workers involved in deconstruction activities were determined by three authors (**Table 10**). 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 $\mu g.L^{-1}$ blood. Centers for Disease Control 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. Concentrations observed by Jacobs (1998) were substantially lower than those identified by Fischbein et al. (1978) and Centers for Disease Control Prevention (1989), well within the HSE's maximum safe limit; possibly indicating that safe systems of work for Pb related activities had improved by the turn of the century.

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.

Open Burning of Construction and Demolition Waste

The combustible fraction of CDW is a potential source of fuel for heat or cooking in LIMICs. If fuel is not 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 open burning activity is not 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. Lemieux et al. (2004) inferred 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 referred to a study by Carroll (2001) that characterizes polychlorinated dibenzo-p-dioxins and polychlorinated dibenzofuran (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 (**Supplementary Table S17**). 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 vapor phase).

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, pentachlorophenol, an organochlorinated compound used in many pressure treated timber products since the late 1950s contained DRCs formed at the time of production (**Supplementary Table S19**).

All chlorinated hydrocarbons have the potential to produce DRCs when combusted, including untreated timber (Zhang et al., 2022). 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). CCA has a high content of three potentially toxic elements Cr, Cu and As which are emitted into the ash and air during combustion. Wasson et al. (2005) characterized emissions from combustion of wood treated with several CCA formulations, finding very large concentrations of As, Cr and Cu in the fly ash (**Supplementary Table S20**).

Emission factors for As, Cr and Cu were also calculated by Wasson et al. (2005) and are presented in

TABLE 9 | Concentrations of Pb measured in air proximate to deconstruction workers (μg.m^{-3}).

Reference	Geog.	Activity context	Receptors	*n*	% *n*	Mean	Range (confidence interval)
Jacobs (1998)	USA	Wrecking and demolition[a]	Demolition workers	178	14%	<1	
					18%	1–99	
					10.7%	100–200[†]	
					57.3%	>200[†]	
		Bridge rehabilitation[b]	Torch burner				220[†] -6,000[†]
			Hammering and drilling				40–360[†]
		Bridge demolition[b]	Torch burner				110–1,200[†]
			Burner helper			330[†]	
			Torch burner				180[†] -1,800[†]
			Rivet removal				500[†] -930[†]
		Paint removal from boiler[b]	Blaster				640[†] -1,400[†]
		Power plant demolition[b]	Torch burner				2,100[†] -22,400[†]
		Bridge repair[b]	Welder				2,200[†] -4,200[†]
			Blaster				1,070[†] -10,400[†]
			Burner				840–4,900[†]
		Paint removal from bridge[b]	Blaster				4–540
			Groundsman				20–640
			Blaster				2–730
		Bridge demolition[b]	Burners				600–4,000[†]
		Paint removal from bridge[b]	Blaster				3,690[†] -29,400[†]
			Groundsman				5–6,720
Scholz et al. (2002)	USA	Residential and commercial painting	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
			High efficiency particulate or arrestance—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[†]
			High efficiency particulate or arrestance—exhausted power sanding	7		1,600[†]	
			Dry scraping	17		1,100[†]	
			Dry sanding	9		6,700[†]	
			Uncontrolled power sanding	10		14,000[†]	
Lange and Thomulka (2000)	USA	Burning and cutting of pipes and removal (demolition) of walls that were painted	No wet methods for cutting	5		379.6[†]	194–571[†] (122.1)
				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	
			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. n, number of samples; geog., geographical context.*

Supplementary Table S21, however the emissions of DRCs reported in the same study were "unremarkable" with mean concentrations of 1.7 ng TEQ.kg^{-1}; indicating that CCA treatment may not contribute substantially to DRC formation.

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

TABLE 10 | Concentrations of elements in blood of workers engaged in deconstruction.

Reference	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 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. n, number of samples; geog., geographical context.*

composition to assist with the improved compilation of a global inventory.

RISK CHARACTERIZATION AND DISCUSSION

Handling and Physical Processing of Construction and Demolition Waste

Asbestos, a longstanding, potentially lethal, and prolific material, continues to cause the occupational deaths of ∼90,000–250,000 people every year, mainly in HICs where its historical use was most prevalent. On this basis our risk assessment indicates that the occupational risk in HICs is medium-high, despite stringent safe system of work being in place in most contexts (**Table 11**). Nonetheless, substantial stocks of asbestos that exist throughout the global built environment mean that exposure to asbestos will continue to be a considerable cause of death and ill-health over the coming decades, as engineered structures are demolished when they reach their end of life. Despite this sustained loss of life, India continues to allow asbestos consumption and consequently, it is anticipated that around half of asbestos deaths may occur there in the coming decades. We scored the risk of asbestos exposure as very high in LIMIC contexts, partially because of lack of awareness and control but also due to the largely informal nature of the workforce. Though asbestos is a prolific killer, we consider the risk to local populations as low in all contexts. Despite the obvious danger from asbestos particles, even when not controlled, the exposure is unlikely to be sustained for prolonged periods.

Non-asbestos related PM is also an important hazard, 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 risk of physical accident in LIMICs was scored medium high as there is evidence for a much higher accident rate. The core assumption driving this score, is that safe systems of work are generally less stringent in LIMICs and businesses engaged in construction and demolition have less access to monetary resources to reduce accidents.

The risks from substances resulting from the previous use of a building were not 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.

Land Disposal of Construction and Demolition Waste

Proportionally (by weight), CDW is mainly composed of biologically inert and non-hazardous material, resulting in generally low to medium risks from CDW when disposed of on land (**Table 11**). Some exceptions are the inclusion of gypsum plasterboard that can produce hydrogen sulfide gas when co-disposed with small amounts of biological material; providing a source of carbon for sulfate 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 to present a negligible risk based on the evidence.

TABLE 11 | Risk characterization 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
Handling and physical processing (non-thermal)										
Physical accident	CDW handling	Construction and demolition workers	EUR	• Eurostat (2020) provides 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	• 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	35	**8**	HIC
							3	5	**12**	LIMIC

(Continued)

TABLE 11 | Continued

Haz.	Pathway	Receptor	Geog.	Evidence and justification for risk assessment	Uncertainty (aleatoric and epistemic)	Receptor vulnerability	L	S	R	Global receptor context
Asbestos	Construction and demolition activities/ inhalation	Construction and demolition worker	Global	• Production and consumption have decreased over recent decades, but large quantities exist in the use phase, meaning that asbestos will remain a hazard for many decades to come. Brazil has now ceased production (Flanagan, 2020), but 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; Delgermaa et al., 2011; Odgerel et al., 2017; World Health Organization, 2019). • Estimated 125 million exposed (Spasiano and Pirozzi, 2017) and fatalities from all sources estimated at ~90,000 (Henderson and Leigh, 2012); 112,000 (Furuya et al., 2018); 255,000 of which 233,000 are occupational (Furuya et al., 2018).	• 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., 2018) 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 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).	4	4	**16**	LIMIC

(Continued)

TABLE 11 | Continued

Haz.	Pathway	Receptor	Geog.	Evidence and justification for risk assessment	Uncertainty (aleatoric and epistemic)	Receptor vulnerability	L	S	R	Global receptor context
		Population					1	4	**4**	HIC LIMIC
Other PM	Construction and demolition activities/ inhalation	Construction and demolition worker	IRN, GBR, DEU, CHN	• Variable concentrations detected by studies depending on activity that was often not reported in enough detail to make a generalized 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). • PM levels return to normal soon after intense demolition / blast demolition (Wagner et al., 2017; Liu et al., 2019). • 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 generalizable, but PM emission from demolition activities are process dependent and therefore spot sampling may not be applicable to all activities.	• In HICs workers 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

(Continued)

TABLE 11 | Continued

Haz.	Pathway	Receptor	Geog.	Evidence and justification for risk assessment	Uncertainty (aleatoric and epistemic)	Receptor vulnerability	L	S	R	Global receptor context
		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
Land disposal										
Misc. substances in, and properties of CDW	Leachate, groundwater, land	Drinking water/ population	USA, SPN, IND	- Several studies (López and Lobo, 2014; Devia and Suryo, 2017; 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
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

(Continued)

TABLE 11 | Continued

Haz.	Pathway	Receptor	Geog.	Evidence and justification for risk assessment	Uncertainty (aleatoric and epistemic)	Receptor vulnerability	L	S	R	Global receptor context
Gypsum drywall—hydrogen sulfide 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

(Continued)

TABLE 11 | Continued

Haz.	Pathway	Receptor	Geog.	Evidence and justification for risk assessment	Uncertainty (aleatoric and epistemic)	Receptor vulnerability	L	S	R	Global receptor context
Thermal deconstruction, open burning and processing 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

(Continued)

TABLE 11 | Continued

Haz.	Pathway	Receptor	Geog.	Evidence and justification for risk assessment	Uncertainty (aleatoric and epistemic)	Receptor vulnerability	L	S	R	Global receptor context
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 (Wahab and Lawal, 2011; Nie et al., 2015; Ogunmakinde et al., 2019) 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; Lemieux et al., 2004; Wiedinmyer et al., 2014; Kodros et al., 2016). • Emissions from CCA treated wood characterized (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**	

The meaning of the colours in column R is explained in Supplementary Section S.3.5, ***Table S5****. CCA, Chromated copper arsenate; CDW, construction and demolition waste; DRC, dioxins and related compounds; EU, European Union; HIC, high income countries;* H_2S*, hydrogen sulfide; L, Likelihood; LIMIC, low income and middle income countries; PM, particulate matter; POP, persistent organic pollutants; PPE, personal protective equipment; PBDE, polybrominated diphenyl ethers; PVC, polyvinyl chloride; R, risk; S, severity.*

Thermal Deconstruction, Open Burning and Processing of Construction and Demolition Waste

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. 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. Our very high scores for these hazard-pathway-receptor combinations (**Table 11**) are based on the assumption that the open burning of CDW is at least as prevalent as the rate of household burning activities, which are reported to be as high as 50% of all MSW (Velis and Cook, 2021). Combined with that assumption is the risk that waste plastics, particularly PVC, may be burned as a form of disposal, resulting in the emission of dioxins and related compounds. Given the mass of CDW generated worldwide, and the very high risk potential, it is recommended that more data are gathered to determine the prevalence of this 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.

DISCUSSION

Our assessment of risk, based on conceptualized, hazard-pathway-receptor combinations, highlights a disparity between the Global North where workers enjoy predominantly safe systems of work to protect them and their surrounding populations from exposure to hazards, and the Global South where such regimes are inconsistently implemented. We propose that two central characteristics of the construction and demolition sector contribute to these heightened risks in the Global South context: (1) A high rate of informality in the construction and demolition sector worldwide (200 million informal workers, 80% of the workforce) (Jewell et al., 2005) (**Supplementary Section S.5.4**); and (2) Fewer resources (financial and technical) are allocated to providing independent and effective environmental and safety regulation (LaDou et al., 2018). These two factors create an environment in which construction and demolition site operators have few reasons to implement safe systems of work (Boadu et al., 2020), let alone to investigate or keep safety monitoring records that can be used to identify unsafe practice (Ahmed et al., 2018). This dearth of evidence is exemplified by the lack of data on the number of injuries and fatalities specifically on demolition sites, given that these workplaces are intuitively high-risk (**Supplementary Section S.3.3**).

The high rate of informality in the construction and demolition sector presents several challenges: (1) Data collection by informal workers is unlikely to be commonplace, as these people are mostly independent operators, there are few reasons for them to keep records (separate to the issue regarding operator records) (Forastieri, 2014; Darbi et al., 2018); (2) Informal workers often operate independently and without safe systems of work including protective equipment, exposing them to greater risk (Boadu et al., 2020); (3) When informal workers sustain injury or fall ill, they may not return to work, biasing data collection on the basis of survivorship.

CONCLUSIONS AND OUTLOOK

As we demonstrate in this PRISMA-ScR systematic scoping review, some construction and demolition processes result in the transformation, physical movement and emission of materials and substances from CDW, thus creating pathways through which humans can be exposed to hazards. Alongside available accident data, we have arranged the diverse and often incongruous evidence base for these processes according to three groups, described here as "challenges" based on the types of activity involved, and more broadly, the emission type and pathways through which hazards may be realized (RQ1), these are: (1) handling and physical processing; (2) land disposal; and (3) thermal deconstruction, open burning and thermal processing.

We used this evidence to develop scenarios—hazard-pathway-receptor linkage combinations—and through doing so were able to assign semi-quantitative risk scores to each so that they could be compared and ranked to enable focus on those which result in the greatest risk exposure. Inherently, virtually all construction activities involve working with or around CDW and therefore the majority of construction workers will undergo frequent exposure to many of the risks associated with it. Yet, with the exception of asbestos, specific data on the occupational risks from CDW are largely absent and the majority of our analysis is conjecture based on the limited or inferred peripheral data. The risks from asbestos are well-documented and supported by several complex and ambitious global burden of disease studies. Though we observed that the methodological approaches (not assessed systematically in this review) in many of the studies on non-asbestos related topics were not well-documented, limiting our ability to infer aleatoric and epistemic uncertainty. Many of the sources reviewed were case studies from which we extrapolated meaning, but some lacked sufficient context to be generalizable across wider socio-economic conditions. This lack of robustly reported 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.

As a consequence of this information paucity, the global burden of disease from CDW related activities remains uncertain and we recommend future studies focus attention on improving understanding of this topic. In particular, high potential risks from the open burning of CDW will continue to be unquantifiable without data on the magnitude of the activity. Surveys combined with on-the-ground observations to determine prevalence combined with modeling would add substantial and much needed evidence to an almost empty research discipline.

The large number of workers engaged in the construction and demolition sector, nearly a quarter of a billion, means that any residual risk affects a substantial population. The high rate of informality reduces efforts to control those risks to populations that may already have compromised health and who are often least prepared or empowered to manage their own exposure. Historically, risk reduction for informal construction and demolition workers has been addressed, either through integration, or outright formalization in many HICs. For instance in the UK, The Construction (Design Management) Regulations (1994) compelled coordination between construction site contractors, which meant that even if workers were effectively informal, that they had to be controlled under a single safety regime.

Although the implementation of health and safety regulation is a critical component of reducing the risk of harm from CDW related activities, if not supported by a well-resourced and independent environmental regulator then it will have limited efficacy. Moreover, if the resources to implement safe systems of work are insufficient amongst construction and demolition sector participants, then the regulator will have few options than to close down construction activities altogether. We did not review or suggest specific policy responses in detail in this review, however a priori data suggest that some authorities may continue to prioritize the need to build infrastructure above worker safety. The lack of documentation of risk in the LIMIC context suggests then health and safety challenges around CDW may continue to constitute a major challenge in the foreseeable future unless full cost for all stakeholders are covered, enabling a sector–wide health and safety culture to be developed.

DATA AVAILABILITY STATEMENT

All data underlying the results are available as part of the article and **Supplementary Information** and there are no additional no source data.

AUTHOR CONTRIBUTIONS

EC: conceptualization, data curation, formal analysis, investigation, methodology, project administration, resources, validation, visualization, writing—original draft, and writing—review and editing. CV: conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, project administration, resources, software, supervision, validation, visualization, writing—original draft, and writing—review and editing. LB: writing—review and editing and validation. All authors contributed to the article and approved the submitted version.

FUNDING

This work was made possible by the Engineering X Safer End of Engineered Life programme which was funded by Lloyd's Register Foundation. Engineering X is an international collaboration, founded by the Royal Academy of Engineering and Lloyd's Register Foundation, that brings together some of the world's leading problem-solvers to address the great challenges of our age.

ACKNOWLEDGMENTS

We are grateful to the Technical Advisory Board of the Engineering X Safer End of Engineered Life programme, of the Royal Academy of Engineering for their steering and insightful feedback, especially on early versions of this research and manuscript. We thank the Programme Board, chaired by Professor William Powrie FREng & the Academy staff, especially Hazel Ingham and Shaarad Sharma who provided support throughout the process. *Ad hoc* advice, guidance and criticism was provided by multiple stakeholder representatives, as listed in the relevant Engineering X report. We are grateful Nick Rigas (D-Waste), for the presentation of infographics and to Dr. Godwin Akpeimeh for preliminary data collection. The research communicated and opinions expressed here are authors' alone. A preprint of this paper is available at https://doi.org/10.31224/osf.io/5tpbz.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frsus.2022.924926/full#supplementary-material

REFERENCES

Ahmed, I., Shaukat, M. Z., Usman, A., Nawaz, M. M., and Nazir, M. S. (2018). Occupational health and safety issues in the informal economic segment of Pakistan: a survey of construction sites. *Int. J. Occup. Saf. Ergon.* 24, 240–250. doi: 10.1080/10803548.2017.1366145

Arachi, D., Furuya, S., David, A., Mangwiro, A., Chimed-Ochir, O., Lee, K., et al. (2021). Development of the "National Asbestos Profile" to eliminate asbestos-related diseases in 195 countries. *Int. J. Environ. Res. Public Health* 18, 1804. doi: 10.3390/ijerph18041804

Arocho, I., Rasdorf, W., and Hummer, J. (2014). "Methodology to forecast the emissions from construction equipment for a transportation construction project," in *Construction Research Congress 2014* (Atlanta, GA: American Society of Civil Engineers).

Asakura, H. (2013). "Removing gypsum from construction and demolition waste (C&DW)," in *Handbook of Recycled Concrete and Demolition Waste*, eds F. Pacheco-Torgal, V. W. Y. Tam, J. A. Labrincha, Y. Ding, and J. de Brito. (Cambridge, UK: Woodhead Publishing), 479–499. doi: 10.1533/9780857096906.4.479

Azarmi, F., and Kumar, P. (2016). Ambient exposure to coarse and fine particle emissions from building demolition. *Atmos. Environ.* 137, 62–79. doi: 10.1016/j.atmosenv.2016.04.029

Boadu, E. F., Wang, C. C., and Sunindijo, R. Y. (2020). Characteristics of the construction industry in developing countries and its implications for health and safety: an exploratory study in Ghana. *Int. J. Environ. Res. Public Health* 17, 4110. doi: 10.3390/ijerph17114110

Brown, A., Barrett, J. E. S., Robinson, H., and Potgieter-Vermaak, S. (2015). Risk assessment of exposure to particulate output of a demolition site. *Environ. Geochem. Health* 37, 675–687. doi: 10.1007/s10653-015-9747-3

Burki, T. (2010). Health experts concerned over India's asbestos industry. *Lancet* 375, 626–627. doi: 10.1016/S0140-6736(10)60251-6

Burns, C. J., LaKind, J. S., Mattison, D. R., Alcala, C. S., Branch, F., Castillo, J., et al. (2019). A matrix for bridging the epidemiology and risk assessment gap. *Glob. Epidemiol.* 1, 100005. doi: 10.1016/j.gloepi.2019.100005

Butera, S., Christensen, T. H., and Astrup, T. F. (2014). Composition and leaching of construction and demolition waste: inorganic elements and organic compounds. *J. Hazard. Mater.* 276, 302–311. doi: 10.1016/j.jhazmat.2014.05.033

Butti, L., Peres, F., and Lops, C. (2018). "Chapter 1.3 - Legal Framework of Landfilling in Different Areas of the World," in *Solid Waste Landfilling*, eds. R. Cossu and R. Stegmann (Amsterdam: Elsevier), 41–50. doi: 10.1016/B978-0-12-407721-8.00003-6

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. *J. Indus. Ecol.* 17, 396–406. doi: 10.1111/j.1530-9290.2012.00568.x

Carroll, W. F. (2001). The relative contribution of wood and poly(vinyl chloride) to emissions of PCDD and PCDF from house fires. *Chemosphere* 45, 1173–1180. doi: 10.1016/S0045-6535(01)00003-0

Centers for Disease Control and Prevention. (1989). "Lead poisoning in bridge demolition workers - Massachusetts," in *Morbidity and Mortality Weekly Report (MMWR)* (Washington, DC: Centers for Disease Control and Prevention (CDC)).

Cerminara, G., and Cossu, R. (2018). "1.2 - Waste Input to Landfills," in *Solid Waste Landfilling*, eds. R. Cossu and R. Stegmann (Amsterdam: Elsevier), 15–39. doi: 10.1016/B978-0-12-407721-8.00002-4

Chawla, P., Kaushik, R., Shiva Swaraj, V. J., and Kumar, N. (2018). Organophosphorus pesticides residues in food and their colorimetric detection. *Environ. Nanotechnol. Monit. Manag.* 10, 292–307. doi: 10.1016/j.enmm.2018.07.013

Chen, K., Wang, J., Yu, B., Wu, H., and Zhang, J. (2021). Critical evaluation of construction and demolition waste and associated environmental impacts: a scientometric analysis. *J. Clean. Prod.* 287, 125071. doi: 10.1016/j.jclepro.2020.125071

Chen, L. C., and Thurston, G. (2002). World Trade Center cough. *Lancet* 360, s37–s38. doi: 10.1016/S0140-6736(02)11814-9

Chen, W., Liu, Y., Wang, H., Hnizdo, E., Sun, Y., Su, L., et al. (2012). Long-term exposure to silica dust and risk of total and cause-specific mortality in Chinese workers: a cohort study. *PLoS Med.* 9, e1001206–e1001206. doi: 10.1371/journal.pmed.1001206

Christensen, T. H., Manfredi, S., Kjeldsen, P., and Wallace, R. B. (2011). "Landfilling: bottom lining and leachate collection," in *Solid Waste Technology and Management,* ed T. H. Christensen (Chichester: Wiley), 800–829. doi: 10.1002/9780470666883.ch51

Colman, C., Bulteel, D., Rémond, S., Zhao, Z., and Courard, L. (2020). Valorization of fine recycled aggregates contaminated with gypsum residues: characterization and evaluation of the risk for secondary ettringite formation. *Materials* 13, 4866. doi: 10.3390/ma13214866

Concha-Barrientos, M., Nelson, D. I., Driscoll, T., Steenland, N. K., Punnett, L., Fingerhut, M. A., et al. (2004). "Selected occupational risk factors," in *Comparative Quantification of Health Risks Global and Regional Burden of Disease Attributable to Selected Major Risk Factors*, eds M. Ezzati, A. D. Lopez, A. Rodgers and C. J. L. Murray (Geneva: World Health Organization), 1651–1801.

Cook, E., and Velis, C. A. (2022). Construction and demolition waste management: A systematic review of risks to occupational and public health. *engrXiv [Preprint]*. doi: 10.31224/osf.io/5tpbz

Cook, E., Velis, C. A., and Derks, M. (2020). Plastic waste reprocessing for circular economy: A systematic review of risks to occupational and public health from legacy substances and extrusion. *engrXiv [Preprint]*. doi: 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 Med. Res. Methodol.* 18, 85. doi: 10.1186/s12874-018-0545-3

Dania, A. A., Kehinde, J. O., and Bala, K. (2007). "A study of construction material waste management practices by construction firms in Nigeria," in *The Third Scottish Conference for Postgraduate Researchers of the Built and Natural Environment* (Glasgow: Glasgow Caledonian University).

Dar, M. A., Baba, Z. A., and Kaushik, G. (2022). A review on phorate persistence, toxicity and remediation by bacterial communities. *Pedosphere* 32, 171–183. doi: 10.1016/S1002-0160(21)60043-7

Darbi, W. P. K., Hall, C. M., and Knott, P. (2018). The informal sector: a review and agenda for management research. *Int. J. Manag. Rev.* 20, 301–324. doi: 10.1111/ijmr.12131

Delgermaa, V., Takahashi, K., Park, E.-K., Le, G. V., Hara, T., and Sorahan, T. (2011). Global mesothelioma deaths reported to the World Health Organization between 1994 and 2008. *Bull. World Health Organiz.* 89, 716C−724C. doi: 10.2471/BLT.11.086678

Deposit of Poisonous Waste Act (1972). *H M Governement (UK)*.

Devia, Y. P., and Suryo, E. A. (2017). "Leachate of demolition waste," in *6th International Conference of Euro Asia Civil Engineering Forum*, eds J. W. Park, H. A. Lie, H. Hardjasaputra, and P. Thayaalan (Seoul: E D P Sciences). doi: 10.1051/matecconf/201713808002

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. *Sci. Total Environ.* 625, 1535–1543. doi: 10.1016/j.scitotenv.2018.01.076

Driscoll, T., Nelson, D. I., Steenland, K., Leigh, J., Concha-Barrientos, M., Fingerhut, M., et al. (2005). The global burden of disease due to occupational carcinogens. *Am. J. Ind. Med.* 48, 419–431. doi: 10.1002/ajim.20209

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. *Sci. Total Environ.* 572, 77–85. doi: 10.1016/j.scitotenv.2016.07.165

Environment Agency. (2017). *Waste Wood: Quick Guide 43_17*.

Ertaş, H., and Erdogan, A. S. (2017). An analysis of occupational accidents in demolition work. *Civil Eng. Archit.* 5, 37–51. doi: 10.13189/cea.2017.050201

European Commission (2009). *Causes and Circumstances of Accidents at Work in the EU (Belgium)*.

European Union (1999). *Council Directive 1999/31/EC of 26 April 1999 on the landfill of waste*. 1999/31/EC.

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", in: L11, p.27-49*. Official Journal of the European Communities.

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", in: L152, P. 169-212.* Official Journal of the European Union.

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", in: L 354/70,–No match found—70–81.*

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)", in: L345*. p. 87–95.

Eurostat (2010). *Accidents at work (ESAW) - until 2007 (hsw_acc7_work): Reference Metadata in Euro SDMX Metadata Structure (ESMS)*. Luxembourg: Eurostat, the statistical office of the European Union. Available online at: https://ec.europa.eu/eurostat/cache/metadata/en/hsw_acc7_work_esms.htm (accessed May 26, 2020).

Eurostat (2019). *Accidents at work statistics*. Eurostat. Available online at: 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 (accessed May 27, 2020).

Eurostat (2020). *Your Key to European Statistics*. Luxembourg: European Commission. Available online at: https://ec.europa.eu/eurostat (accessed June 2, 2020).

Evans, L. (2014). Traffic fatality reductions: United States compared with 25 other countries. *Am. J. Public Health.* 104, 1501–1507. doi: 10.2105/AJPH.2014.301922

Ferronato, N., and Torretta, V. (2019). Waste mismanagement in developing countries: a review of global issues. *Int. J. Environ. Res. Public Health* 16, 1060. doi: 10.3390/ijerph16061060

Fischbein, A., Daum, S. M., Davidow, B., Slavin, G., Alvares, A. P., Sassa, S., et al. (1978). Lead hazard among ironworkers. Dismantling lead-painted elevated subway line in New York City. *N. Y. State J. Med.* 78, 1250–1259.

Flanagan, D. M. (2020). *U.S. Geological Survey, Mineral Commodity Summaries: Asbestos*.

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. *Sci. Total Environ.* 497–498, 123–132. doi: 10.1016/j.scitotenv.2014.07.060

Forastieri, V. (2014). *Occupational Safety and Health in the Informal Economy*.

Frank, A. L. (2006). "The history of the extraction and use of asbestos," in *Asbestos?Risk Assessment, Epidemiology, and Health Effects*, eds. R. F. Dodson and S. P. Hammar (Portland, OR: Taylor and Francis Group), 1–7. doi: 10.1201/9781420038149.ch1

Frank, A. L., and Joshi, T. (2014). The global spread of asbestos. *Ann. Glob. Health* 80, 257–262. doi: 10.1016/j.aogh.2014.09.016

Freeman, M. H., Nicholas, D. D., and Schultz, T. P. (2006). "Nonarsenical wood protection: alternatives for chromated copper arsenate, creosote and pentachlorophenol," in *Environmental Impacts of Treated Wood, 1st Edn.*, eds T. G. Townsend and H. Solo-Gabriele (Boca Raton, FL: Taylor and Francis). doi: 10.1201/9781420006216.ch2

Frost, G. (2013). The latency period of mesothelioma among a cohort of British asbestos workers (1978-2005). *Br. J. Cancer* 109, 1965–1973. doi: 10.1038/bjc.2013.514

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. *Atmos. Environ.* 38, 4993–5002. doi: 10.1016/j.atmosenv.2004.06.024

Furuya, S., Chimed-Ochir, O., Takahashi, K., David, A., and Takala, J. (2018). Global asbestos disaster. *Int. J. Environ. Res. Public Health* 15, 1000. doi: 10.3390/ijerph15051000

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. *Trans. Am. Soc. Agric. Eng.* 48, 1731–1738. doi: 10.13031/2013.20007

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, 1–18. doi: 10.3390/ma13132970

Gottesfeld, P., Kuepouo, G., Tetsopgang, S., and Durand, K. (2013). Lead concentrations and labeling of new paint in Cameroon. *J. Occup. Environ. Hyg.* 10, 243–249. doi: 10.1080/15459624.2013.768934

Guidotti, T. L. (1996). Hydrogen sulphide. *Occup. Med.* 46, 367–371. doi: 10.1093/occmed/46.5.367

Gürcanli, G. E., and Müngen, U. (2013). Analysis of construction accidents in turkey and responsible parties. *Ind. Health* 51, 581–595. doi: 10.2486/indhealth.2012-0139

Hamby, D. M. (1995). A comparison of sensitivity analysis techniques. *Health Phys.* 68, 195–204. doi: 10.1097/00004032-199502000-00005

Health and Safety Executive (2009). *The control of lead at work regulations 1998*. Health and Safety Executive. Available online at: https://www.hse.gov.uk/foi/internalops/ocs/200-299/298_15.htm#para-7 (accessed June 5, 2020).

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)*.

Health and Safety Executive (2020b). *Information and services*. Health and Safety Executive. Available online at: https://www.hse.gov.uk/ (accessed October 13, 2020).

Henderson, D. W., and Leigh, J. (2011). "The history of asbestos utilization and recognition of asbestos-induced diseases," in *Asbestos: Risk Assessment, Epidemiology, and Health Effects*, eds. R. F. Dodson and S. P. Hammar (Boca Raton, FL: Taylor & Francis Group), 1–22. doi: 10.1201/b10958-2

Huang, S., Zhao, X., Sun, Y., Ma, J., Gao, X., Xie, T., et al. (2016). Spatial distribution of organic pollutants in industrial construction and demolition waste and their mutual interaction on an abandoned pesticide manufacturing plant. *Environ. Sci. Processes Impacts* 18, 482–492. doi: 10.1039/C6EM00019C

Hunter, P. R., Payment, P., Ashbolt, N., and Bartram, J. (2003). "Assessment of risk," in *Assessing Microbial Safety of Drinking Water: Improving Approaches and Methods*. (Paris: Organisation for Economic Cooperation and Development and World Health Organisation), 79–109.

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," in *IARC Monographs on the Evalauation of Carcionogenic Risks to Humans* (Lyon: World Health Organization).

International Chrysotile Association (nd). *For environmental occupational health safe and responsible use: Products*. International Chrysotile Association. Available online at: https://chrysotileassociation.com/chrysotile/products/default.php (accessed May 28, 2020).

International Labour Organization (2020a). "Cases of fatal occupational injury by economic activity: Annual," in *Occupational Safety and Health Statistics (OSH). 04/10/2020 06:19:58 ed.* Available online at: https://www.ilo.org/ilostat-files/Documents/Excel/INDICATOR/INJ_FATL_ECO_NB_A_EN.xlsx

International Labour Organization (2020b). *ILOSTAT: The leading source of labour statistics*. International Labour Organization. Available online at: https://ilostat.ilo.org/ (accessed October 13, 2020).

Jacobs, D. E. (1998). Occupational exposures to lead-based paint in structural steel demolition and residential renovation work. *Int. J. Environ. Pollut.* 9, 126–139.

Jadhav, A. V., and Gawde, N. C. (2019). Current asbestos exposure and future need for palliative care in India. *Indian J. Palliat. Care* 25, 587–591. doi: 10.4103/IJPC.IJPC_51_19

Jambeck, J. R., Townsend, T. G., and Solo-Gabriele, H. M. (2008). Landfill disposal of CCA-treated wood with construction and demolition (CandD) debris: arsenic, chromium, and copper concentrations in leachate. *Environ. Sci. Technol.* 42, 5740–5745. doi: 10.1021/es800364n

Jewell, C., Flanagan, R., and Cattell, K. (2005). "The Effects of the Informal Sector on Construction," in *Construction Research Congress 2005: Broadening Perspectives* (San Diego, CA: American Society of Civil Engineers).

Jiménez-Rivero, A., and García-Navarro, J. (2017). Best practices for the management of end-of-life gypsum in a circular economy. *J. Clean. Prod.* 167, 1335–1344. doi: 10.1016/j.jclepro.2017.05.068

Kaya, G. K., Ward, J. R., and Clarkson, P. J. (2018). A framework to support risk assessment in hospitals. *Int. J. Qual. Health Care* 31, 393–401. doi: 10.1093/intqhc/mzy194

Kazan-Allen, L. (2019a). *Chronology of Asbestos Bans and Restrictions*. International Ban Asbestos Secretariat. Available online at: http://www.ibasecretariat.org/chron_ban_list.php (accessed May 28, 2020).

Kazan-Allen, L. (2019b). *Current Asbestos Bans: National Asbestos Bans*. International Ban Asbestos Secretariat. Available online at: http://www.ibasecretariat.org/alpha_ban_list.php (accessed May 29, 2020).

Kitazaki, S., Xiao, K., Nakagawa, K., Kindaichi, T., and Asakura, H. (2014). Hydrogen sulfide generation suppression by nitrate addition – application to solid waste landfill site. *Am. J. Environ. Prot.* 3, 267–274. doi: 10.11648/j.ajep.20140305.20

Kodros, J. K., Wiedinmyer, C., Ford, B., Cucinotta, R., Gan, R., Magzamen, S., et al. (2016). Global burden of mortalities due to chronic exposure to ambient PM2.5 from open combustion of domestic waste. *Environ. Res. Lett.* 11, 124022. doi: 10.1088/1748-9326/11/12/124022

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 Manag.* 85, 445–451. doi: 10.1016/j.wasman.2018.12.039

Kumar, P., and Morawska, L. (2014). Recycling concrete: an undiscovered source of ultrafine particles. *Atmos. Environ.* 90, 51–58. doi: 10.1016/j.atmosenv.2014.03.035

Kumar, P., Mulheron, M., and Som, C. (2012). Release of ultrafine particles from three simulated building processes. *J. Nanoparticle Res.* 14, 771. doi: 10.1007/s11051-012-0771-2

LaDou, J., London, L., and Watterson, A. (2018). Occupational health: a world of false promises. *Environmental Health* 17, 81. doi: 10.1186/s12940-018-0422-x

Landrigan Philip, J., Lioy Paul, J., Thurston, G., Berkowitz, G., Chen, L. C., Chillrud Steven, N., et al. (2004). Health and environmental consequences of the world trade center disaster. *Environ. Health Perspect.* 112, 731–739. doi: 10.1289/ehp.6702

Lange, J. H., and Thomulka, K. W. (2000). Effectiveness of engineering controls for airborne lead exposure during renovation/demolition of a commercial building. *Indoor Built Environ.* 9, 207–215. doi: 10.1177/1420326X0000900310

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 Manag.* 26, 526–533. doi: 10.1016/j.wasman.2005.10.010

Lemieux, P. M., Lutes, C. C., and Santoianni, D. A. (2004). Emissions of organic air toxics from open burning: a comprehensive review. *Progress Energy Combust. Sci.* 30, 1–32. doi: 10.1016/j.pecs.2003.08.001

Leung, C. C., Yu, I. T. S., and Chen, W. (2012). Silicosis. *Lancet* 379, 2008–2018. doi: 10.1016/S0140-6736(12)60235-9

Li, J., Dong, Q., Yu, K., and Liu, L. (2014). Asbestos and asbestos waste management in the Asian-Pacific region: trends, challenges and solutions. *J. Clean. Prod.* 81, 218–226. doi: 10.1016/j.jclepro.2014.06.022

Lippmann, M., Cohen, M. D., and Chen, L.-C. (2015). Health effects of World Trade Center (WTC) dust: an unprecedented disaster with inadequate risk management. *Crit. Rev. Toxicol.* 45, 492–530. doi: 10.3109/10408444.2015.1044601

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. *Appl. Ecol. Environ. Res.* 17, 14543–14559. doi: 10.15666/aeer/1706_1454314559

López, A., and Lobo, A. (2014). Emissions of CandD refuse in landfills: a European case. *Waste Manag.* 34, 1446–1454. doi: 10.1016/j.wasman.2014.04.004

Maeda, H., Fujita, M. Q., Zhu, B.-L., Quan, L., Kamikodai, Y., Tsuda, K., et al. (2003). Labor-related fatalities in forensic postmortem investigations during the past 6 years in the southern half of Osaka city and surrounding areas. *Leg. Med.* 5, S325–S327. doi: 10.1016/S1344-6223(02)00162-1

McGee John, K., Chen Lung, C., Cohen Mitchell, D., Chee Glen, R., Prophete Colette, M., Haykal-Coates, N., et al. (2003). Chemical analysis of World Trade Center fine particulate matter for use in toxicologic assessment. *Environ. Health Perspect.* 111, 972–980. doi: 10.1289/ehp.5930

Mella, A., and Savage, M. (2018). *Construction Sector Employment in Low-Income Countries*.

Molla, A. S., Tang, P., Sher, W., and Bekele, D. N. (2021). Chemicals of concern in construction and demolition waste fine residues: a systematic literature review. *J. Environ. Manage.* 299, 113654. doi: 10.1016/j.jenvman.2021.113654

Montero, A., Tojo, Y., Matsuo, T., Matsuto, T., Yamada, M., Asakura, H., et al. (2010). Gypsum and organic matter distribution in a mixed construction and demolition waste sorting process and their possible removal from outputs. *J. Hazard. Mater.* 175, 747–753. doi: 10.1016/j.jhazmat.2009.10.072

Morrell, J. J. (2006). "Chromated copper arsenate as a wood preservative," in *Environmental Impacts of Treated Wood*, eds. T. G. Townsend and H. Solo-Gabriele, 1st ed (Boca Raton, FL: Taylor & Francis), 1–14. doi: 10.1201/9781420006216.sec1

National Minerals Information Center. (2018). *Asbestos Statistics and Information: Minerals Yearbook: Advance Data Release of the 2018 Annual Tables* Available online at: https://prd-wret.s3.us-west-2.amazonaws.com/assets/palladium/production/atoms/files/myb1-2018-asbes-adv.xlsx (accessed May 28, 2020).

Nie, Z., Yang, Z., Fang, Y., Yang, Y., Tang, Z., Wang, X., et al. (2015). Environmental risks of HBCDD from construction and demolition waste: a contemporary and future issue. *Environ. Sci. Pollut. Res.* 22, 17249–17252. doi: 10.1007/s11356-015-5487-2

Normohammadi, M., Kakooei, H., Omidi, L., Yari, S., and Alimi, R. (2016). Risk assessment of exposure to silica dust in building demolition sites. *Saf. Health Work* 7, 251–255. doi: 10.1016/j.shaw.2015.12.006

Odgerel, C. O., Takahashi, K., Sorahan, T., Driscoll, T., Fitzmaurice, C., Yoko, O. M., et al. (2017). Estimation of the global burden of mesothelioma deaths from incomplete national mortality data. *Occup. Environ. Med.* 74, 851–858. doi: 10.1136/oemed-2017-104298

Ogunmakinde, O., Sher, W., and Maund, K. (2019). An assessment of material waste disposal methods in the nigerian construction industry. *Recycling* 4, 13. doi: 10.3390/recycling4010013

Ogunseitan, O. A. (2015). The asbestos paradox: global gaps in the translational science of disease prevention. *Bull. World Health Organ* 93, 359–360. doi: 10.2471/BLT.14.142307

Peters, M. D. J., Marnie, C., Tricco, A. C., Pollock, D., Munn, Z., Alexander, L., et al. (2020). Updated methodological guidance for the conduct of scoping reviews. *JBI Evid. Synth.* 18, 2119–2126. doi: 10.11124/JBIES-20-00167

PubChem (1998). *Parathion. National Library of Medicine: National Center for Biotechnology Information*. Available online at: https://pubchem.ncbi.nlm.nih.gov/source/hsdb/197#section=EPA-Hazardous-Waste-Number (accessed February 24, 2022).

Puthussery, J. V., Kumar, R., and Garg, A. (2017). Evaluation of recycled concrete aggregates for their suitability in construction activities: an experimental study. *Waste Manag.* 60, 270–276. doi: 10.1016/j.wasman.2016.06.008

Rodríguez-Quijano, M., Jiménez-Rivero, A., de Guzmán-Báez, A., and García-Navarro, J. (2015). *Gypsum Plasterboard Deconstruction to Recycling Economic Study in Europe*, 665–674.

Saca, N., Dimache, A., Radu, L. R., and Iancu, I. (2017). Leaching behavior of some demolition wastes. *J. Mater. Cycles Waste Manag.* 19, 623–630. doi: 10.1007/s10163-015-0459-7

Schiopu, N., and Tiruta-Barna, L. (2012). "Wood preservatives," in *Toxicity of Building Materials*, eds F. Pacheco-Torgal, S. Jalali and A. Fucic (Cambridge, UK: Woodhead Publishing Limited), 138–165. doi: 10.1533/9780857096357.138

Scholz, P. F., Materna, B. L., Harrington, D., and Uratsu, C. (2002). Residential and commercial painters' exposure to lead during surface preparation. *Am. Ind. Hyg. Assoc. J.* 63, 22–28. doi: 10.1080/15428110208984687

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)*.

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).

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)*.

Secretariat of the Basel Convention (nd). *Framework for the Environmentally Sound Management of Hazardous Wastes and Other Wastes*. Geneva: United Nations Environment Programme. Available online at: http://www.basel.int/Implementation/CountryLedInitiative/EnvironmentallySoundManagement/ESMFramework/tabid/3616/Default.aspx (accessed October 7, 2020).

Secretariat of the Stockholm Convention (nd). *Hexabromocyclododecane*. United Nations Environment Program (UNEP). Available online at: http://chm.pops.int/Implementation/Alternatives/AlternativestoPOPs/ChemicalslistedinAnnexA/HBCD/tabid/5861/Default.aspx (accessed June 4, 2020).

Shim, Y., Jeong, J., Jeong, J., Lee, J., and Kim, Y. (2022). Comparative analysis of the national fatality rate in construction industry using time-series approach and equivalent evaluation conditions. *Int. J. Environ. Res. Public Health* 19, 195–204. doi: 10.3390/ijerph19042312

Shoji, T., and Egawa, Y. (2006). The structure of safety climates and its effects on workersandapos; attitudes and work safety at Japanese construction work sites. *J. UOEH* 28, 29–43. doi: 10.7888/juoeh.28.29

Singh, A., and Ladusingh, L. (2013). Increasing life expectancy and convergence of age at death in India. *Genus* 69, 83–99. Available online at: https://www.jstor.org/stable/genus.69.1.83

Sirrs, C. (2016). Accidents and apathy: the construction of the 'Robens Philosophy' of occupational safety and health regulation in Britain, 1961–1974. *Soc. Hist. Med.* 29, 66–88. doi: 10.1093/shm/hkv068

Soltaninejad, K., and Shadnia, S. (2014). "History of the use and epidemiology of organophosphorus poisoning," in *Basic and Clinical Toxicology of Organophosphorus Compounds*, eds M. Balali-Mood and M. Abdollahi (London: Springer London), 25–43. doi: 10.1007/978-1-4471-5625-3_2

Spasiano, D., and Pirozzi, F. (2017). Treatments of asbestos containing wastes. *J. Environ. Manage* 204, 82–91. doi: 10.1016/j.jenvman.2017.08.038

Stacey, P., Thorpe, A., and Roberts, P. (2011). *Levels of Respirable Dust and Respirable Crystalline Silica at Construction Sites (UK).*

Stayner, L., Welch, L. S., and Lemen, R. (2013). The worldwide pandemic of asbestos-related diseases. *Annu. Rev. Public Health* 34, 205–216. doi: 10.1146/annurev-publhealth-031811-124704

Stevulova, N., Estokova, A., Holub, M., Singovszka, E., and Csach, K. (2020). Characterization of demolition construction waste containing asbestos, and the release of fibrous dust particles. *Appl. Sci.* 10, 4048. doi: 10.3390/app10114048

t Mannetje, A., Steenland, K., Attfield, M., Boffetta, P., Checkoway, H., DeKlerk, N., et al. (2002). Exposure-response analysis and risk assessment for silica and silicosis mortality in a pooled analysis of six cohorts. *Occup. Environ. Med.* 59, 723. doi: 10.1136/oem.59.11.723

Takahashi, H. (2019). "An investigation of fatal accidents in demolition work of buildings," in *Tenth International Structural Engineering and Construction Conference* (Chicago, IL: ISEC Press).

Tame, N. W., Dlugogorski, B. Z., and Kennedy, E. M. (2007). Formation of dioxins and furans during combustion of treated wood. *Progress Energy Combust. Sci.* 33, 384–408. doi: 10.1016/j.pecs.2007.01.001

The Air Quality Standards Regulations (2010). *he Air Quality Standards Regulations 2010.*

The British Standards Institution (BS 8500-2:2015+A2:2019). *Concrete—Complementary British Standard to BS EN 206 - Part 2: Specification for Constituent Materials and Concrete.* London, UK: The British Standards Institution.

The Construction (Design and Management) Regulations (1994). *The Construction (Design and Management) Regulations.*

The World Bank (2020). *World Bank Open Data: Free and Open Access to Global Development Data.* Available online at: https://data.worldbank.org/ (accessed December 14, 2020).

The World Bank. (nd). *World Bank Country and Lending Groups.* The World Bank. Available online at: https://datahelpdesk.worldbank.org/knowledgebase/articles/906519-world-bank-country-and-lending-groups (accessed June 3, 2020).

Townsend, T., Chadik, P., Bitton, G., Booth, M., Lee, S., and Yang, K. (2000). *Gypsum Drywall Impact on Odor Production at Landfills: Science and Control Strategies* (Gainesville, VA).

Tricco, A. C., Lillie, E., Zarin, W., O'Brien, K. K., Colquhoun, H., Levac, D., et al. (2018). PRISMA Extension for Scoping Reviews (PRISMA-ScR): checklist and explanation. *Ann. Intern. Med.* 169, 467–473. doi: 10.7326/M18-0850

Turner, A., and Solman, K. R. (2016). Lead in exterior paints from the urban and suburban environs of Plymouth, south west England. *Sci. Total Environ.* 547, 132–136. doi: 10.1016/j.scitotenv.2015.12.125

United States Environmental Protection Agency (2000). *Effluent Limitations Guidelines, Pretreatment Standards, and New Source Performance Standards for the Landfills Point Source Category.*

U. S. Geological Survey (2020). *Mineral Commodity Summaries 2020.* Reston: U. S. Geological Survey.

Van Praagh, M., and Modin, H. (2016). Leaching of chloride, sulphate, heavy metals, dissolved organic carbon and phenolic organic pesticides from contaminated concrete. *Waste Manag.* 56, 352–358. doi: 10.1016/j.wasman.2016.07.009

Velis, C. A., and Cook, E. (2021). Mismanagement of plastic waste through open burning with emphasis on the global south: a systematic review of risks to occupational and public health. *Environ. Sci. Technol.* 55, 7186–7207. doi: 10.1021/acs.est.0c08536

Vodyanitskii, Y. N. (2016). Biochemical processes in soil and groundwater contaminated by leachates from municipal landfills (mini review). *Ann. Agrar. Sci.* 14, 249–256. doi: 10.1016/j.aasci.2016.07.009

Wagner, A. C., Bergen, A., Brilke, S., Bühner, B., Ebert, M., Haunold, W., et al. (2017). Characterization of aerosol particles produced by a skyscraper demolition by blasting. *J. Aerosol Sci.* 112, 11–18. doi: 10.1016/j.jaerosci.2017.06.007

Wahab, A. B., and Lawal, A. F. (2011). An evaluation of waste control measures in construction industry in Nigeria. *Afr. J. Environ. Sci. Technol.* 5, 246–254. Available online at: https://academicjournals.org/journal/AJEST/article-abstract/A67F57114037

Wasson, S. J., Linak, W. P., Gullett, B. K., King, C. J., Touati, A., Huggins, F. E., et al. (2005). Emissions of chromium, copper, arsenic, and PCDDs/Fs from open burning of CCA-treated wood. *Environ. Sci. Technol.* 39, 8865–8876. doi: 10.1021/es050891g

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. *Environ. Sci. Technol.* 48, 9523–9530. doi: 10.1021/es502250z

Wielgosiński, G. (2011). The reduction of dioxin emissions from the processes of heat and power generation. *J. Air Waste Manag. Assoc.* 61, 511–526. doi: 10.3155/1047-3289.61.5.511

Wilson, D. C., Rodic, L., Modak, P., Soos, R., Carpintero, A., Velis, K., et al. (2015). *Global Waste Management Outlook* (Nairobi, Kenya: United Nations Environment Programme).

World Health Organization (1999). "hazard prevention and control in the work environment: airborne dust," in *Protection of the Human Environment Occupational and Environmental Health Series* (Geneva: World Health Organization).

World Health Organization (2012). *Rapid Risk Assessment of Acute Public Health Events.* Geneva: World Health Organization.

World Health Organization (2019). "Download the raw data files of the WHO mortality database," in *Health Statistics and Information Systems. 15 December 2019 ed.* (World Health Organization). Available online at: https://web.archive.org/web/20200714065349/https://www.who.int/healthinfo/statistics/mortality_rawdata/en/

World Health Organization (2020). *World Health Data Platform.* World Health Organization. Available online at: https://www.who.int/data (accessed October 13, 2020).

Xu, Q., Townsend, T., and Bitton, G. (2011). Inhibition of hydrogen sulfide generation from disposed gypsum drywall using chemical inhibitors. *J. Hazard. Mater.* 191, 204–211. doi: 10.1016/j.jhazmat.2011.04.063

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, 1130–1138. doi: 10.1080/10473289.2006.10464544

Zaharuddin, W., Paraskevas, I., and Liu, C. (2009). "Accident avoidance importance for building demolition," in *CIB W099 Working Commission on Construction Safety and Health*, eds H. Lingard, T. Cooke, and M. Turner (Melbourne, VIC:. RMIT University).

Zhang, C., Bai, L., Yao, Q., Li, J., Wang, H., Shen, L., et al. (2022). Emission characteristics of polychlorinated dibenzo-p-dioxins and dibenzofurans from industrial combustion of biomass fuels. *Environ. Pollut.* 292, 118265. doi: 10.1016/j.envpol.2021.118265

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.