Medical and healthcare waste generation, storage, treatment and disposal: A systematic review of risks to occupational and public health

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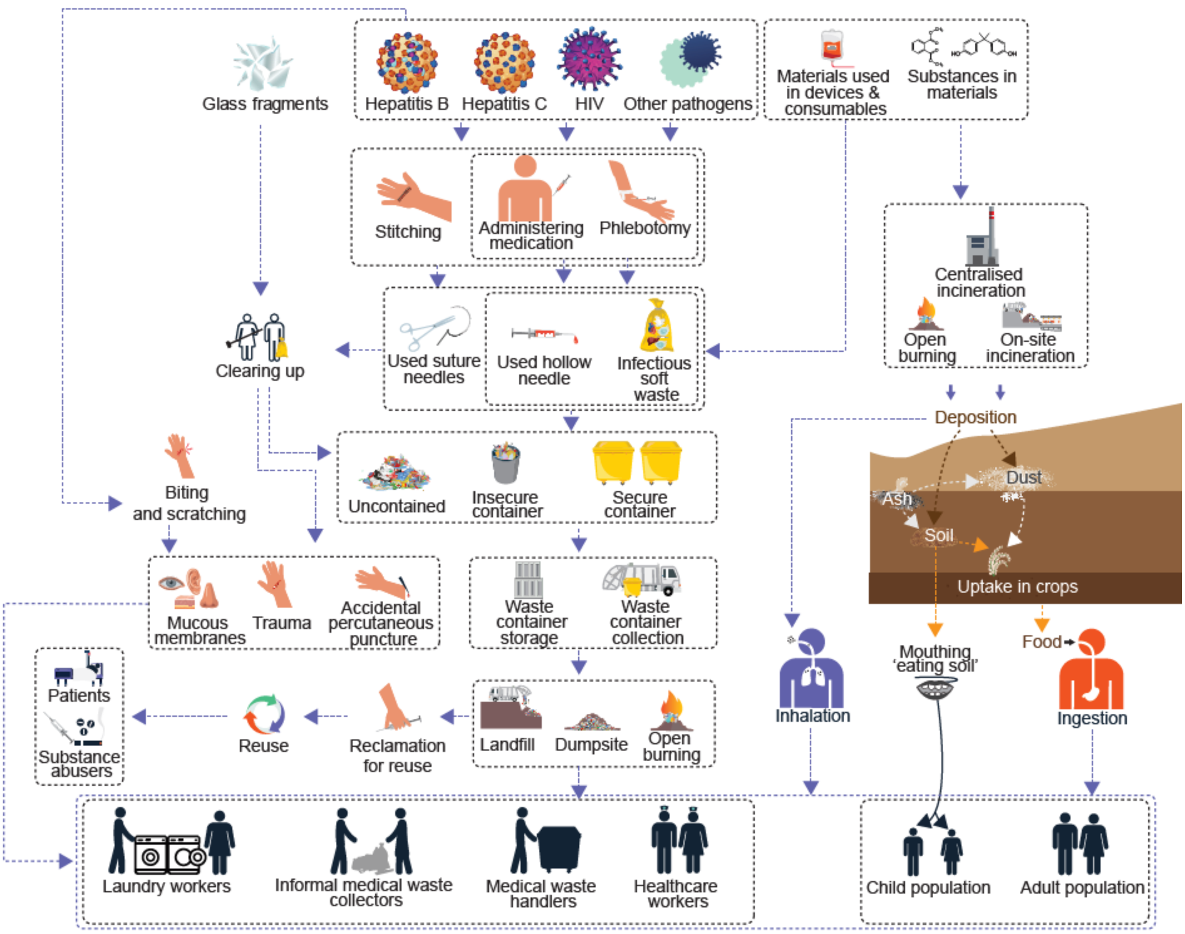
Abstract

Systems to safely store, handle, treat and dispose of medical (healthcare) waste are well developed in the 21st century. Yet across many parts of the Global South (low- and middle-income countries) such systems, resources and knowhow are lacking; to the extent that medical waste could be posing a serious threat to the health, safety and lives of millions of healthcare workers and waste handlers who regularly interact with this material. We present here a novel scope and dimension to investigating the risks and hazards to people who come into contact with medical waste, focusing on activity types and established medical practice. Based on a systematic review of the evidence (PRISMA approach, adapted), we critically analysed and comparatively summarised data, and identified prevalent combinations of hazards, exposure and risk with a global scope. Subsequently, we assigned indicative comparative risk scores for such combinations. Our critical analysis unveils extensive mismanagement of medical waste globally, including the co-disposal with municipal solid waste (MSW), burning in open pits, and dumping even on public streets. Alarmingly, a small but non-negligible trade in reused medical equipment is proliferated by a cohort of waste reclamation specialists (sub-group of waste pickers): they collect hypodermic needles, and other single use medial items for resale to substance abusers and back into the healthcare system. We also highlight the dilemma faced by medical waste handlers in many parts of the world where a difficult choice is made between creating hazardous emissions from burning waste in the open or discarding it on land (e.g. in dumpsites) from where it risks accidentally infecting people with pathogens.

Keywords: Healthcare waste, Solid waste, Health and safety, Risk, Global South, Resource recovery, Circular economy, Sharps injury, Medical waste incineration, Open burning, Medical waste.

Graphical Abstract



Abbreviations

As	arsenic
BC	black carbon
Cd	cadmium
CI	confidence interval
CO	carbon monoxide
Cr	chromium
Cr (VI)	chromium IV
DRC	dioxins and related compounds
DWH	domestic waste handler
EC	elemental carbon
EU	European Union
EWC	European Waste Catalogue
Fe	iron
haz.	hazard
HBV	hepatitis B virus
HCB	hexachlorobenzene
HCl	hydrochloric acid
HCV	hepatitis C virus
HCW	healthcare workers
Hg	mercury
HIC	high income countries
HIV	human immunodeficiency virus
I-TEQ	international toxic equivalent
L	likelihood
LIC	low income countries
LIMIC	low income and middle income countries
LMC	lower middle income countries
Mn	manganese
MSW	municipal solid waste
MWH	medical waste handler
NHS	National Health Service (UK)
Ni	nickel
NMVOC	non-methane volatile organic compounds
NO_X	Nitrogen oxides
PAH	polycyclic aromatic hydrocarbons
Pb	lead
PM	particulate matter
PVC	polyvinyl chloride
R	risk
S	severity
SDG	Sustainable development Goals
SO_2	sulphur dioxide
SO_X	Sulphur dioxides
TSP	Total suspended particles
UMC	upper middle income countries
USEPA	United States Environmental Protection Agency
WASH	Water, Sanitation and Health

1. Introduction

Despite extensive global knowledge of the potential hazardousness of medical (healthcare) wastes, there are considerable shortcomings with medical waste management across the world, particularly in low and middle income countries (LIMICs) where medical waste is often stored, transported and co-disposed alongside other waste fractions (Harhay et al., 2009). Whereas many of the materials, substances and objects that become medical waste are similar in nature to household waste, the World Health Organization (2014) (WHO) estimates that approximately 15% is potentially hazardous to human health, not least due to its potential to harbour pathogens that can subsequently cause infection at multiple points across a complex system (**Figure 1**).

In high income countries (HIC), systems to neutralise pathogens in medical waste are advanced, supported by protocols for separation at source, of for instance sharps (injection equipment), so that they can be stored, transported and treated or disposed of safely and efficiently. Infectious material is often incinerated or disposed of in specially designed hazardous waste landfills that prevent the risk of interaction with people or, the environment (Hossain et al., 2011; Windfeld and Brooks, 2015). The specialist engineering required and effort undertaken to protect human health and the environment in this way, results in considerable cost. For instance, a median of $440-620 per tonne for infectious waste treated in the UK in 2015-16 (Royal College of Nursing, 2018) and $790 per tonne in the US (Lee et al., 2004). For healthcare providers in LIMICs, these costs are often prohibitive, and research undertaken by the Water, Sanitation and Health (WASH) team of WHO (World Health Organization and the United Nations Children's Fund, 2019) indicated that out of 48 countries that provided sufficient data, only 30 were able to provide data on healthcare waste generation and management and of those, more than 50% lacked basic waste management services (**Section S.5**).

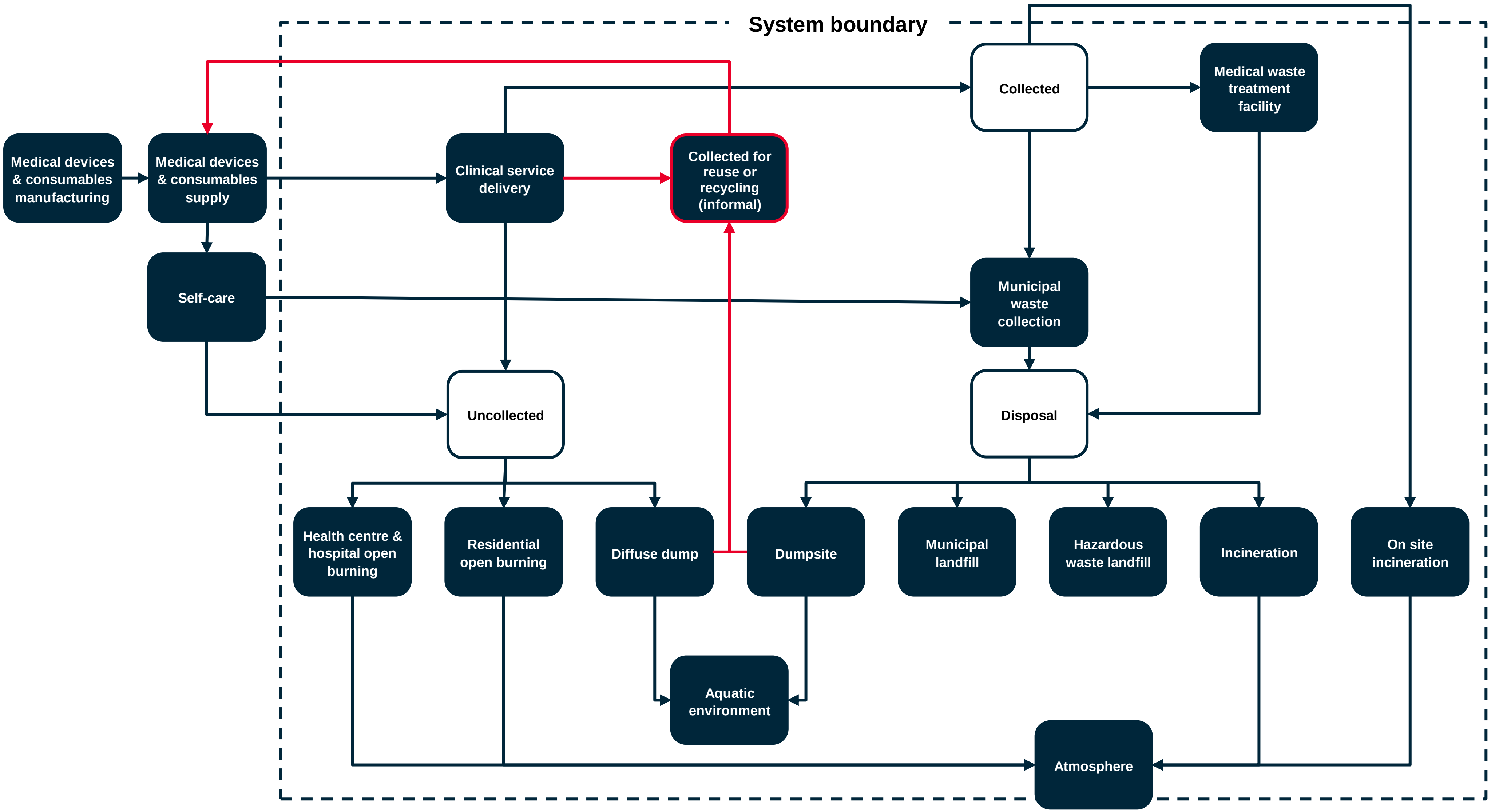


Figure 1: Generalised material flow system for medical waste. System boundary denotes the parts of the system that fall within scope of this review. Red arrows highlight pathways through which single-use medical devices are reclaimed for reuse.

Fundamentally, medical waste is any object, substance or item that is discarded as a result of healthcare provision. Some of it may be hazardous, some infectious, and much of it is likely to be relatively benign. For instance, Vaccari et al. (2017) found that approximately 44% of waste generated in an Italian hospital was hazardous, the Royal College of Nursing (2018) found that 32.8% of waste generated in hospitals in England and Wales was infectious in 2015-16, and World Health Organization (2005a) reported that just 19% of waste generated in healthcare centres was potentially hazardous. However, a globally unified definition of medical waste is absent, which means that there is ambiguity over how it should be stored, collected and transported. This basic lack of clarity may expose medical waste generators, handlers, treatment and disposal operators to an unacceptably high risk of exposure, due to interaction with wastes, some of which have hazardous properties.

Several reviews on medical waste management practice already exist. For instance, Ali et al. (2017), Kerdsuwan and Laohalidanond (2015) and Khan et al. (2019) have each carried out mini-reviews of medical waste management in developing countries, listing information on medical waste generation, composition, management and hazardousness, alongside narrative on the challenges faced by healthcare workers and medical waste handlers. On a national scale, reviews also exist for Ethiopia (Israel Deneke et al., 2010), Jordan (Al-Momani et al., 2019), India (Patil and Shekdar, 2001) and Turkey (Ciplak and Kaskun, 2015) amongst others. The World Health Organisation has also provided several reviews, including an extensive global review on the safe management of healthcare wastes (World Health Organization, 2014), one that focussed on Southeast Asia specifically (World Health Organization, 2017a), and another that is dedicated to the safe management of sharps (used injection, phlebotomy and stitching equipment) (World Health Organization, 2019c). Two global reviews also exist in the academic literature. Hossain et al. (2011) provided more in depth context, also reviewing the main treatment technologies that exits to reduce the risk it poses to human health, including some advanced methods such as the use of super-critical fluids and microwaves. Windfeld and Brooks (2015) briefly summarised the general legislator approaches in Canada the US and the UK, also very briefly discussing on developing countries. Lastly, Caniato et al. (2015) carried out a systematic review of global governance structures, which highlighted the widely varying approaches to the regulation and practices, particularly in LIMICs where investment in medical waste management was found to correlate with its effectiveness.

In common, these reviews provide an overview of the existing literature and general practices in medical waste management, describing and listing the general issues that relate to the topic. Yet, a comparative review of evidence indicating or assessing the potential or actual harm caused by established medical waste management practice is not available. This research gap creates major challenges for medical waste mangers and policy-makers to implement effective and efficient measures toward mitigating the risk of negative interactions between medical waste, people and the natural environment.

Therefore, we attempt here to bring three key contributions to the record to address these challenges, by way of a systematic review. **First**, we provide an overview of the medical waste system, generation, size of the sector. **Second**, we have systematically reviewed evidence that indicates hazards associated with medical waste to which receptors can be plausibly exposed through evidenced or inferred pathways. We focus on medical devices and consumables, specifically excluding pharmaceuticals, contraceptive devices and electrical equipment, for which more specialist reviews are needed. **Third**, we have aggregated and presented these data for comparison according to the hazards and risks observed according to the phase of the waste management system to assist the reader with navigating the relevant concepts, namely: waste generation; waste storage, collection and handling; and reuse recovery and disposal (**Figure 2**). **Fourth**, we arrange identified risks into hazard-pathway-receptor combinations that enable a semi-quantitative comparison of relative harm so that risks can be ranked and prioritised for further research, innovation and wider interventions.

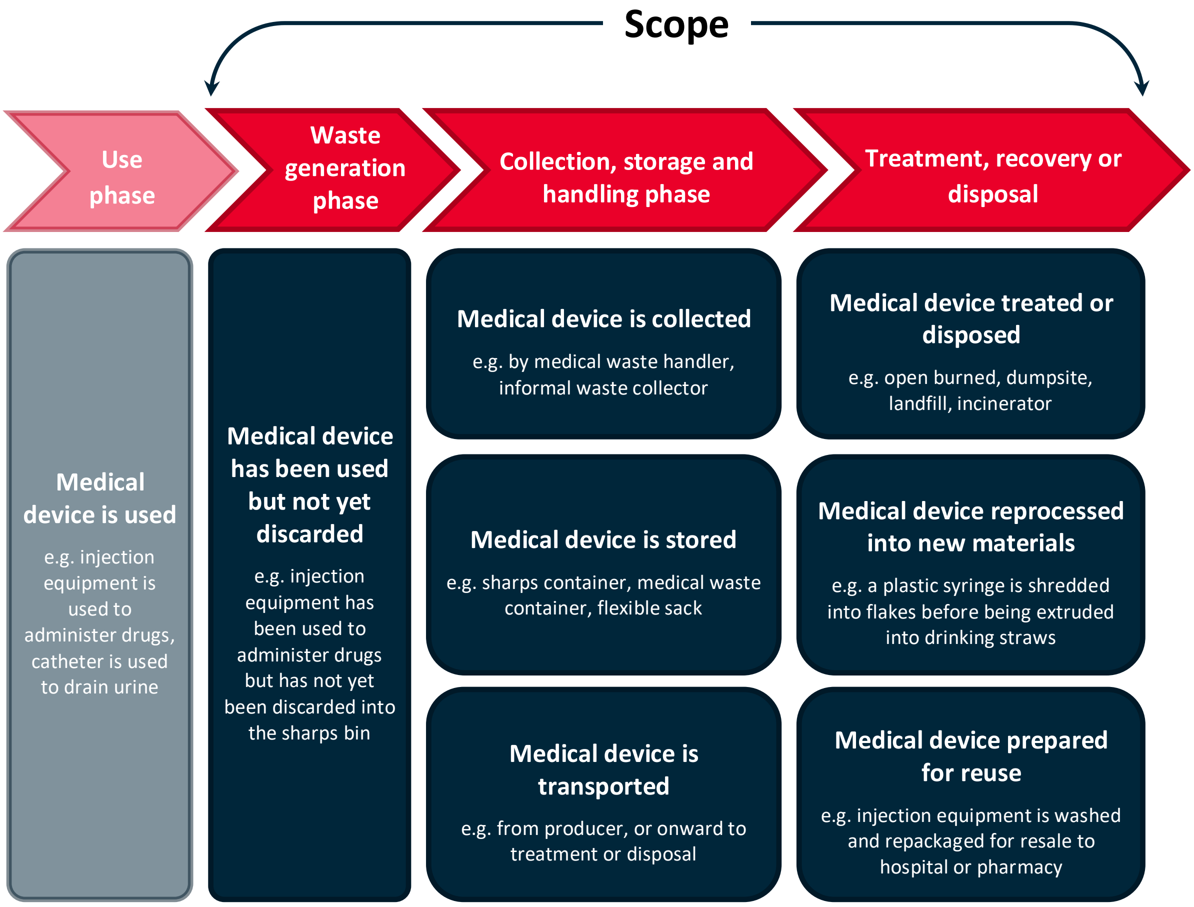


Figure 2: Phases during which hazard potential exists for medical devices after-use. Greyed out section is outside the system boundary of this research.

The scope of the study encompasses the entire 'after-use' (end-of-engineered-life) phase which is defined here by the Directive 2008/98/EC (European Commission, 2008), as the point in time at which the requirement to discard an item first takes place. For example, a needle that has been withdrawn from a patient's arm after administering medication has completed its intended purpose and is considered waste because there exists a societal and/or institutional requirement to discard it immediately to prevent potential harm to others from a blood-born pathogen. Of course, there may be an unsanctioned intent to reuse an item; however, there is almost always an expectation that this should not happen, and it is therefore considered 'waste' for the purposes of our research.

2. Methods

2.1. Systematic review

We followed methods reported by Cook et al. (2020) to carry out a systematic review based on PRISMA guidelines (Moher et al., 2009), exploring three research questions (RQ) as follows:

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

The Boolean search queries used to search three databases, Scopus, Web of Science and Google Scholar are shown in **Section S.1** alongside the exclusion criteria (**Table S 1**) and the basic statistical results of the review (**Figure S 1** and **Figure S 2**). These were tested using one at a time sensitivity analysis to obtain the optimum number of papers with the fewest terms. Further snowball and citation searching (Cooper et al., 2018) was undertaken as well as searches of databases from institutions such as The World Bank (2020), International Labour Organization (2020), World Health Organization (2020), Health and Safety Executive (2020) (HSE).

As described by Cook et al. (2020), risks, hazards, pathways and receptors were combined into realistically experienced combinations according to scenarios reported in the literature, which enabled the production of source-pathway-receptor diagrams illustrating hazard flow to receptors, as shown in the unified diagram in **Figure 3**.

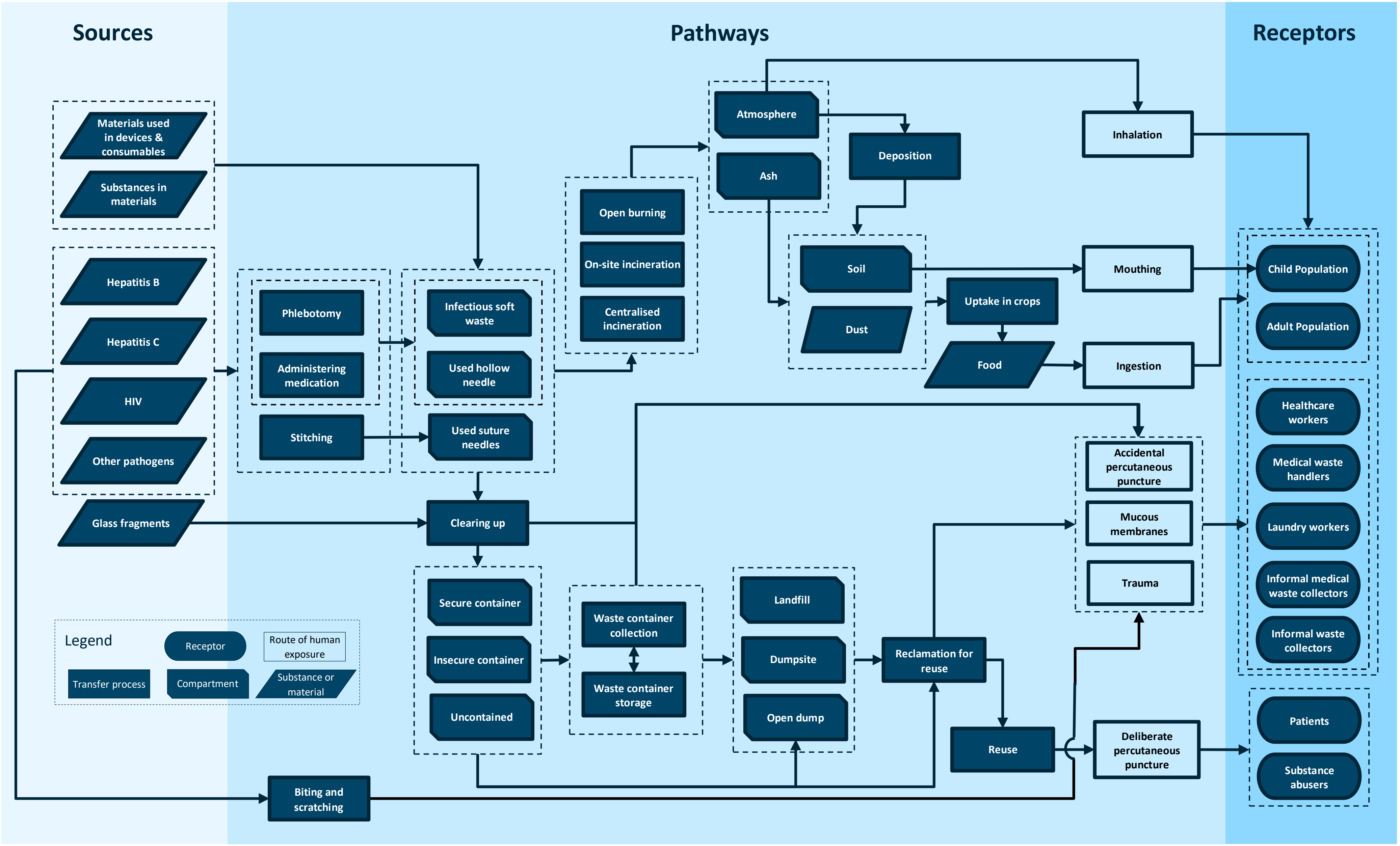


Figure 3: Conceptual overview of the main sources, pathways and receptors for hazards associated with medical waste.

2.2. Risk based approach

A risk based approach, also described by Cook et al. (2020), and adapted from World Health Organization (2012), Hunter et al. (2003), Kaya et al. (2018) and Burns et al. (2019), assessed the likelihood and severity in each hazard-pathway-receptor combination, assigning an indicative risk score (**Table 1** and **Table 2**) that was used to rank and compare them. It is important to note that this process did not and was not intended to quantify risk in each combination, but to be used as a decision support method that can be used to inform a future research agenda; aggregated and ranked results are shown in **Section S.3**.

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

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

Table 2: Colour coding used to rank hazard potential qualitatively in each category.

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

2.3. Medical waste generation

Data for medical waste generation were collected as a separate search exercise from the main review using the same pool of papers, and the same citation and snowball searching strategy. Descriptive statistics were illustrated as box and whisker plots. Outliers were defined as data points that were more than 1.5 times the length of the interquartile range distant from either end of the interquartile range.

2.4. Other

Calculation of cost of waste treatment in the introduction at 1.305 USD to 1 GBP)

3. Overview of medical waste

3.1. Definitions and scope

Agreeing clear, shared definitions, for waste is critical to implementing policy and best practice to mitigate its harmful effects (Cheyne and Purdue, 1995). However, our research indicates that there is still no unified global definition of medical waste and the terms 'medical waste' and 'healthcare waste' are used interchangeably by different organisations and authors reviewed here. According to the World Health Organization (2017b), healthcare waste includes: *"[…] all the waste generated within health-care facilities, research centres and laboratories related to medical procedures. In addition, it includes the same types of waste originating from minor and scattered sources, including waste produced in the course of health care undertaken in the home".*

The Commission of the European Communities (2010) uses a similar definition for classification of healthcare and biological wastes, which includes all material generated in the pursuit of healthcare of humans and animals including: body parts and organs, sharps, bandages, plaster casts, clothing, diapers (from hospitals) and chemicals from hospitals and laboratories. The category also encompasses residential care activities, treatment of prevention care for humans and animals, human health activities, research.

Despite these definitions, the medical and healthcare waste categories are not applied consistently, and are often used liberally to describe specific fractions of waste generated by healthcare activities or often those that arise from specific healthcare facilities. For instance, the term 'medical waste' may be used as a proxy for:

- The hazardous fraction of healthcare waste
- The clinical fraction of healthcare waste
- Waste generated in hospitals
- Waste generated across a range of healthcare facilities.

3.2. Medical sector workforce

Approximately 59 million people worked in healthcare worldwide in 2006, more than half of whom worked in Europe and the US (**Figure 4**) (World Health Organization, 2006). Health service providers make up the majority of the healthcare workforce, with significant managerial and support workers providing ancillary services in Europe and the Americas. Conversely, in the Western Pacific Region, Eastern Mediterranean and Africa, the healthcare workforce is primarily made up of healthcare providers with successively fewer management and support workers as a proportion of the total workforce in these regions.

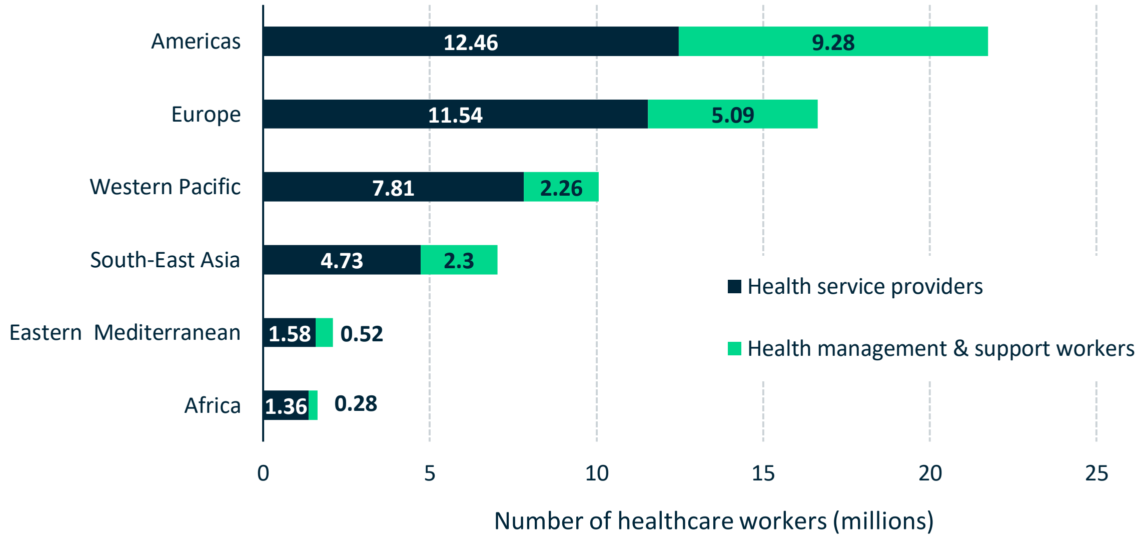


Figure 4: Number of healthcare workers by WHO region absolute numbers (World Health Organization, 2006). WHO regions are detailed in **Section S.4.**

Europe and the Americas have considerably more (21.74) healthcare workers per 1,000 population compared to the global average of 9.3. Africa has comparatively few healthcare workers, with just 2.3 per 1,000 head of population, indicating that countries with greater access to resources are able to provide more healthcare workers (**Figure 5**).

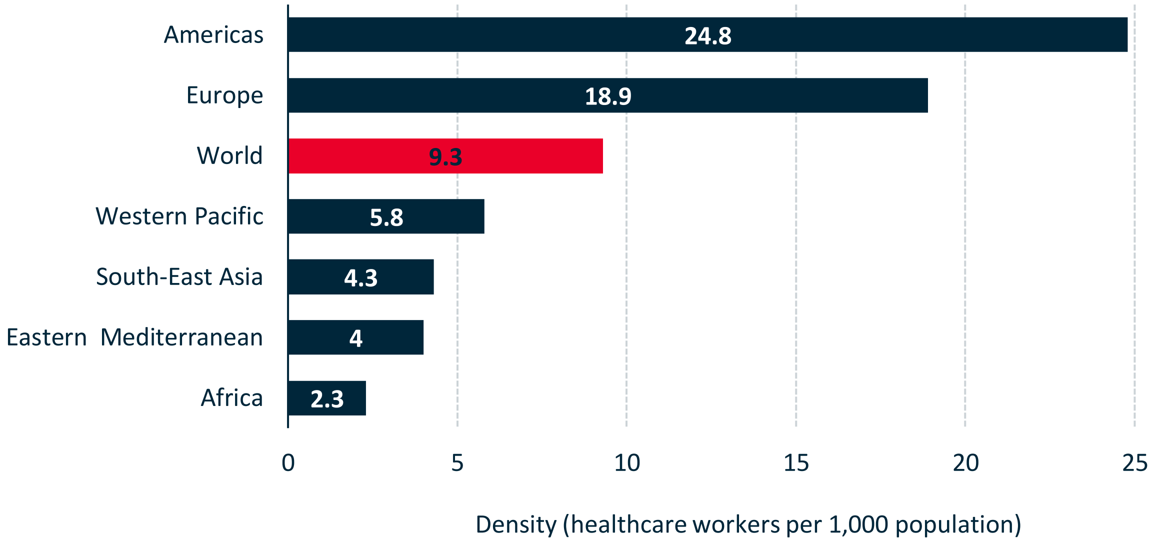


Figure 5: Density of healthcare workers by WHO region (World Health Organization, 2006). WHO regions are detailed in **Table S 4.** Red bar represents global average.

3.3. Medical waste composition

As indicated by the data shown in **Figure 9**, medical waste is made up of both hazardous and non-hazardous components. As a rule of thumb, World Health Organization (2005b) suggests that HCW is approximately 20% non-infectious and non-hazardous, with the remaining 80% having similar properties to domestic waste. (World Health Organization, 2005a) provides the following indicative composition of healthcare waste, shown in **Figure 6**. Few studies provide more detail on the material composition of medical waste. One study (Eleyan et al., 2013) of medical waste generated at three hospitals in Palestine provides detail on both hazardous and non-hazardous fractions (**Figure 7**).

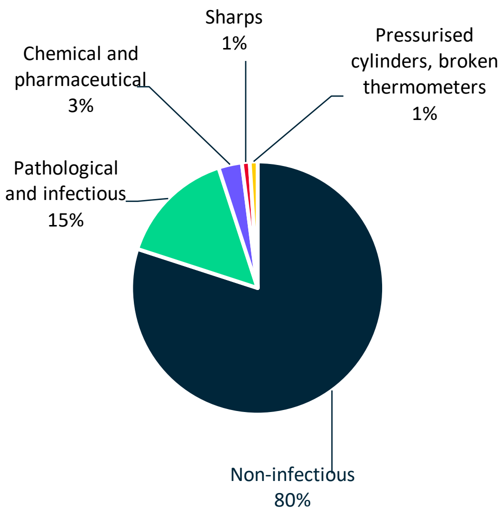


Figure 6: Approximate proportions of HCW at public health centres reported by WHO. Data after World Health Organization (2005a).

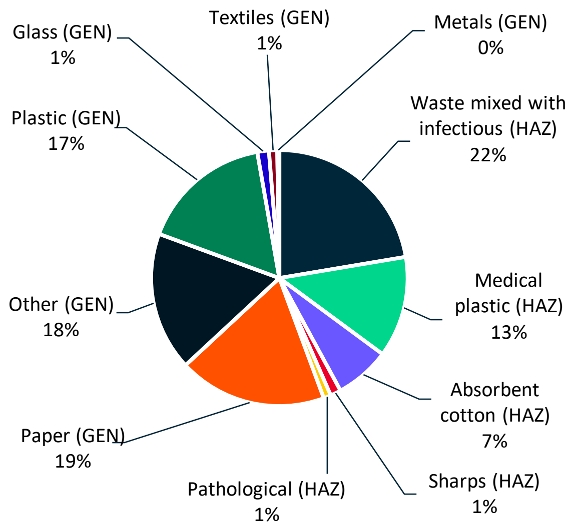


Figure 7: Material composition of waste sampled at three hospitals in Palestine. Data after Eleyan et al. (2013).

3.4. Medical waste generation

Medical waste generation data is reported using a variety of metrics and definitions worldwide. As revealed here, the most common convention in low income and middle income countries (LIMICs) is to report waste generated at healthcare facilities on a kg per bed per day basis. Here, 136 medical waste generation data points from 59 separate sources in 27 countries were reviewed and categorised by the World Bank income category at the time that the primary research was conducted (**Figure 8**). The data showed some commonality in LIMICs, however few data points were found for high income countries (HICs), as the convention is to report on a whole country or hospital basis, thus the arithmetic mean was skewed for HICs by two very high data points. The majority of the data identified were for LIMICs, with an arithmetic mean of 2.8 kg and 2.9 kg per bed per day for low income countries (LICs) and upper middle income countries (UMCs) respectively. LMCs showed a lower healthcare waste generation, with an arithmetic mean of 1.1 kg per bed per day and median of 0.68 kg per day.

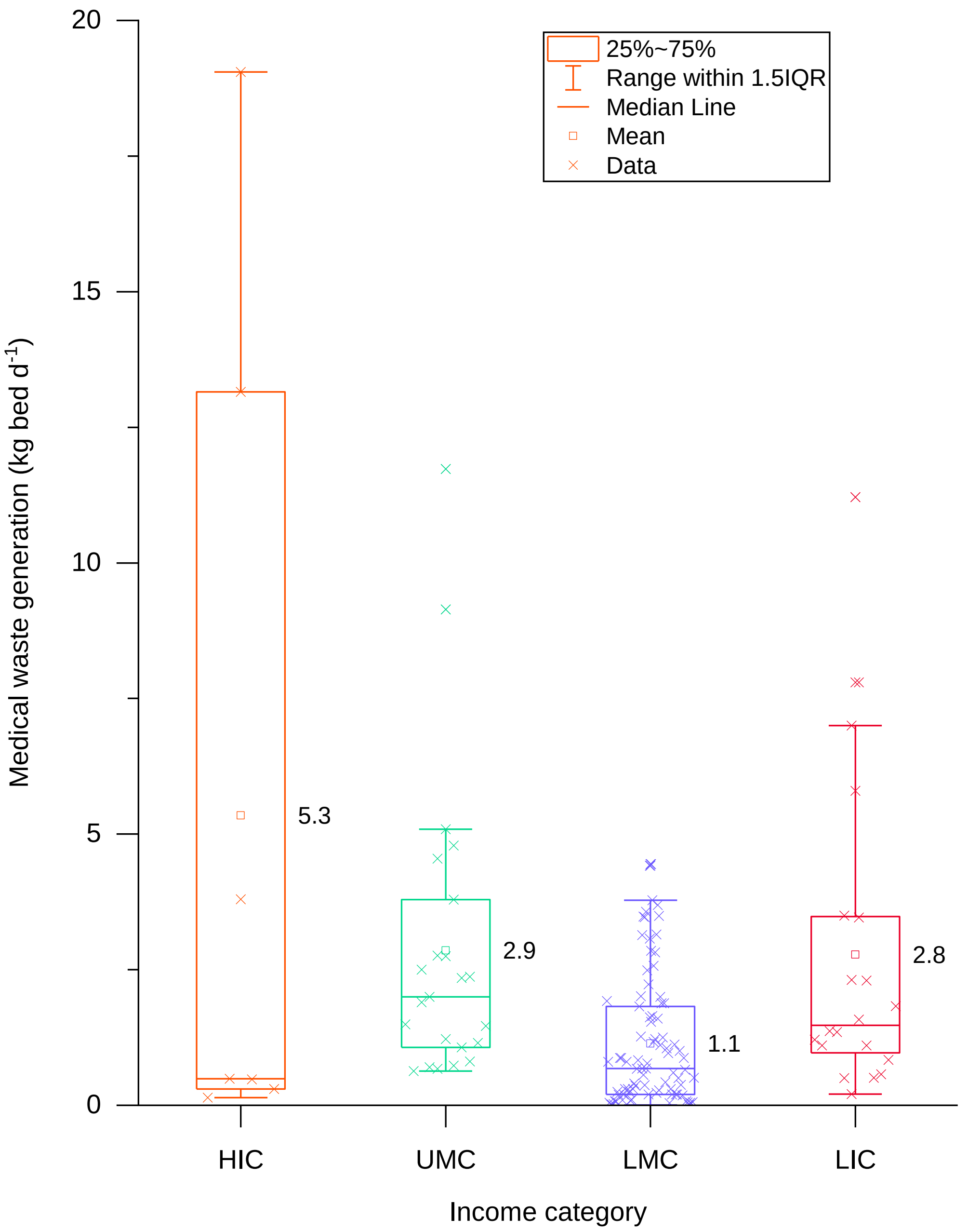


Figure 8: Side by side comparison of central tendency and spread for waste generation in medical facilities by income category; sources detailed in **Table S 2**. Both UMCs and LICs showed a similar waste generation, more than a third greater than LMCs. Abbreviations: high income country (HIC); low income country (LIC); upper-middle income country (UMC); lower middle income country (LMC); inter-quartile range (IQR).

Though hospital waste is widely published on a per bed basis, statistics on the absolute mass of medical waste generated are less commonly reported outside the European Union. Eurostat (2016a) publishes data for European countries (**Figure 9**), which reported collective healthcare and biological waste generation of approximately 2.1 million tonnes in 2016. Approximately 56% of Europe's healthcare and biological waste is classified as hazardous; but, as shown in **Figure 9**, there are clear differences in the way waste is categorised in different countries. Moreover, there is wide variation in the medical waste generation per capita, which is comparatively high for both Belgium and Ireland and low for Turkey and the average of all the other European countries.

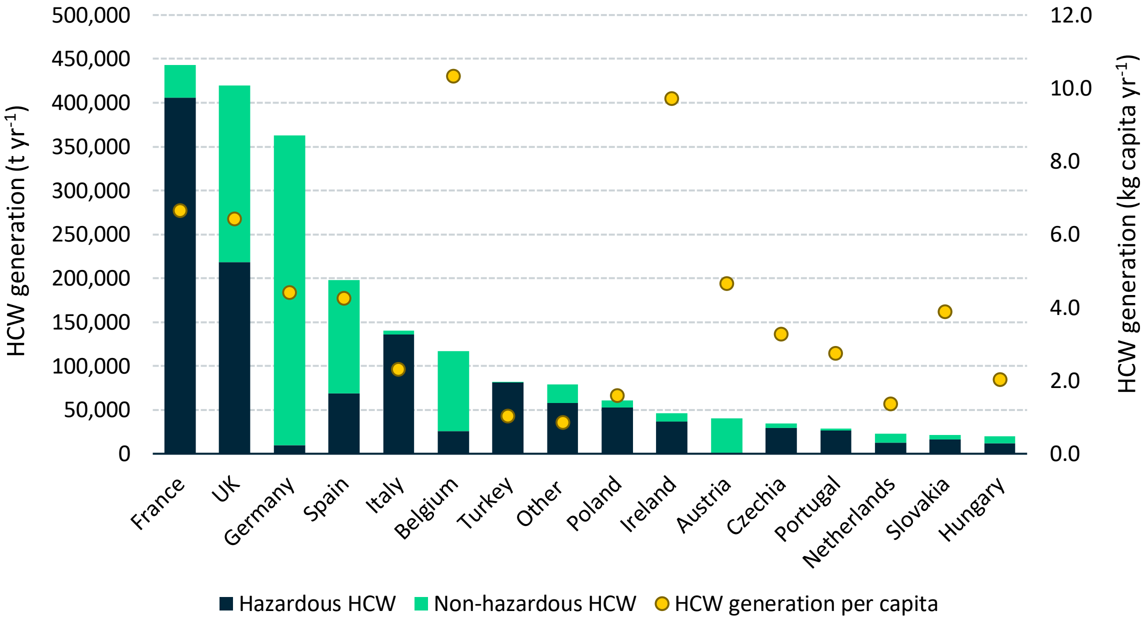


Figure 9: Healthcare and biological waste generation in selected European countries Eurostat (2016a). High variability in healthcare waste generation is reported, possibly reflecting inconsistencies in definitions and variability in the level of accurate reporting between member states. Abbreviations: healthcare waste (HCW).

Reporting of medical waste generation in the EU relies on the accurate submission of paperwork and correct classification of wastes according to Chapter 18 in the European Waste Catalogue (EWC) (European Union, 2018). In practice, member states may have a variety of interpretations of the central EU requirements under Directive 2008/98/EC (The Waste Framework Directive) (European Commission, 2008), and often businesses and individual instructions may not be provided with adequate guidance on how to report the waste they generate under the correct EWC code.

As a way of contextualising European healthcare and biological waste generation, it is shown in **Figure 10** as proportion of MSW generation as reported by Eurostat (2016b). As with the data shown in **Figure 9,** there is considerable variation between some countries, for which there is no obvious explanation. Again both Belgium and Ireland show healthcare waste generation as a proportion of MSW, with Turkey and the other European nations showing very low proportions in comparison to the mean average generation of approximately 0.7%.

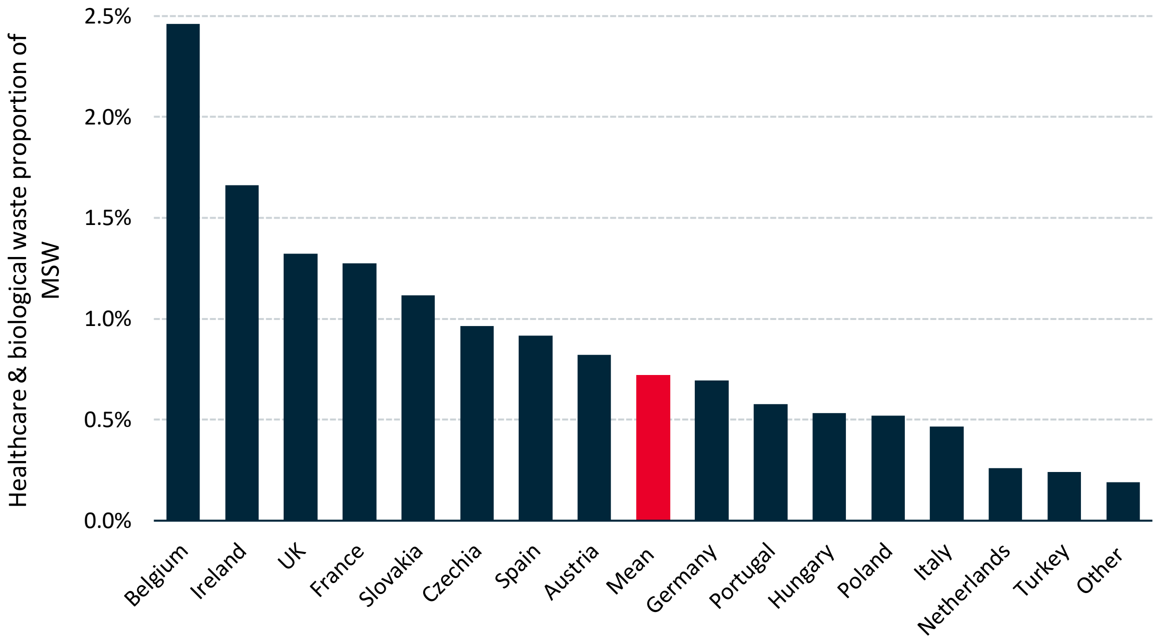


Figure 10: Healthcare and biological waste in Europe shown as a proportion of MSW (Eurostat, 2016a; Eurostat, 2016b). There is no obvious explanation for the large variation in healthcare waste generation between member states.

The considerable variation in reported categories and mass of medical waste by different countries suggests that it is unlikely that accurate estimates of medical waste generation will be forthcoming at a country, regional or global basis. Furthermore, several other types of waste arisings that could be considered to be part of healthcare waste are unlikely to be reported at all, the majority of which will be discarded alongside domestic MSW collected waste, such as self-care products (e.g. incontinence products, blood glucose testing kits, dressings and catheters) administered at home.

4. Challenge 1: Medical waste generation phase

4.1. Context

We summarise here data on the key hazards identified that exist at the point of waste generation in healthcare. With a few exceptions, most of the studies focus on sharps and needlestick injuries, which are the dominant category of injury relating to medical waste at the point of generation in many contexts (Akpieyi et al., 2015; Elder and Paterson, 2006). As shown in the conceptual model (**Figure 11)**, the main hazards associated with both the sharps and needlestick injuries and also exposure to soft infectious medical waste, for example, dressings or personal protective equipment (PPE), are identified as those from infection with hepatitis C virus (HCV), hepatitis B virus (HBV) and human immunodeficiency virus (HIV). In isolation, these pathogens pose little risk, however, there are several circumstances through which these pathogens may be carried by medical devices and consumables, and thereafter could in principle enter the bodies of those who may come into contact with them (subject to specific conditions for pathogen survival).

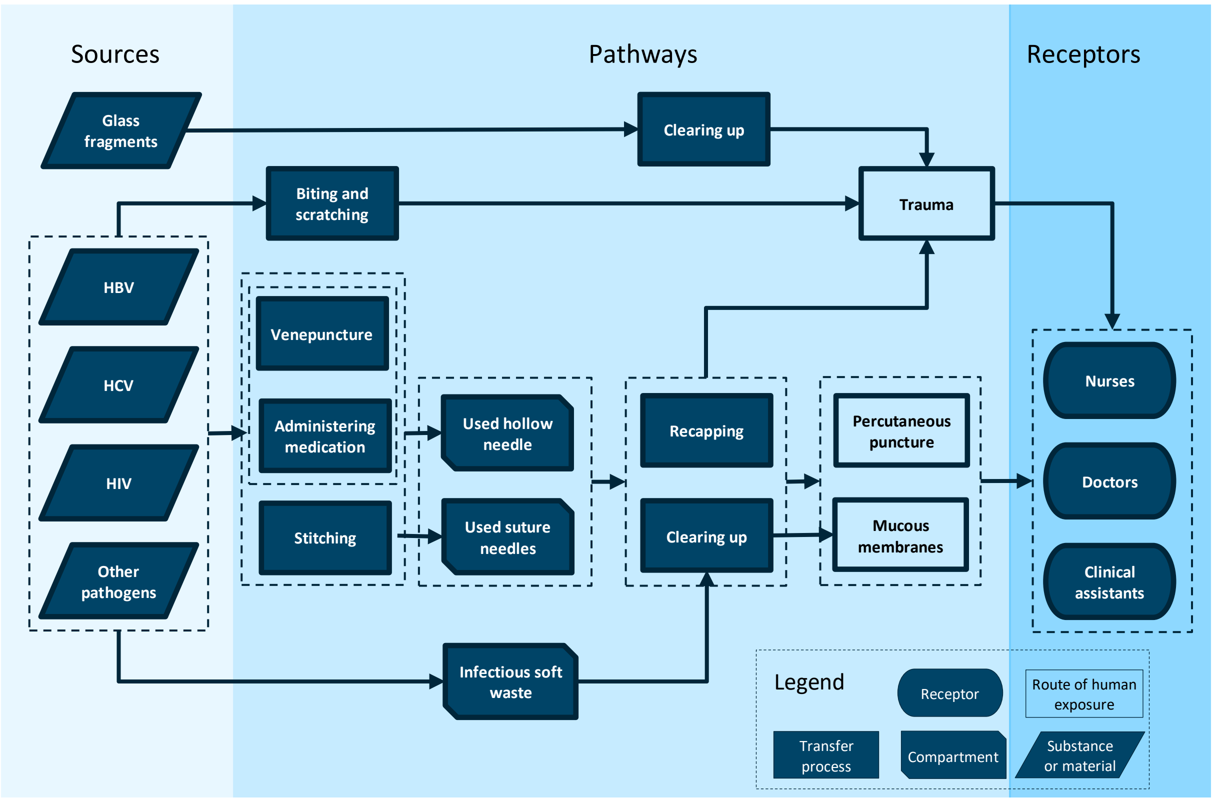


Figure 11: Hazard exposure conceptual model (source–pathway–receptor) associated with medical waste at the point of generation phase.

Other less common pathogens are reported by NHS Employers (2015) and are summarised in **Table 3**. However, the studies reviewed here did not report exposure or risk of exposure to these pathogens, which may denote a gap in other relevant research efforts.

Table 3: List of less common blood-borne pathogens other than hepatitis B virus (HBV), hepatitis C virus (HCV) and human immunodeficiency virus (HIV) which are transmissible through needlestick injuries; after NHS Employers (2015).

• Human tlymphotrophic retroviruses (HTLV I & II)	• Parvovirus B19
• Hepatitis D virus (HDV or delta agent, which is activated in the presence of HBV) hepatitis G virus (GB virus or GBV-C)	• Transfusion Transmitted virus (TTV)
• Cytomegalovirus (CMV)	• West Nile virus (WNV)
• Prion agents such as those associated with transmissible spongiform encephalopathies (TSE)	• Malarial parasites
	• Epstein-Barr virus (EBV)

The terms 'sharps injury' and 'needlestick injury' are often used interchangeably by some authors and as separate, distinct categories by others. For clarity, here we report using the following definitions adapted from the Canadian Centre for Occupational Health & Safety (2020):

- **Needlestick injuries** include all injuries that involve hollow needles for percutaneous removal or addition of fluids. Examples of hollow needles include fixed syringe or winged steel needles (butterfly).
- **Sharps injuries** involve all other injuries excluding hollow needles. Examples include injury by glass shards, suture needles and safety pins.

While every effort was made to convey the findings of the reviewed studies using the above definitions, in several occasions where the terms were ill defined in the original text and therefore it is likely that there are occasional incidences where categories have overlapped, but it has not been reported as such.

4.2. Sharps and needlestick injuries to healthcare workers (HCW)

Nine studies reviewed in our research reported rates of injury or prevalence of sharps and needlestick injury to healthcare workers at the point of waste generation (**Table 4**). The review carried out by Elder and Paterson (2006) standardised findings from multiple studies on the basis of the number of exposures to sharps and needlestick injuries per 100 person years. While this standardisation was a helpful comparison within the paper, other authors reported on the basis of prevalence in the past 12 months of working life; that is whether a worker had experienced a single exposure or not over that timeframe.

Table 4: Needlestick injury rate and prevalence* among healthcare workers.

Ref.	Year	Context	Summary method	Exposed workers	Clinical /non/ both	Type of injury	12 month prevalence* Mean	12 month prevalence* 95% CI	Lifetime prevalence* Mean	Lifetime prevalence* 95% CI	Injury rate per 100 person years
Auta et al. (2017)	2017	Western Africa	Meta-analysis (n=65) of occupational exposure to body fluid, mainly through percutaneous injury (2002 - 2017)	Healthcare workers [c]	Clinical	Blood and bodily fluid exposure incl. needlestick (95% CI)	47.93%	31.52–64.33	56.68%	37.2-76.17	
		Central Africa					51.68%	37.52–65.84	68.01%	44.89-91.13	
		Eastern Africa					47.29%	36.66–57.92	67.98%	59.06-76.9	
		Southern Africa					33.92%	16.48–51.36	61.07%	48.35-73.79	
		Northern Africa					60.70%	56.89–64.51	82.9%	70.55-95.24	
		Africa (overall)					47.96%	40.65–55.27	65.66%	59.69-71.64	
		Africa 2000-2009[d]					49.7%	42.8–56.6			
		Africa 2010-2017[d]					47.8%	34.5–61.1			
		Western Africa				Needlestick (95% CI)	35.98%	24.43–47.52	52.91%	45.7-60.12	
		Central Africa					55.00%	48.41–61.59			
		Eastern Africa					33.26%	28.54–37.98	53.07%	43.59-62.56	
		Southern Africa					16.40%	10.64–22.16	67.89%	64.76-71.02	
		Northern Africa					47.92%	32.63–63.22			
		Africa (overall)					35.97%	31.15–40.79	54.35%	48.4-60.31	
		Africa 2000-2009[d]					39.2%	31.6–46.9			
		Africa 2010-2017[d]					31.5%	28.1–34.9			
World Health Organization (2017a)	2017	LKA	Survey at hospital	Doctors, nurses, support staff (n=121)	Both	Needlestick	54%				
Kosgeroglu et al. (2004)	2003	TUR	Survey at three hospitals over six months	Nurses (n=595)	Both	Needlestick			56.4%		
						Sharps			20%		
Enwere and Diwe (2014)	2014	NGA	Knowledge assessment of injection safety	HCW (n= 156) [e]	Both	Needlestick			50.6%		
Mercier (1994)	1994	GBR	All HCW (n=4,000)	Nursing	Both	Needlestick and sharps	3.33%				5.15[f]
				Medical			6.25%				
				Medical student			5.88%				
Elmiyeh et al. (2004)	2004	GBR	Clinical healthcare professionals surveyed	Doctors (n=125); nurses (n=175)	Clinical	Needlestick	38%		57-74%[e]		74 [f]
Astbury and Baxter (1990)	1990	GBR		Healthcare workers (n=1,800)	Clinical	Needlestick and sharps [g]	32%				116 [f]
	1994	GBR		Medical students	Clinical	Needlestick			22%		

Ref.	Year	Context	Summary method	Exposed workers	Clinical /non/ both	Type of injury	12 month prevalence* Mean	95% CI	Lifetime prevalence* Mean	95% CI	Injury rate per 100 person years
Cossart and deVries (1994)			Survey of medical and dentistry students; nurses	Dentistry students					72%		
				Nurses (medical)					17%		
				Nurses (surgical)					42%		
				Doctors (medical)					57%		
				Doctors (surgical)					100%		
				Emergency staff					50%		
Elder and Paterson (2006)	nd			All HCW and support staff							1.8
	2002			All HCW and support staff							4
	2003			All HCW and support staff							3.66
	2004			All HCW and support staff	Both						0.78
	1995			Occupational health staff	Both						0.9–4.4
	1992			Medical students (n=275)							30
	1990			Medical students (n=151)							65
	2002			Dental students (n=183)							38
	1993	GBR	Review of needlestick injury research	Operating department staff (n=158)	Clinical	Needlestick and sharps					284

* Unless specified, is the mean proportion of workers who have experienced one exposure over the time period; [a] collecting waste from producer premises and returning to depot for handling and onward processing; [b] exposure was reported as 1 per 29,000 man hours, adjusted for comparability on the basis of 1,864 working hours per annum; [c] category includes nurses, doctors, auxiliary healthcare workers, students undertaking clinical training or gaining experience; [d] pooled results; [e] nurses (62.8%); waste handlers (11.5%); ward assistant (12.2%); doctors (8.3%); lab scientists (5.1%); abbreviations: healthcare workers (HCW); confidence interval (CI); [e] rate reported in results does not match the abstract so both reported; [f] Calculated by Elder and Paterson (2006); [g] incl. scratches and bites. Abbreviations: healthcare workers (HCW); confidence interval (CI)

The Elder and Paterson (2006) review found a large range (0.78–284 injuries per 100 person years) of reported injury rates, and suggested that this may be a result of reporting inconsistencies and variations in reporting rate. Closer inspection reveals that the much higher rates of injury were reported when the denominator is workers who are more likely to experience direct exposure to used hollow needles. For instance, the operating department staff showed a rate of 284 injuries per 100 person years, whereas when data is reported for the whole hospital staff, or occupational health staff, rates of injury were within the range of 0.78-5.15 injuries per 100 person years, including Mercier (1994). Needlestick injury data reported for clinical staff by Elmiyeh et al. (2004), Astbury and Baxter (1990) were 74-116 per 100 person years and for students, the rate was slightly lower at 30-65 per 100 person years (Elder and Paterson, 2006), reflecting the level of clinical involvement of each group.

Auta et al. (2017) reviewed 65 studies across Africa on the basis of prevalence of injury over 12 months or the lifetime of healthcare workers, finding a mean 12 month prevalence of 35.97% (CI 95%: 31.15-40.79%) and mean lifetime prevalence of 54.35% (CI 95%: 48.4-60.31%). These data are a similar range to those reported in other LIMICs such as World Health Organization (2017a) in Sri-Lanka, Kosgeroglu et al. (2004) in Turkey and Enwere and Diwe (2014) in Nigeria. However, they are also similar to those reported in the UK: Elmiyeh et al. (2004), Astbury and Baxter (1990) report 38% and 32% prevalence over 12 months, respectively.

Several other correlations can be observed between income level and prevalence of needlestick and sharps injuries among HCWs. For instance, the prevalence of these type of injuries in Southern Africa (Auta et al., 2017) are lower than those for poorer parts of Africa and in a similar range to those reported in Great Britain (Astbury and Baxter, 1990; Elmiyeh et al., 2004). There is also evidence of a reduction in prevalence over time in the first and second decades of the 21st century, as reported by Auta et al. (2017).

Three authors highlight considerable under-reporting rates of exposure to needlestick and sharps injury of between 22% and 58.3% (**Table 5**). The obvious implication is that considerably more HCWs may experience needlestick and sharps injury than incident reporting data suggest; indicating that the reported rates of injury may need to be adjusted by between 30% and 50% to estimate exposure to the HCW population.

Table 5: Reporting rates of needlestick and sharps injury.

Ref.	Worker	Reporting rate
Mercier (1994)	All HCW	58.3%
Elmiyeh et al. (2004)	Clinical	51%
	Doctors	28%
	Nurses	44%
	Dentistry students	45%
	Medical students	22%
Cossart and deVries (1994)	Emergency staff	47%

Abbreviations: healthcare workers (HCW)

Survey data may be more reliable in comparison to incident reporting data as it does not rely on the volition of HCWs toward completing an incident report. However, surveys of people's historical experiences are subject to recall bias, which may over or under inflate the results. Furthermore, the probability that a HCW will participate in a survey may also be commensurate with propensity to complete incident reports, meaning that part of the workforce may always remain under-represented.

While the prevalence of sharps injuries, including non-reported rates, provide insight into the potential hazard exposure, they do not indicate risk of infection from blood-borne viruses that are the principle hazard aside from localised trauma (NHS Scotland, nd). While it is acknowledged that other pathogens may be contracted through needlestick injuries, the main infection risks are considered to be HCV, HBV and HIV. The global probability of infection by these three viruses has been modelled by Prüss-Üstün et al. (2005) who estimated potential exposure incidents at: HBV: 926,000 (upper estimate 340,000; lower estimate 1,490,000); HCV: 2,100,000 (770,000 to 3,300,000); and HIV: 327,000,000 (61,000 to 1,300,000).

The most notable number of potential exposures identified in Prüss-Üstün et al. (2005) is the very high number reported in the West Pacific region for HBV (**Figure 12**). This results from a combination of a mid-range estimate of the number of sharps injuries per healthcare worker per year in China and the marginal sea states to its south, as well as the very large population in that region and hence number of healthcare workers. Furthermore, rates of HBV infection are high in this region, which increases the likelihood of needles containing the pathogen.

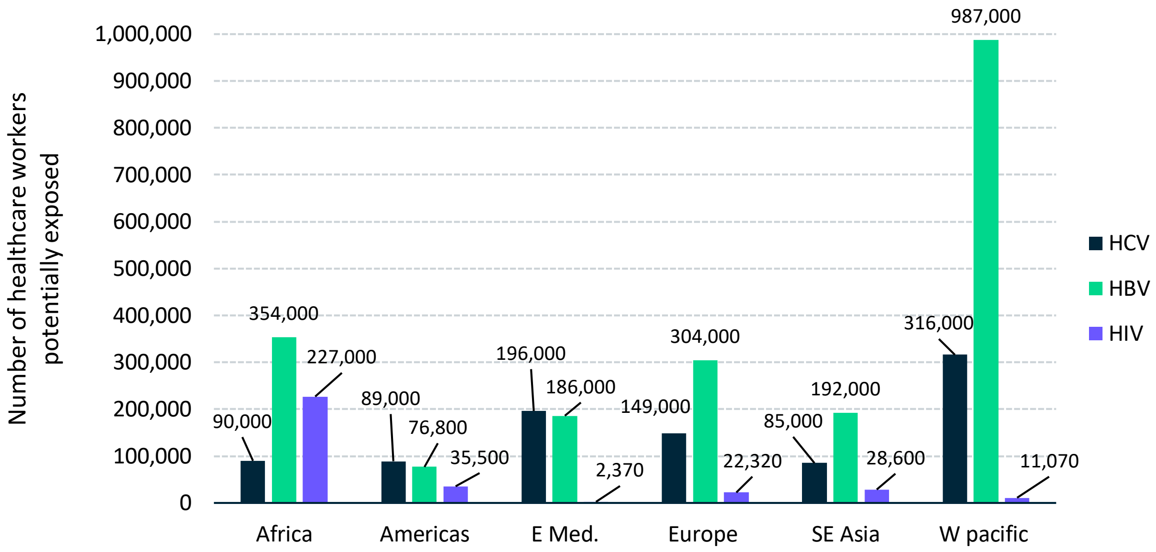


Figure 12: Number of healthcare workers potentially exposed to hepatitis C (HCV), hepatitis B (HBV) and human immune deficiency virus (HIV) through needlestick injuries in World Health Organization Regions (**Section S.4**); data after Prüss-Üstün et al. (2016); Prüss-Üstün et al. (2005). HBV prevalence amongst healthcare workers in Western Pacific is very high as a reflection of large population and high population prevalence of the infection.

Potential HIV exposures were low in most regions, except Africa where the population level of HIV infection is much higher than in other regions (World Health Organization, 2019b) (**Figure 12**). The number of modelled HIV infections (**Figure 13**) is broadly proportional to the number of exposures (**Figure 12**) and much lower as HIV has a very low risk of transmission (0.3%) compared to HCV (3%) and HBV (33%) (Cheng et al., 2017). However, the level of HBV infection is not proportional to the modelled exposure in the Americas, Eastern Mediterranean and Western Pacific regions. No mention is made of this by Prüss-Üstün et al. (2005); however, we suggest that this may be a consequence of a higher rate of prophylactic administration and also vaccination in , which historically has been much higher (49% to 93%) than the global average (30% to 85%) since 2000 (World Health Organization, 2019a).

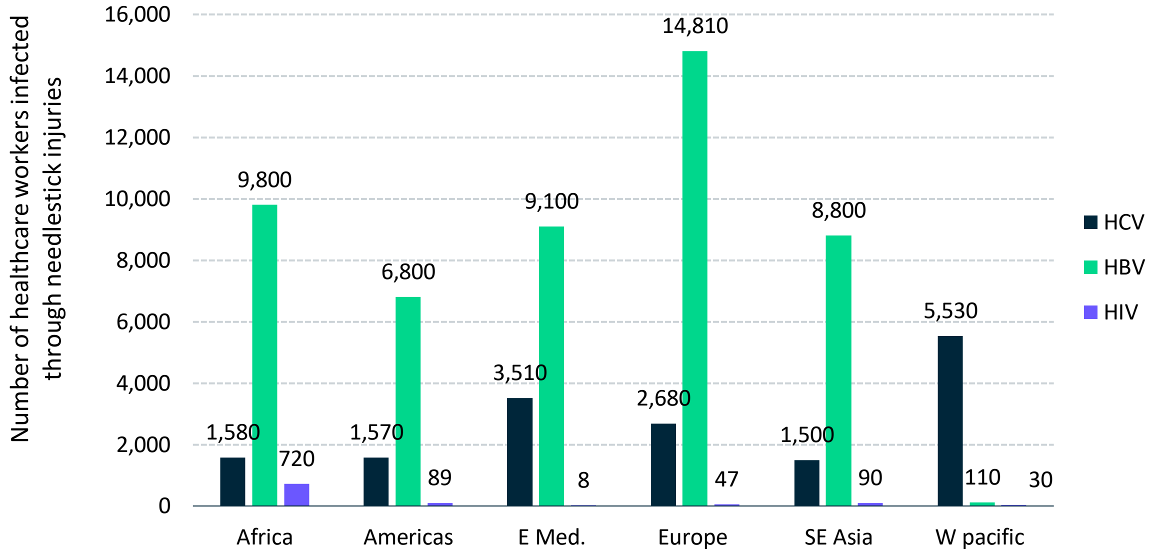


Figure 13: Number of healthcare workers infected with hepatitis C (HCV), hepatitis B (HBV) and human immunodeficiency virus (HIV) through needlestick injuries in World Health Organization Regions (see **Section S.4**); data after Prüss-Üstün et al. (2005). Although exposure to HBV is highest in Western Pacific (**Figure 12**), numbers of infected individuals are very small, possibly reflecting the high rate of historical immunisations compared to the global average (World Health Organization, 2019a).

Overall, Prüss-Üstün et al. (2005) estimated that between 2,000 and 2,030 infections from needlestick and sharps injuries to healthcare workers will result in approximately 1,142 (268 to 5,267) early deaths as follows: HCV 145 (53 to 766); HBV 261 (86 to 923) and HIV 736 (129 to 3,578). Their research highlights several uncertainties, particularly with the transmission potential of the viruses, and acknowledges the absence of data in some regions, which has been approximated using data from similar countries. Importantly, Prüss-Üstün et al. (2005) highlighted the fact that needlestick infections are largely preventable through a range of measures. For instance, immunisation of workers from HBV has an efficacy of 80% to 95% (Cheng et al., 2017), which if implemented at scale could be effective against infections contracted by approximately 40,000 per year.

4.3. Activity context: where healthcare workers experience sharps and needlestick injuries

Targeting interventions to reduce the incidences of needlestick and sharps injuries requires greater understanding of the context in which they occur. Two papers (Mercier, 1994; Nagao et al., 2007) reported the location in which sharps and needlestick injuries occurred among hospital healthcare workers (**Figure 14**). Unsurprisingly, they were most prevalent in clinical areas, with more than 50% reported on hospital wards. While these provide a useful indication of where to focus efforts to mitigate the likelihood of future injury, the data appear to reflect the level of activity. We suggest that further studies could focus efforts to determine the rate of injury per procedure, which might help to identify the circumstances in which the highest rates of injury occur.

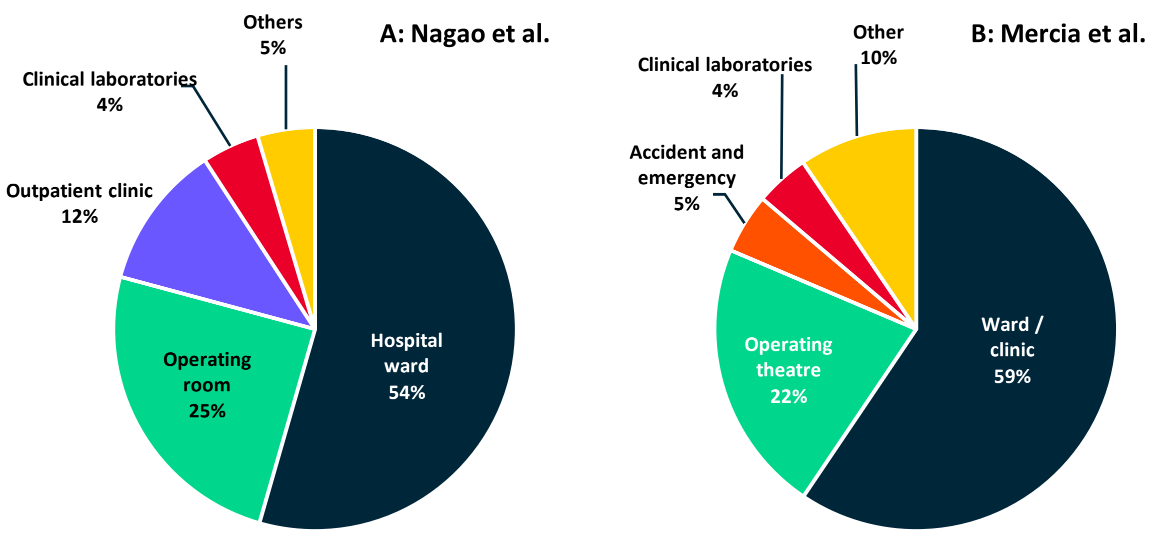


Figure 14: Location of sharps injuries reported (**A**)*: in Japan by Nagao et al. (2007); and **(B)** in the UK by Mercier (1994). *Sharps injuries were recorded over seven years at a hospital employing 1,346 healthcare workers and with 1,051 beds.

Three studies (Cullen et al., 2006; Nagao et al., 2007; World Health Organization, 2017a) reported the type of activity being carried out when needlestick and sharps injuries took place (**Figure 15**). The lack of compatibility between the categories makes comparisons challenging, although several patterns can be observed. For instance, World Health Organization (2017a), Cullen et al. (2006) and Nagao et al. (2007) (doctors) observed that approximately 50% to 73% of injuries occurred during a procedure. For nurses in Japan, the proportion of injuries during a procedure was much lower and the proportion sustained during clearing up was higher. No reason was suggested by Nagao et al. (2007) for the disparity between doctors and nurses however we speculate that either doctors carry out more procedures than nurses or that doctors are more careless. Both World Health Organization (2017a) and Cullen et al. (2006) observed 11% and 4% of injuries taking place after sharps had been discarded, but it is noteworthy that the studies did not explicitly include medical waste handlers, which may mean that downstream injuries were not captured in the research.

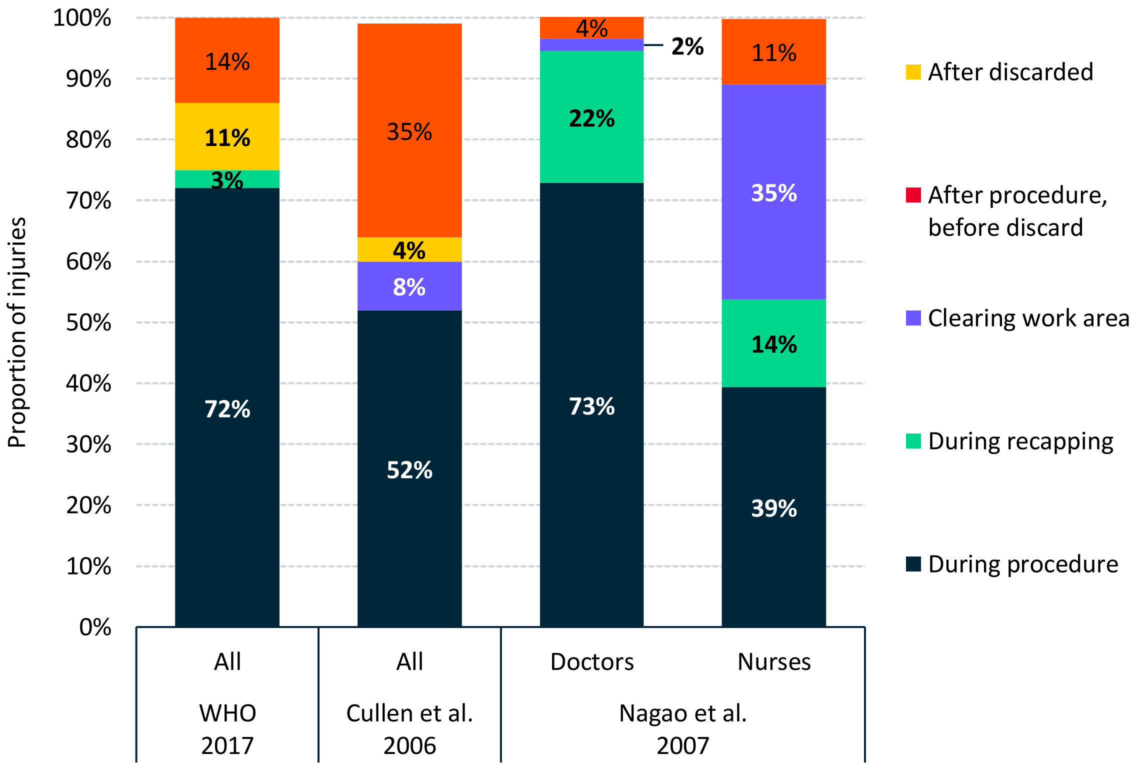


Figure 15: Proportion of needlestick and sharps injuries occurring by activity (Cullen et al., 2006; Nagao et al., 2007; World Health Organization, 2017a). Some categories reported were merged for comparability. Cullen et al. (2006) does not sum to 100% due to rounding. Needlestick injuries were most prevalent during a procedure across all studies. In the hospital in Japan studied by Nagao et al. (2007), more injuries took place during procedures for doctors compared to nurses, which we speculate may be a result of different roles or differing levels of diligence.

We compare four studies (Cullen et al., 2006; Nagao et al., 2007; Woode et al., 2014; World Health Organization, 2017a) reporting the procedural phase at which needlestick and sharps injuries occur (**Figure 16)**. Two of these (Cullen et al., 2006; Nagao et al., 2007) show data already presented in **Table 5** that is harmonised by procedural phase. World Health

Organization (2017a) shows broad alignment with the other two, showing ca 45% of injuries occurring during procedures, however the age of the study. The exception is suture needle injuries reported by Nagao et al. (2007), which took place during use in more than 75% of all cases on average (data not shown). A comparatively recent study by Woode et al. (2014) reported a broadly similar pattern to the other three studies in that the procedural phase showed the highest prevalence of needlestick injuries. The higher rate of prevalence amongst dental health professionals during the period just after use but before disposal indicates a lack of procedural adherence during that phase, specific to dentistry.

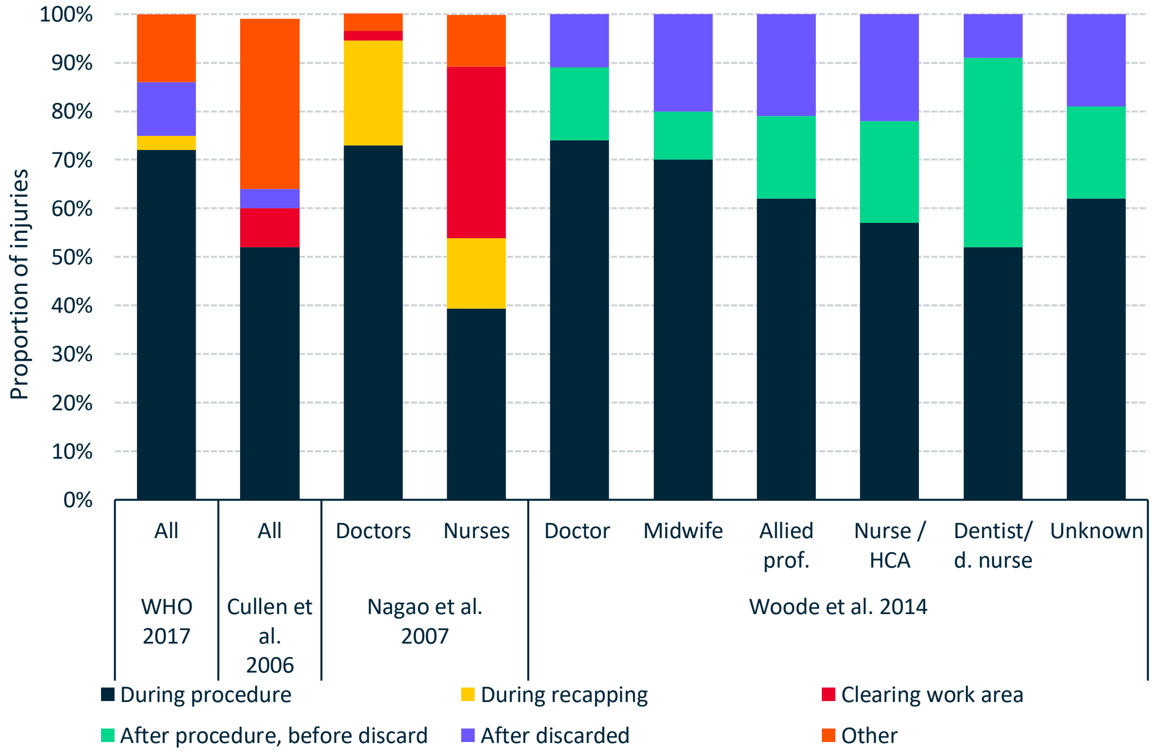


Figure 16: Procedural phase during which injury occurred reported by Cullen et al. (2006), Nagao et al. (2007), World Health Organization (2017a) and Woode et al. (2014). The majority of injuries with suture needles appear to occur during use in comparison to hollow needles which show a higher proportion post-use.

Both fixed syringe and winged (butterfly) needles resulted in considerably higher prevalence of injury after procedures had taken place (data not shown), but before the devices were discarded (**Figure 16**). We speculate that this difference could highlight an opportunity for a reduction in injury rate by providing portable rigid sharps containers and enforcing adherence to guidance to deposit sharps immediately following a procedure. The number of injuries taking place after being discarded was low, 6% (Cullen et al., 2006) to 11% (World Health Organization, 2017a), in comparison to other procedural phases.

4.4. Risk characterisation for medical waste hazards at the point of generation

The semi-quantitative risk assessment for medical waste during the waste generation phase focused solely on infection from HIV, HBV and HCV from used medical sharps: rationale and justification for scoring is detailed in **Table 6**. The risk assessment is based largely on data already modelled by Prüss-Üstün et al. (2016) that estimated global exposure, infection and death rate in HCWs for HIV, HBV and HCV through needlestick and sharps injury. We assess that the risks to workers in HICs are comparatively low, because they are less likely to experience injury, the population level of infection is much lower, access to prophylactic treatment is more likely, and treatment of infection results in better outcomes. The highest risk of contracting HBV is scored very high, because of greater prevalence of the disease among the LIMIC populations and higher likelihood of infection in LIMIC hospitals where safe systems of work are often not comprehensively implemented.

Table 6: Risk characterisation summary for medical waste hazards during the waste generation phase.

Haz.	Pathway	Receptor	Geog.	Evidence and justification for risk assessment	Uncertainty (aleatoric and epistemic)	Receptor vulnerability	L	S	R	Global receptor context
HIV	Medical sharps	HCW	LKA, TUR, NGA, GBR, all Africa global	• Prevalence of sharps and needlestick injuries strongly evidenced in HICs and LIMICs (Astbury and Baxter, 1990; Auta et al., 2017; Cossart and deVries, 1994; Elder and Paterson, 2006; Elmiyeh et al., 2004; Enwere and Diwe, 2014; Kosgeroglu et al., 2004; Mercier, 1994; World Health Organization, 2017a). • Exposure and infection rate modelled for HIV, HBV and HCV (Prüss-Üstün et al., 2016). • Death rate between 2000 and 2030: 1,142 (268 to 5,267) and early deaths as follows: HCV 145 (53 to 766); HBV 261 (86 to 923) and HIV 736 (129 to 3,578) (Prüss-Üstün et al., 2016). • The prevalence of blood-borne viruses is unacceptable, but the rate of infection and deaths in HICs is low compared to LIMICs where rates are commensurate with general population levels of infection. • HIV has a very low risk of transmission (0.3%) compared to HCV (3%) and HBV (33%) (Cheng et al., 2017).	• Evidence that many reported needlestick exposure events are underestimated (Cossart and deVries, 1994; Elmiyeh et al., 2004; Mercier, 1994).	• Lack of procedural adherence common in HICs and LIMICs (Akpieyi et al., 2015; Cullen et al., 2006; Rice et al., 2015). • Many workers carrying out procedures without PPE, particularly in LIMICs (Kosgeroglu et al., 2004) but also in HICs.	1	4	**4**	HIC
							2	5	**10**	LIMIC
HBV							2	3	**6**	HIC
							4	4	**16**	LIMIC
HCV							2	3	**6**	HIC
							3	4	**12**	LIMIC

Abbreviations: Geographical research context (geog.); likelihood (L); severity (S); risk (R); hazard being assessed (Haz.); personal protective equipment (PPE); high income country (HIC); low income and middle income countries (LIMIC); hepatitis C virus (HCV); hepatitis B virus (HBV); human immunodeficiency virus (HIV).

5. Challenge 2: Storage, collection and handling phase

5.1. Context

As with the point of waste generation phase, the hazards associated with medical waste at the storage, collection and handling phase stem from pathogens that exist within the bodies of those receiving healthcare (**Figure 17**). Again, the pathways through which those pathogens may reach other people involve them being carried through medical devices, which can pierce the skin of those who come in to contact with them or enter mucous membranes through direct handling.

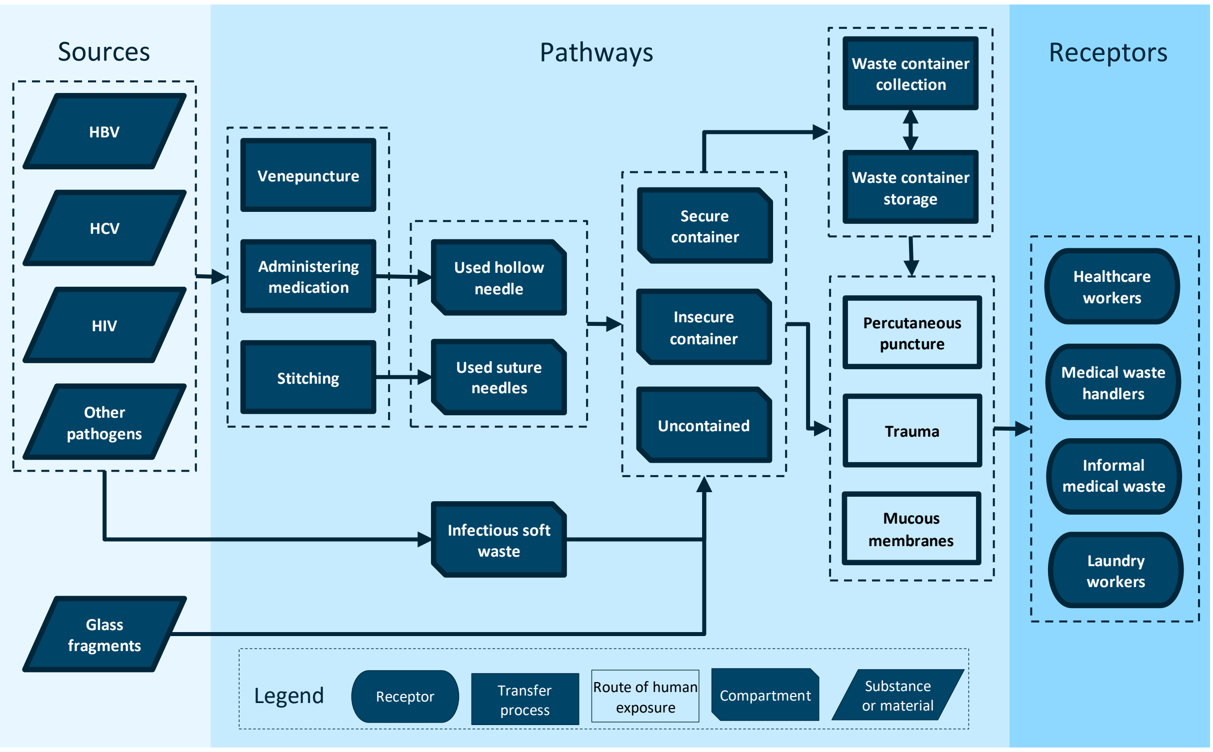


Figure 17: Hazard exposure conceptual model (source–pathway–receptor) associated with medical waste during the storage, collection and handling phase. Abbreviations: hepatitis C virus (HCV); hepatitis B virus (HBV); human immunodeficiency virus (HIV).

As with the medical waste generation phase, health care workers (HCWs) are also at risk of infection during the storage, collection and handling phase, if they become involved with the handling of contained or uncontained discarded medical waste. However, it is the medical waste handlers (MWHs) who are most exposed to infection during this phase, because they are inherently more likely to come into contact with it. Informal waste workers are also at risk of infection during this phase, whether through deliberate contact because of involvement with the illicit trade in reused medical equipment when collecting it for reprocessing, or indirectly when they are exposed to medical waste whilst they hunt for other valuable materials.

5.2. Sharps and needlestick injuries to medical waste handlers (MWH)

We identified six papers (Amsalu et al., 2016; Anagaw et al., 2012; Mol et al., 2016; Shiferaw et al., 2012; Yizengaw et al., 2018) that reported on the prevalence of pathogen exposure to medical waste handlers (MWHs) through sharps and needlestick injuries (**Table 7**). Three of these papers surveyed MWHs working in hospitals in Ethiopia, one in Sudan, and one in Brazil, finding a 12 month prevalence of between 33.3% and 75% in workers and a lifetime prevalence of 27% to 47.4%. The ranges were broadly in line with those reported for injury prevalence to HCWs at the point of generation (**Table 4** and **Table 5**), with the exception of one further study (Yizengaw et al., 2018) of MWHs working in Ethiopian hospitals for whom an 18.6% prevalence was observed.

Table 7: Needlestick injury rate and prevalence among medical waste handlers (MWH).

Ref.	Context	Exposed workers	Location	Type of injury	12 month prevalence*	Lifetime prevalence*
Shiferaw et al. (2012)	ETH	MWH[b]	Inpatients	Sharps	34.2%	
			Emergency		33.3%	
			Operating rooms		45%	
			Laboratory		50%	
			Delivery		50%	
			Laundry		46.7%	
			On-site storage		53.3%	
			Total		42.1%	
			Inpatients	Bloodstained bodily fluid exposure to mucous membranes	71.1%	
			Emergency		55.6%	
			Operating rooms		75%	
			Laboratory		75%	
			Delivery		75%	
			Laundry		60%	
			On-site storage		60%	
			Total		67.5%	
Amsalu et al. (2016)	ETH	MWH (n=152)		Sharps		47.4%
Anagaw et al. (2012)	ETH	MWH (n=100)				43%
Yizengaw et al. (2018)	ETH	HCW (n=268) MWH (n=130)		Needlestick		18.6%
Mol et al. (2016)	BRA	DWW (n=461)		Needlestick/cuts		53.9%[a]
		MWH (n=61)		Needlestick/cuts		75%[a]

Ref.	Context	Exposed workers	Location	Type of injury	12 month prevalence*	Lifetime prevalence*
Elya and Babiker (2015)	SDN	MWH (n=52)		Injury (assumed needlestick)		27%

* Unless specified, is the mean proportion of workers who have experienced one exposure over the time period; [a] participants were asked to respond with the type of accident they last had; [b] medical waste handlers (n=126) surveyed three hospitals in 2010 to assess injury rates and attitudes to personal protective equipment (PPE); abbreviations: medical waste handler (MWH); healthcare worker (HCW); domestic waste handler (DWH).

The high prevalence of needlestick injuries experienced by waste workers surveyed in Ethiopia is concerning, given the higher than average rates of blood-borne virus infection among the Ethiopian population (**.**

Table 8). Brazil has more comparable HIV and HCV prevalence with many HIC countries, but the prevalence of HBV is similar to Ethiopia and many other African countries (Benzaken et al., 2019).

Table 8: Individuals infected as a proportion of population (data for most recent reported year shown); selected countries shown for comparison.

Country/ region	HIV		HCV		HBV	
	Proportion	Ref.	Proportion	Ref.	Proportion	Ref.
Ethiopia	5.2%	Belyhun et al. (2016)	3.1%-11%	Belyhun et al. (2016)	7.4%	Belyhun et al. (2016)
Brazil	0.5%	UNAIDS (2018a)	0.53%	Benzaken et al. (2019)	2-8%	Souto (2016)
Western Europe			≤0.5%	Kretzer et al. (2014)		
United States	0.4%	UNAIDS (2018b)	1.7%	Hofmeister et al. (2019)	0.4%	Kim (2009)
France	0.3%	UNAIDS (2018b)			1.4%	European Centre for Disease Prevention and Control (2016)
United Kingdom					0.0%	European Centre for Disease Prevention and Control (2016)

Abbreviations: hepatitis C virus (HCV); hepatitis B virus (HBV); human immunodeficiency virus (HIV)

Only one HIC context study (Blenkharn and Odd, 2008) was identified which analysed accident and injury records over three and a half years at three medical waste collection and storage premises, employing 85 waste handlers collectively. The study reported needlestick and sharps injury frequency of 1 per 29,000 man-hours or 6.45 injuries per 100 person years. Interestingly, the paper also reported the site of injury, finding injuries not only occurred to hands (n=24), but also the legs (n=11) and bodies of MWHs (Figure 18). The contractors who participated in the study were responsible for collecting waste from hospitals and 'surgeries' (local doctor's practice), which is where the 90% (36/40) of reported injuries occurred. Of the 40 injuries reported over the study period, the research found that 15% were caused by incorrect or inadequate closure of sharps containers and 85% were the result of sharps being discarded in sacks intended for soft waste.

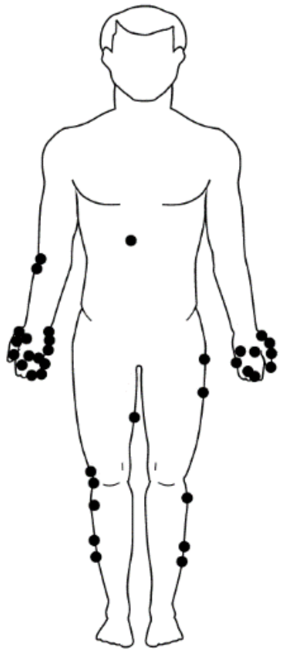


Figure 18: Sharps injuries to medical waste handlers, by position on the body; after Blenkharn and Odd (2008) (permission sought for reproduction).

Shiferaw et al. (2012) also reported the causes of sharps injuries among MWHs in hospitals in Ethiopia, finding that 19% of survey respondents reported that incidents of sharps and needlestick injury were due to inadequately closed sharps containers (insufficient containment) and approximately 81% reported that sharps were placed in bags or sacks intended for soft waste. (**Figure 18**). As the study by Shiferaw et al. (2012) was a cross-sectional self-reported survey, and Blenkharn and Odd (2008) was a longitudinal study based on incident reports, caution should be taken when directly comparing the two datasets, as they were not collected and reported on the same basis.

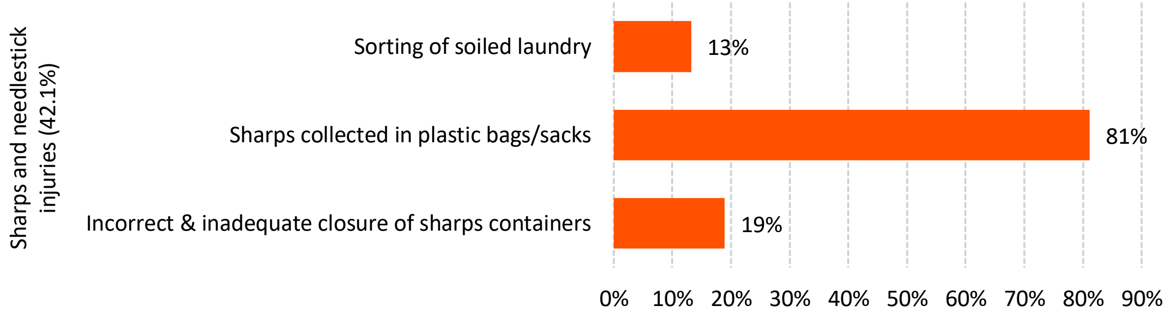


Figure 18: Self-reported incidents of causes of injuries among medical waste handlers (MWHs) in hospitals in Ethiopia; data after Shiferaw et al. (2012).

Further evidence of sharps being discarded in flexible sacks rather than rigid sharps boxes was reported by Kanisek et al. (2018) who carried out compositional analysis of infective medical waste discarded in sacks (n=50) in Croatia. The study found sharps content at a rate of 30 g per five days (14.5-74.5) at 'family practices' (local doctor's practice) and 11 g per five days (1-18) at dental practices. The inclusion of these items in soft waste, indicates almost routine non-adherence to safe working practices; threatening the safety and lives of MWHs.

Speculatively, MWHs may have an expectation that sharps will be present in some bags designed for soft wastes and therefore have the opportunity to modify their own practices to avoid exposure. However, this expectation may be less prevalent in hospital laundry sorters, 13% of whom reported sharps injuries during their work in the study by Shiferaw et al. (2012) (**Figure 18**). Injuries from sharps arising in laundry is particularly worrying, as it indicates that sharps had either been discarded with the laundry in error or had not been discarded at all and ended up there accidentally.

Despite the obvious risk of exposure to MWHs from needlestick and sharps injuries, Blenkharn and Odd (2008) found that ballistic protection gloves were not worn in 55% (22/40) of the incidents reported at the three medical waste handling facilities studied, including two incidents where no gloves were worn at all. While Blenkharn and Odd (2008) reported lack of ballistic glove use in reported sharps injuries, Shiferaw et al. (2012) reported ballistic glove use rate for exposed and non-exposed MWHs, finding gloves were not used by 20.6% of MWHs. Both Franka et al. (2009) and Shiferaw et al. (2012) also noted differences between prevalence of glove use between male and female MWHs, finding men less likely to wear gloves than women in both studies (**Table 9**). While the data are scarce, if this pattern is observed elsewhere it would indicate that men may be at considerably greater risk of exposure due to their non-adherence to safe working practices.

Table 9: Comparison of the rate of use of ballistic protective gloves by sex.

Ref	Context	Male	Female	Total	Odds ratio	P
Shiferaw et al. (2012)	ETH	75%	81.4%	79.4%	0.921	0.410
Franka et al. (2009)	LBY	50.2%	88.1%	57.7%	7.37	<0.0000001

Exposure to blood-borne viruses is not limited to percutaneous injury, but can also occur through exposure of blood to mucous membranes. Shiferaw et al. (2012) reported the prevalence of this type of exposure to be higher (67.5%) than needlestick injuries (42.1%) among MWHs, although the statistical significance of this difference was not calculated (**Figure 19**).

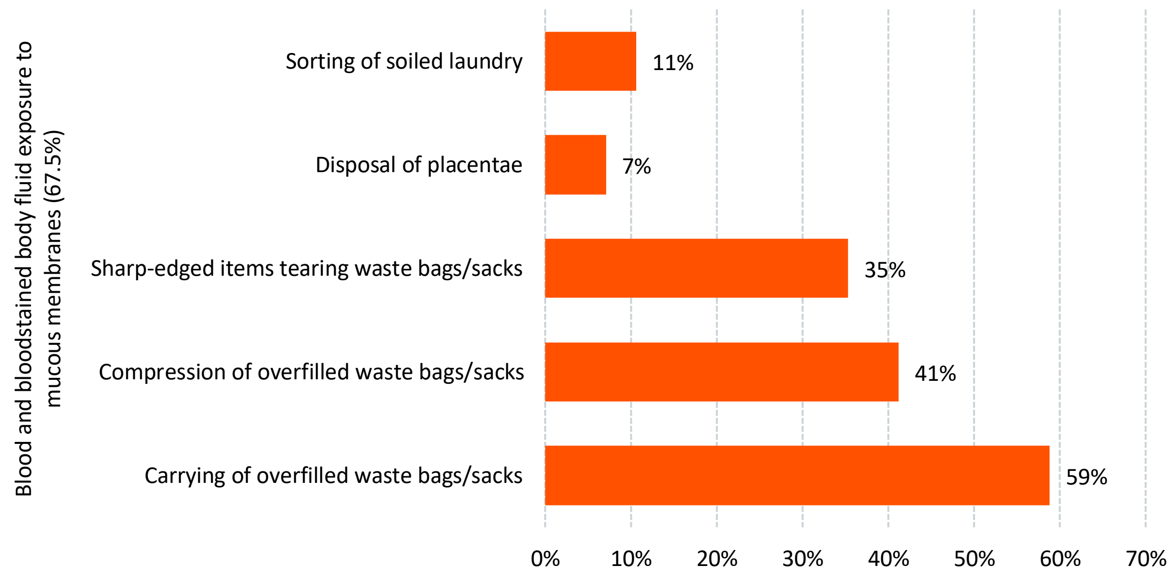


Figure 19: Self-reported incidents of exposure to mucous membranes by blood and bodily fluids by activity among medical waste handlers (MWHs) in hospitals in Ethiopia, after Shiferaw et al. (2012). Overfilled or poorly handled bags were a factor in the majority of mucous membrane exposures.

Whereas sharps and needlestick injuries were the most prevalent injury to MWHs reported by seven of the authors reviewed here, there are several injury categories in which MHWs may experience lower prevalence compared to other waste workers. For instance, Mol et al. (2016) compared injuries experienced by MWHs with domestic waste collection workers finding that the latter experienced a lower prevalence of sharps and needlestick injury but higher prevalence of traffic related injury, fracture or lesion (**Figure 20**). Speculatively, these differences are unsurprising given that domestic waste collection workers spend more of their working day interacting with traffic, and less time handling waste with a high medical sharps concentration. However, the data are limited and further research is needed to understand the differences between these two exposure-resulting activities in different contexts; socio-economic, cultural or otherwise.

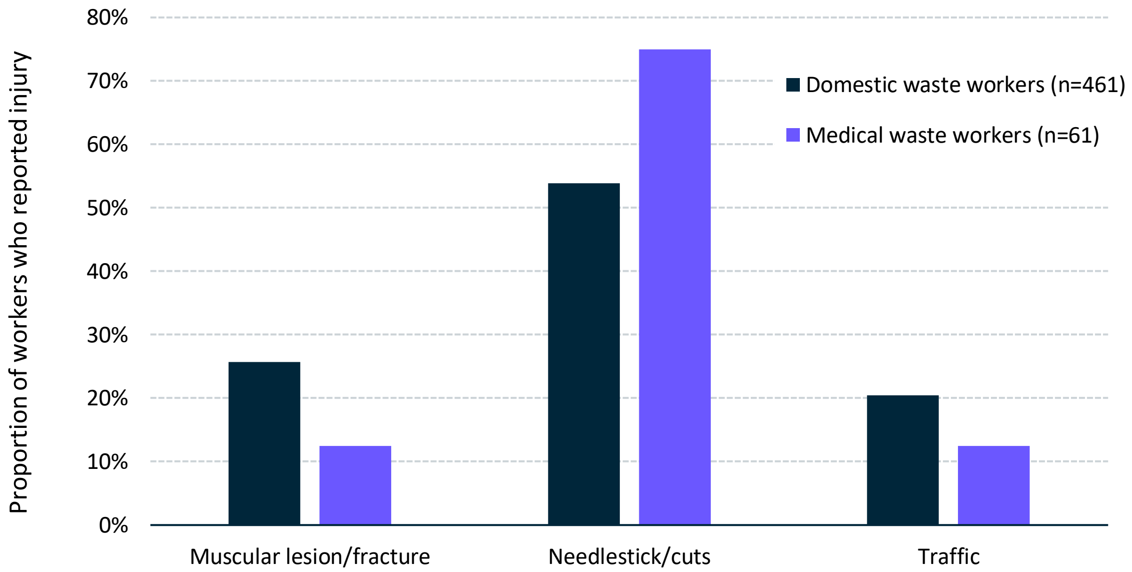


Figure 20: Comparison of injury types experienced by waste workers in Brazil, after Mol et al. (2016). Although needlestick injuries are highest amongst MWH in comparison to other waste workers, MHWs experience fewer road traffic accidents and muscular lesions or fractures.

5.3. Risk of infection to medical waste handlers (MHWs) from contaminated sharps

Two studies investigated the prevalence of blood borne virus infection among MHWs specifically. Franka et al. (2009) compared the rate of infection of MWHs with non-MWHs in Tripoli, Libya, finding the prevalence of HBV and HIV 7.14 (*p* <0.04) and 15.74 (*p*

<0.0004) times greater in MHWs compared to non-MWHs and significantly (*p* <0.005) higher incidents of HCV albeit at a very low rate of infection (0.3%).

Arafa and Eshak (2020) included the results from the study by Franka et al. (2009) in a meta-analysis of HBV prevalence among MWHs in different contexts between 1992 and 2018, finding a significantly (*p*=0.008) higher prevalence of HBV infection among MHWs (**Figure 21**). The study highlighted considerable heterogeneity between the results modelled by each author and suggested that small samples sizes, variation in sociodemographic characteristics, and cross-sectional study design may have been factors which contributed to this variation.

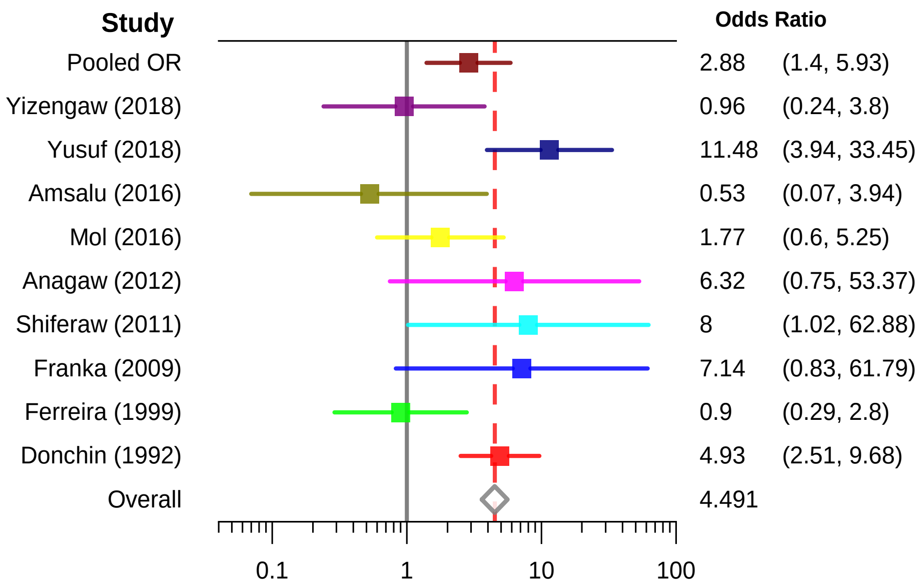


Figure 21: Studies that determined correlation between medical waste handling and hepatitis B (HBV), adapted from Arafa and Eshak (2020) (95% CI I2=61.36%, p=0.008). Abbreviations: odds ratio (OR) (permission sought for reproduction).

Analysis of sub-groups by Arafa and Eshak (2020) identified a greater probability of African MWHs being infected by HBV. Arafa and Eshak (2020) highlight that workers are at particular risk compared to their counterparts in HICs as they are less likely to be vaccinated against HBV; unlikely to have health insurance; and have limited knowledge about the use of PPE or the risks associated with injury from blood-borne viruses.

5.4. Risk characterisation during the storage, collection and handling phase

The semi-quantitative risk assessment shown in **Table 10** is a reflection of the number of

MWHs who may suffer infection from blood-borne viruses as a consequence of injuries from medical sharps sustained at work. The risk in HICs is estimated to be low for all viruses, partially as a consequence of the low infection rates among the population. The risk of HIV infection in HICs is the lowest risk compounded by the low transmission risk of 0.3% from needlestick injuries. HBV risk is estimated to be very high in LIMICs, as a consequence of the high rate of infection throughout the populations and also the strong likelihood of exposure through poor practices, equipment and training, which is endemic in many LIMICs.

Table 10: Risk characterisation summary for medical waste hazards during the collection, storage and handling phase.

<table>
<tr><th>Haz.</th><th>Pathway</th><th>Receptor</th><th>Geog.</th><th>Evidence and justification for risk assessment</th><th>Uncertainty (aleatoric and epistemic)</th><th>Receptor vulnerability</th><th>L</th><th>S</th><th>R</th><th>Global receptor context</th></tr>
<tr><td rowspan="2">HIV</td><td rowspan="6">Medical sharps</td><td rowspan="6">MWH</td><td rowspan="6">ETH, BRA, SDN, GBR, LBY, Global</td><td rowspan="6">• Prevalence of sharps and needlestick injuries among MWHs evidenced in LIMICs (Amsalu et al., 2016; Anagaw et al., 2012; Mol et al., 2016; Shiferaw et al., 2012; Yizengaw et al., 2018) but less so in HICs (Blenkharn and Odd, 2008).
• Speculatively, risk of exposure is lower in HICs as more stringent guidance, equipment and practices are in place to mitigate exposure.
• Specific concern that laundry workers suffer unexpected exposure to needles which have been discarded with bedding (Shiferaw et al., 2012).
• Speculatively, disposal of sharps in soft waste bags may be commonplace in some contexts, though only limited evidence was revealed (Kanisek et al., 2018).
• Risk of HBV infection compared in meta-analysis (Arafa and Eshak, 2020) indicated odds ratio of 2.88 for MWHs compared to general population.
• Risk of HIV and HCV was not calculated but it may be reasonable to assume it is on the same ratio as for HCWs.</td><td rowspan="6">• Evidence that many reported needlestick exposure events are underestimated (Cossart and deVries, 1994; Elmiyeh et al., 2004; Mercier, 1994)</td><td rowspan="8">• Lack of procedural adherence common in HICs and LIMICs (Kanisek et al., 2018)
• Some evidence of workers carrying out procedures without gloves, particularly in LIMICs (Franka et al., 2009; Shiferaw et al., 2012) but also in HICs (Shiferaw et al., 2012)</td><td>1</td><td>4</td><td>4</td><td>HIC</td></tr>
<tr><td>2</td><td>5</td><td>10</td><td>LIMIC</td></tr>
<tr><td rowspan="2">HBV</td><td>2</td><td>3</td><td>6</td><td>HIC</td></tr>
<tr><td>4</td><td>4</td><td>16</td><td>LIMIC</td></tr>
<tr><td rowspan="2">HCV</td><td>2</td><td>3</td><td>6</td><td>HIC</td></tr>
<tr><td>3</td><td>4</td><td>12</td><td>LIMIC</td></tr>
<tr><td rowspan="2">Blood-borne viruses</td><td rowspan="2">Infectious soft waste</td><td rowspan="2">MWH</td><td rowspan="2">ETH</td><td rowspan="2">• Limited evidence as most studies focus on needlestick and sharps, though greater prevalence of exposure to mucous membranes compared to sharps in one study (Shiferaw et al., 2012).</td><td rowspan="2">•</td><td>na</td><td>na</td><td>na</td><td>HIC</td></tr>
<tr><td>3</td><td>4</td><td>12</td><td>LIMIC</td></tr>
</table>

Abbreviations: Geographical research context (geog.); likelihood (L); severity (S); risk (R); hazard being assessed (Haz.); high income country (HIC); low income and middle income countries (LIMIC); hepatitis C virus (HCV); hepatitis B virus (HBV); human immunodeficiency virus (HIV); medical waste handlers (MWH); healthcare workers (HCW).

6. Challenge 3: Reuse, recovery and disposal phase

6.1. Context

Medical waste treatment and disposal is a critical component of any waste and resources recovery management system. It should involve sufficient controls to ensure that pathogens and potentially hazardous substances are either treated to reduce or eliminate their hazardousness or contained and stored to prevent them interacting with human or environmental receptors (**Figure 22**). The reuse, recovery and disposal phase of medical waste represents the point in time where waste is no longer undergoing intermediate storage, has ceased being transported, and is being handled. However, **Sections 6.2-6.5** describe how several activities that take place during the collection, processing and handling of waste can result in serious potential hazard exposure to certain groups of people.

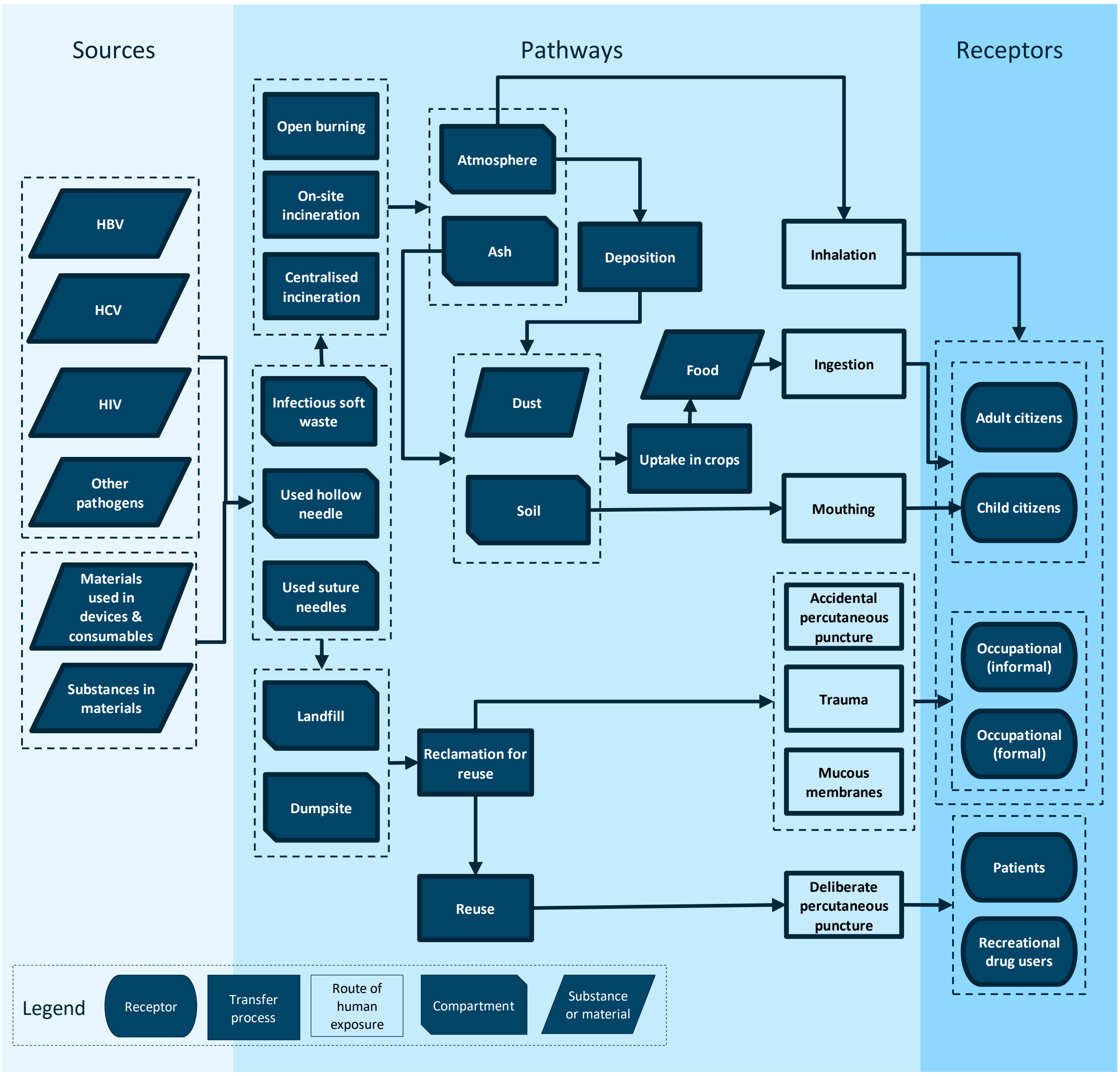


Figure 22: Hazard exposure conceptual model (source–pathway–receptor) associated with medical waste during the reuse, recovery and disposal phase. Abbreviations: hepatitis C virus (HCV); hepatitis B virus (HBV); human immunodeficiency virus (HIV).

6.2. Combustion of medical waste

Combustion (delimited here as complete oxidation under controlled engineered conditions) is an effective method for the destruction of pathogens in medical waste; and is, therefore, widely implemented in Europe, the US, and many other HICs (World Health Organization, nd). On-site incinerator units are common in Europe, but less so in the UK, reducing the risk of transporting infectious waste to another facility and associated costs. Historically, three broad types of localised incinerator technologies have been used: dual-chamber; multiple-chamber; and rotary kilns (National Research Council (US) Committee on Health Effects of Waste Incineration, 2000). In contrast to large-scale municipal or commercially run solid waste incinerators/ energy form waste plants, smaller site-based facilities may be used infrequently or have a low throughput. This results in a requirement for significant auxiliary fuel to maintain the required combustion temperature as well as the temperature of the off-gasses (Batterman, 2004; National Research Council (US) Committee on Health Effects of Waste Incineration, 2000).

Medical waste itself has a markedly different composition to MSW. For instance, medical waste typically contains 30% wt. plastic (Pandelova et al., 2009) compared with approximately 11.5% wt. (Kaza et al., 2018) content in MSW worldwide. In particular, medical waste often has a high polyvinyl chloride (PVC) content through the inclusion of items such as: colostomy bags; blood bags; intravenous tubes; catheters; urine bags; plasma collection bags; infusion sets; draw sheets; and gloves (3R South Asia Expert Workshop, 2006). Thus, when medical waste is combusted, significantly higher concentrations of dioxins and related compounds (DRCs) could be released into the air and ash (**Table 11**).

Table 11: Comparison of dioxin related compounds (DRC) emissions from medical and MSW incinerators without emissions cleaning; after Hagenmaier et al. (1987).

Substance	MSW incinerator (ng g^{-1} fly ash)	Hospital waste incinerator (ng g^{-1} fly ash)
Total dioxins	6.9-80.3	1,155-1,737
Total furans	31.3-119.5	895-2,140

Modern incinerator plant designs incorporate air pollution control (APC) units that mitigate the emissions to meet strict limits imposed by the relevant authorities, some examples of which are shown in **Table 12**. Importantly, many small scale incinerators exist across LIMICs that feature no APC at all (Azage and Kumie, 2010; Bassey et al., 2006; Bazrafshan and Kord Mostafapoor, 2010; Manyele and Tanzania, 2004; Mesdaghinia et al., 2009; Musa et al., 2006; Phengxay et al., 2005; Unicomb et al., 2018).

Table 12: Example emission thresholds; after World Health Organization (nd).

		US EPA emission limits			EU emission limits		
Pollutant	**Units**	**Small**	**Medium**	**Large**	**Daily average**	**0.5-hour average**	**0.5-8 hour average**
Particulates	mg m^{-3}	50	17	14	10	10, 30	
CO	mg m^{-3}	18	1.6	9.8	50	100, 100	
Dioxins/furans	ng TEQ m^{-3}	0.0099	0.011	0.027			0.1
HCl	mg m^{-3}	17	8.9	5.9	10	10, 60	
SO_2	mg m^{-3}	2.8	2.8	16	50	50, 200	
Mercury (Hg)	mg m^{-3}	0.011	0.0027	0.00099			0.05
Lead (Pb)	mg m^{-3}	0.24	0.014	0.00053			

All reference conditions: 273°K, 101.3kPa, 11% O_2, dry; small ≤ 91 kg hr^{-1}, medium > 91 to 227 kg hr^{-1}, and large > 227 kg hr^{-1}; for half hour averages, at least 97% of concentrations must meet the first value and 100% must meet the second value. Abbreviations: carbon monoxide (CO); hydrochloric acid (HCl); mercury (Hg); lead (Pb); sulphur dioxide (SO_2); United States Environmental Protection Agency (USEPA); European Union (EU).

To provide an indication of the potential emissions from medical waste combustion, a selection of factors are presented in **Table 13**. The concentrations reported by Walker and Cooper (1992) are nearly 30 years old and it is conceivable that medical waste composition may have changed since then. Nonetheless, the Walker and Cooper data provide a useful comparison with the more contemporary concentrations reported by Trozzi et al. (2016), because they indicate the characteristics and quantity of substances emitted in incinerators currently operated in LIMICs.

Table 13: Typical emission factors for medical waste incinerators without emissions controls.

Substance	Units	Walker and Cooper (1992)			Trozzi et al. (2016)	
		Red bag waste[e]	General hospital waste[f]	Pathological[g]	Clinical waste	
		Uncontrolled emissions incineration			Uncontrolled rotary kiln incinerator	Controlled air incinerator
NO_X	mg kg^{-1} waste	1,450 [c]	1,350 [c]	4,290 [c]	2,300	1,800
CO [b]	mg kg^{-1} waste	13,300	2,500	750	190	1,500
NMVOC	mg kg^{-1} waste				700	700
SO_X	mg kg^{-1} waste	1,050 [d]	566 [d]	2,940 [d]	540	1,100
TSP	mg kg^{-1} waste				17,000	2,300
BC[a]	mg kg^{-1} waste				2,300	2,300
Pb	µg kg^{-1} waste	50,800	28,600	4,310	62,000	36,000
Cd	µg kg^{-1} waste	1,680	2,020	6,150	8,000	3,000
Hg	µg kg^{-1} waste	110,000	25,500	637	43,000	54,000
As	µg kg^{-1} waste	57.3	118	339	200	100
Cr (Total)	µg kg^{-1} waste	202	422	3,900	2,000	400
Cr (VI)	µg kg^{-1} waste	NA	31.7	680		
Fe	µg kg^{-1} waste	10,300	4,780	NA		
Mn	µg kg^{-1} waste	98.7	245	5,500		
PM	mg kg^{-1} waste	6,580	3,090	4,240	98,000	6,000
Ni	µg kg^{-1} waste	<208	<124	440	2,000	300
Benzene	µg kg^{-1} waste	33.1	1,320	4,500	20	20
	µg kg^{-1} waste	62.1	31.6	7.17		
Dioxin/furan	mg I-TEQ Mg^{-1} waste				40	40
Total 4 PAHs	µg kg^{-1} waste				0.0400	0.0400
HCB	mg kg^{-1} waste				100	100
HCl	mg kg^{-1} waste	23,000	11,200	1,060		

[a] Black carbon (BC) emission factors are assumed to equal those for elemental carbon (EC); [b] CO EF is high for red bag waste due to a large number of data points from one older, single chamber incinerator operating in batch mode. CO one for four multi-chamber incinerators averaged 5,860 mg kg^{-1}; [c] as NO; [d] As SO; [e] red bag waste: includes any waste generated in the diagnosis, treatment, or immunisation of humans or animals, in research pertaining thereto, or in the production or testing of biologicals. For example, contaminated sharps, cultures and stocks of infectious agents, pathological waste, contaminated wastes from patient care, and discarded biologicals; [f] general hospital waste: includes a mixture of red bag waste and municipal waste generated by the hospital (for example, food waste, administrative waste, yard trash); [g] pathological waste: includes human and animal remains, tissues, body fluids, and cultures. Abbreviations: international toxic equivalent (I-TEQ); non-methane volatile organic compounds (NMVOCs); total suspended particles (TSP); nitrogen oxides (NO_X); carbon monoxide (CO); sulphur dioxides (SO_X); total suspended particles (TSP); black carbon (BC); lead (Pb); cadmium (Cd); mercury (Hg); arsenic (As); chromium (Cr); iron (Fe); manganese (Mn); particulate matter (PM); nickel (Ni); hexachlorobenzene (HCB); hydrochloric acid (HCl).

Healthcare facility scale incinerators operating in LIMICs include sophisticated models with emission abatement (APC), but more commonly, older, smaller types of installation, which range from industrial engineered facilities (Khan et al., 2019) through to locally constructed brick-built furnaces (Musa et al., 2006). Open burning is also widely practiced, as shown in **Table 14**, which indicates the proportion of medical waste treated by different methods in seven studies, ranging from 26%-100% of healthcare facilities reporting that open burning was used to treat medical waste. The proportions of medical waste open burned worldwide are unknown, and the evidence presented in **Table 13** does not constitute a representative global sample. However, it is estimated that MSW is open burned at a rate of between 13% and 50% across LIMICs (Bundhoo, 2018; Chanchampee, 2010; Christian et al., 2010; Cogut, 2016; Nagpure et al., 2015; Pansuk et al., 2018; Reyna-Bensusan et al., 2018; US Environmental Protection Agency, 2001), which may provide an indicator of how medical waste is treated in these socio-economic regions.

Table 14: Proportion of waste or establishments reporting treatment of waste by different methods of medical waste.

Ref.	Context	Sample	Waste type	Treatment type	Proportion treated or no. of healthcare facilities reported
Bazrafshan and Kord Mostafapoor (2010)	IRN	Hospitals (n=14)	Healthcare waste	Open burning	Most common method
				Dumpsite	Second most common method
				Incineration	21.4%[a]
Mesdaghinia et al. (2009)	IRN	Primary care hospitals (n=120)	Hazardous solid waste	Incineration	32.5%
				Temp. incineration	8.3%
				Open burning	42.5%
				No treatment	16.7%
Musa et al. (2006)	NGA	Static immunisation centres (n=13)	Injection equipment	Open burning	100%
Azage and Kumie (2010)	ETH	Health centres (n=10)	Healthcare waste	Brick incinerator [b]	40%
				Open burning (pit)	60%
Bassey et al. (2006)	NGA	Hospitals (n=2)	Healthcare waste	Brick incinerator [b]	18.3%
				Open burning (pit)	36.3%
				Burying	9.1%
				Municipal dumpsite	36.3%
Phengxay et al. (2005)	LAO	Urban hospitals (n=11)	Healthcare waste	Open burning	73%
		Urban/rural hospitals (n=10)		Open burning	90%
Unicomb et al. (2018)	BGD	All	Healthcare waste	Burying	16%
				Open burning	35%
				Incineration	4%
				Dismantle/reuse	2%
				Nothing	43%
		Urban		Burying	8%
				Open burning	26%
				Incineration	4%
				Dismantle/reuse	2%
				Nothing	58%
		Rural		Burying	17%
				Open burning	36%
				Incineration	4%
				Dismantle/reuse	1%
				Nothing	41%

[a] 35.7% of hospitals had incinerators; however, only 21.4% were in use; [b] local brick incinerator design.

No specific data were available to quantify emissions from open burning of medical waste; however, the data for uncontrolled incineration (**Table 13)** of medical waste can serve as an indicator. Even if an open fire reaches a high temperature at its peak combustion point, there will be periods at the start and end, and also areas on the periphery of the fire where incomplete combustion takes place (Secretariat of the Stockholm Convention on Persistent Organic Pollutants, 2008). Though assisted by chimney effect, which draws air through the combustion chamber, even small scale, low technology incinerators may have a similar emission profile to waste that is openly burned (Mitchell et al., 2019), as they lack auxiliary fuel that is often supplied through the addition of gas or oil to the process (Jiang et al., 2012). Furthermore, when auxiliary heat is provided, poor quality fuel such as coal may be used which can result in combustion temperature of below 800 °C, 50 °C below the temperature recommended for medical waste combustion (Cogut, 2016).

Despite the shortcomings of open burning as a method for treating medical waste, the World Health Organization (2019c) apparently recommends it as a last resort treatment option where there are no alternatives, recommending it as a 'safe final disposal' method for sharps and infectious waste (World Health Organization, 2015). It is not clear whether or not the WHO has quantitatively assessed the relative risk of emissions from open burning in comparison to the risk of infection from medical waste that has been buried or open dumped, and no published evidence was found to substantiate the advice. The fact that medical waste incinerators are reported to be a source of DRC emissions broadly equivalent to MSW incinerators worldwide (Fiedler, 2007; Quaß et al., 2004), but with considerably less throughput, it is likely that open burning is also a significant source. It is therefore recommended that further research is conducted to assess the evidence for the WHO's advice in more detail to ascertain whether it is still up to date given the current state of knowledge in this area.

6.3. Reuse or recycling of medical waste

The recovery of medical waste for reuse or recycling is a deeply concerning practice, not only because of the risk of exposure to infection of patients, but also for the participants in the activity who are at significant risk of being infected by the devices they handle. The legality of reclaiming waste medical equipment for reuse is not reviewed here, but it is unlikely that syringe reuse is considered publicly acceptable in most, if not all countries (Patwary et al., 2011a; Patwary et al., 2011b; Stringer, 2011). This creates a challenge for researchers when gathering data to estimate the nature and magnitude of the practice. Over 16 billion injections are administered every year (Hauri et al., 2004) and the World Health Organization (2016) estimates that approximately 40% of them are given reused injection equipment based on modelling by Hauri et al. (2004) and Simonsen et al. (1999). It should be noted that reuse of medical devices is not inherently unsafe; however, where equipment has been exposed to pathogens during its first use, there is a risk that they may be transmitted to a subsequent user.

In this review, six articles were identified which evidence the reclamation of waste medical devices for reuse or recovery after they have been discarded (**Table 15**). The most comprehensive study is by Patwary et al. (2011a) who observed informal recycling sector workers in Dhaka, Bangladesh, involved with the reclamation of medical equipment. The researchers estimated that a small number of waste pickers were involved with the activity, possibly only around 75 in Dhaka; suggesting that this is a highly specialist field of ‘entrepreneurs’, however it is impossible to accurately estimate the numbers due to the informal and illicit nature of the business.

Table 15: Evidence of reclamation of medical waste by the informal recycling sector for reuse or recycling.

Ref.	Context	Survey sample	Observed reclamation practice
Taghipour and Mosaferi (2009)	IRN	Review of waste management practices at healthcare facilities (n=875)	• Survey team observed medical waste being collected for recycling at one hospital. • Recorded reports from hospital staff that used injection equipment is occasionally stolen for injection of illegal drugs.
Yusuf et al. (2018)	NGA	Survey of waste pickers (n=236)	• 52.5% of waste pickers have been engaged in medical waste scavenging at least once.
Patwary et al. (2011a)	BGD	Survey (n=45) of waste pickers specialising in medical waste recovery	• Identified members of the informal recycling sector engaged in medical waste recovery for reuse and recycling and interviewed them about their practices.
Unicomb et al. (2018)	BGD	Review of waste management practices at healthcare facilities (n=875)	• 2% of healthcare facilities admitted selling single use medical equipment for reuse
Syed et al. (2012)	BGD	Review of medical waste management (n=36)	• Indication that medical waste is recovered for reuse and recycling by informal recycling sector
Stringer (2011)	BGD; TZA	Review of healthcare waste management and human rights	• Includes photographic and personal observation evidence of collection, separation and processing of waste medical devices for recycling and reuse in Bangladesh and Tanzania

Patwary et al. (2011a) found evidence that a wide range of medical equipment was being recovered for reuse, including: scalpels, knives, saline drip bags, cotton, and injection equipment. This clearly indicates that, at least in Dhaka, there are buyers for used medical equipment within or on the periphery of the healthcare sector. The existence of this market in Bangladesh is supported by evidence from Unicomb et al. (2018) who carried out a nationwide survey of medical facilities across Bangladesh, finding that 2% of facilities admitted selling single use medical devices for reuse. Stringer (2011) also provided multiple photographic examples and personal observation data that evidence medical waste collection, sorting and recovery for reuse in Tanzania and Bangladesh.

Similarly limited evidence exists for the reclamation of material for recycling from medical waste. The cohort studied by Patwary et al. (2011a) consisted of 20 waste pickers who collected medical waste plastics metal and glass, which were sold to reprocessors or dealers ('junk shops'). In the case of metals, plastics and glass, the temperatures reached in reprocessing are likely to be high enough to limit the risk of exposure to product users. However, the risks to the collectors, sorters, and reprocessors are likely to be considerable. Almost no further evidence was identified in this review except a single BBC television news article (BBC Urdu, 2013) that reported on the practice in Lahore, Pakistan. The article showed video evidence of material being collected and passed to plastics recyclers for reprocessing. It also indicated that they might be used in the production of drinking straws: however, the direct link between the two streams was not directly stated and remains ambiguous.

6.4. Infections from reuse of injection equipment

The recapping of needles on injection equipment is a common practice across many LIMICs (Enwere and Diwe, 2014; Macaulay and Odiase, 2016; World Health Organization, 2014) and some HICs (NHS Scotland, nd; Watterson, 2004), enabling healthcare providers to reduce the cost of replacing equipment. This practice not only exposes HCWs to the risk of infection, but also patients who are seeking to improve their health rather than endanger it further.

The worldwide prevalence of injection equipment reuse was investigated by Hauri et al. (2004) who estimated that approximately 41% of injections are carried out with reused equipment (**Figure 23**). The study found that rates of injection equipment reuse were extremely low in Western Europe and North America, and high in parts of Eastern

Mediterranean and Western Pacific Regions, which showed rates of 70–75% respectively (details of World Bank sub-regions are provided in **Table S 4**).

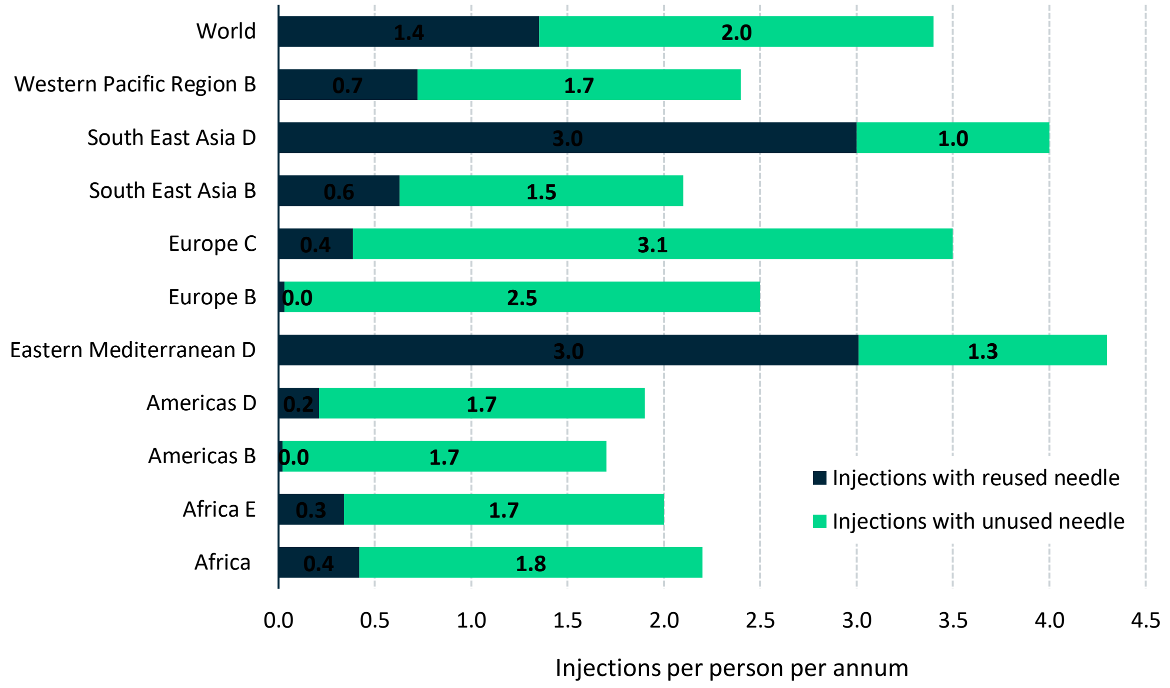


Figure 23: Reuse of injection equipment in World Health Organization (WHO) Global Burden of Disease regions (detailed in **Table S 4)**; after Hauri et al. (2004).

The rates of blood borne virus infection from reused injection equipment were also modelled by Hauri et al. (2004), who found the infection profile dominated by HBV infections across all regions, with comparatively large numbers of infections across Western Pacific and South East Asia regions (**Figure 24**). As with the global burden of disease modelling of risks to HCWs carried out by (Prüss-Üstün et al., 2005), the modelled exposure presented by Hauri et al. (2004) (**Figure 24**) is not always proportional to the recapping prevalence (**Figure 23**); as in the case of the Western Pacific Region.

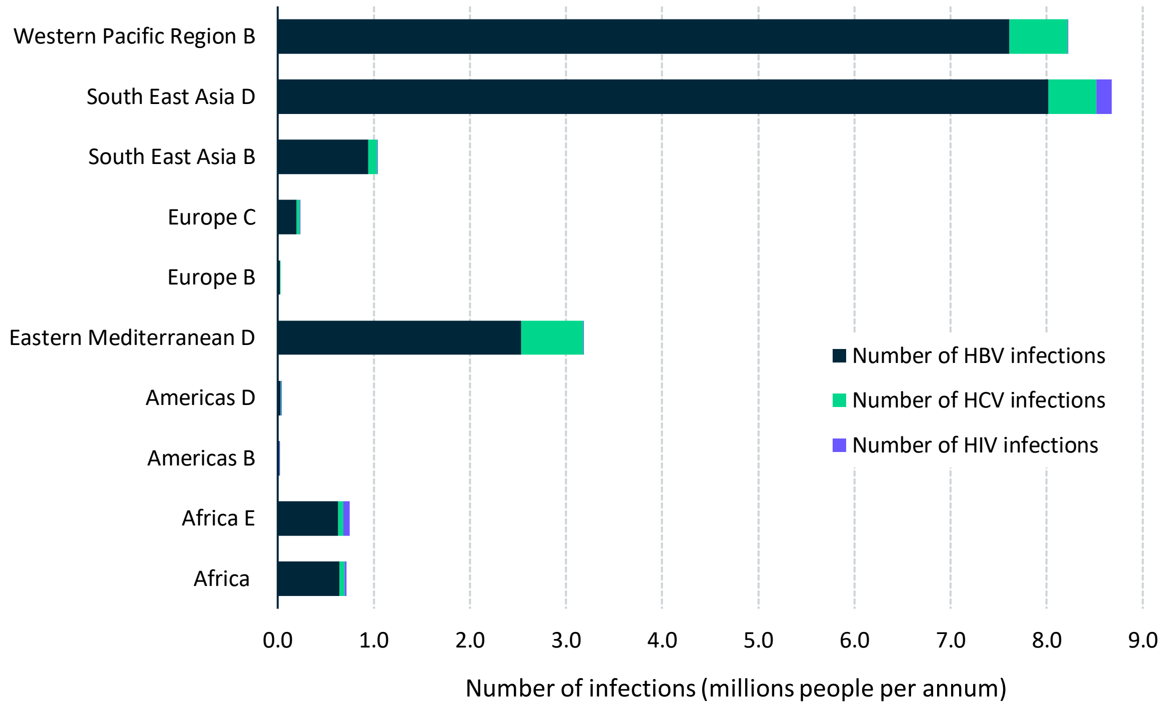


Figure 24: Infections due to reuse of injection equipment in World Health Organization (WHO) Global Burden of Disease regions (detailed **Section S.4)**; after Hauri et al. (2004).

The rate of infection from HIV was comparatively low in all regions according to Hauri et al. (2004), with the highest prevalence of infection in South East Asia with 200,000 new cases per annum. In the African regions, the rate of HIV infection from used injection equipment was modelled to be low, despite the high numbers of people living with HIV which is up to 20% of the population in some areas (UNAIDS, 2018b). This is partly a result of the low reuse rate (15-18%) reported. But, also the fact that HIV transmission risk is just 0.3% compared with HCV which is 3%, and with HBV which is 33% (Cheng et al., 2017).

6.5. Sharps and needlestick injuries to informal waste collectors

Whereas small numbers of informal waste workers are known to purposefully seek medical waste as a valuable resource to be reused or recycled, waste pickers also encounter medical waste accidentally while searching for other valuable materials (Zolnikov et al., 2019). Consequently, informal waste workers are exposed to infection from blood-borne viruses and other pathogens, often unexpectedly, as medical waste is collected, processed and co-disposed along with MSW.

Pathogens from medical waste may enter the body through the skin or mucous membranes. Here we compare six studies reporting the prevalence of percutaneous exposure to pathogens among informal waste collectors, ranging 3.4-61.6% (**Table 16**). The studies were carried out in South Asia, South America and West Africa, indicating that the risk of injury to informal waste workers may be geographically widespread.

Table 16: Prevalence of sharps and needlestick injuries among waste pickers from cross-sectional surveys.

Ref.	Year	Context	Survey sample	Work site	Injury	Period	Prevalence
Black et al. (2019)	2019	NPL	1,278	Not reported	Medical sharps	12 month	3.4%
Cunningham et al. (2012)	2012	PRY	102	Landfill	Needlestick	Lifetime	23%
					Exposed to blood other than own		13%
Parizeau (2015)	2015	ARG	397	Streets	Needlestick	Lifetime	10%
Chokhandre et al. (2017)	2017	IND	200	Dumpsite [b]	Needles and glass	6 month	35%[a]
Patwary et al. (2011a)	2011	BGD	45[c]	Streets, treatment plants, dumpsites	Medical sharps	Lifetime	56%
Afon (2012)	2012	NGA	112	Dumpsite	Sharp objects	Lifetime	61.6%

[a] Laceration (needles and glass) 35% (70/200) compared to control group 11% (11.7/103) (Chi squared = 92.58; p = 0.000); [b] the method reports that the waste pickers lived near the dumpsite so it is assumed that they work there too, however this was not explicitly clarified; [c] all interviewees were medical waste specialists.

The lowest lifetime prevalence of 3.4% reported by Black et al. (2019) was observed in a comparatively large sample of waste pickers in Nepal and the highest lifetime prevalence (61.6%) was reported by Afon (2012) in a study of waste pickers working in Nigeria. The large range could be a result of differing medical waste disposal practices in each country whereby infectious medical waste is separated and disposed of separately in one country, reducing exposure to informal collectors, and frequently co-disposed in another.

The large differences may also be related to the sample selection. For instance, Black et al. (2019) did not report the location where the survey respondents carried out their activities. It is therefore feasible that the workers interviewed worked in locations where medical waste was not disposed of, such as on urban streets or door-to-door. Conversely, the subjects surveyed by Afon (2012), worked exclusively on dumpsites, which speculatively, are more likely to contain medical waste that has been co-disposed with MSW. Moreover, the categories reported by researchers were similar, but not fully aligned. For instance, the category reported by Afon (2012) was ‘wound from sharp objects’ which could include non-medical sharps and inflate the reported prevalence. Similarly, the category reported by Chokhandre et al. (2017) included injuries from glass.

In summary, there is little doubt that informal waste collectors are occupationally exposed to pathogens from medical waste in several global locations. However, there is significant uncertainty over the prevalence of this exposure, and it is therefore challenging to determine the risk to their health. There are possibly 10 to 20 million informal waste workers globally collecting virtually all of the post-consumer recyclate in LIMICs (Lau et al., 2020; Wilson et al., 2015). The continued co-disposal of medical waste within their feedstock represents a serious and unacceptable risk that would not be tolerated in the formal economy, highlighting continued inequality between the two sectors.

6.6. Risk characterisation for medical waste during the reuse recovery, treatment and disposal phase

Despite the comparatively high levels of chlorine in medical waste, the qualitative risk assessment shown in **Table 17** indicates a very low level of risk from medical waste incineration in HICs. This is because facilities in these countries are subject to strict regulation and enforcement to ensure that emissions are restricted to very low levels. In contrast, incineration of medical waste in LIMICs is categorised as medium high risk as facilities in countries in these income group categories are less likely to incorporate emissions cleaning in to their facilities.

Evidence suggests that open burning or rudimentary incineration is widely practiced in LIMICs (Azage and Kumie, 2010; Bassey et al., 2006; Bazrafshan and Kord Mostafapoor, 2010; Manyele and Tanzania, 2004; Mesdaghinia et al., 2009; Musa et al., 2006; Phengxay et al., 2005; Unicomb et al., 2018). Given the high content of plastics, particularly chlorinated plastics, the emissions are likely to be extremely hazardous to those in close proximity and beyond. Therefore, this is scored here as representing a very high risk to human health due to significant emissions of potentially hazardous substances highlighted in our research. Open burning is not assessed in HICs, because the practice is considered to be unlikely to occur.

The population risk from reused injection equipment qualitatively assessed in **Table 18**, shows a very high risk for HBV, and a medium high risk of HCV in LIMICs. The risk in HICs is scored very low for HIV and HBV, partly because of the low prevalence among the population but also the low rate of injection equipment reuse in countries under this income category.

The risk of infection from sharps injury to members of the informal waste collection sector is assessed to be very high for workers who specialise in medical waste recovery. The risk is medium-high for those who recover other materials as their encounters with injection equipment are considered to be less frequent than the medical waste specialists. Both sets of workers have been shown to have a low rate of personal protective equipment (PPE) use, which increases their chances of viral transmission.

Table 17: Risk characterisation summary for medical waste hazards during the recovery, treatment and disposal phase: combustion of medical waste.

Activity	Haz.	Pathway	Receptor	Geog.	Evidence and justification for risk assessment	Uncertainty (aleatoric and epistemic)	Receptor vulnerability	L	S	R	Global receptor context
Medical waste incineration	Potentially hazardous substances (particularly DRCs)	Atmosphere/ inhalation	Population	IRN, NGA, ETH, LAO, BGD	• Medical waste typically contains 30% plastic (Pandelova et al., 2009) compared to approximately 11.5% (Kaza et al., 2018) content in MSW worldwide. • PVC is used extensively in single use medical products (3R South Asia Expert Workshop, 2006) which results in a high chlorine content and thus higher DRC emissions when it is combusted (Fiedler, 2007; Hagenmaier et al., 1987; Quaß et al., 2004). • Modern incinerator designs, which are prevalent in HICs, incorporate components that effectively mitigate emissions of potentially hazardous substances, however many small scale incinerators exist across LIMICs that have no emission cleaning at all (Azage and Kumie, 2010; Bassey et al., 2006; Bazrafshan and Kord Mostafapoor, 2010; Manyele and Tanzania, 2004; Mesdaghinia et al., 2009; Musa et al., 2006; Phengxay et al., 2005; Unicomb et al., 2018). • Evidence for potential emissions from medical waste incinerators which have no pollution control devices indicate emissions of potentially hazardous substances (Trozzi et al., 2016; Walker and Cooper, 1992) which are far greater than the emissions thresholds in Europe and the US (World Health Organization, nd).	• No specific data available to quantify emissions from open burning of medical waste, however data for uncontrolled incineration of medical waste are indicative. • A priori data suggests even if open fires reach high temperatures at peak combustion, periods at the start and end and also areas on the fire periphery where incomplete combustion takes place.	• Emissions cleaning likely to be implemented in most cases to comply with stringent legal thresholds (World Health Organization, nd).	1	2	2	HIC
							• Lack of emissions cleaning in medical waste incinerators in LIMICs (Azage and Kumie, 2010; Bassey et al., 2006; Bazrafshan and Kord Mostafapoor, 2010; Manyele and Tanzania, 2004; Mesdaghinia et al., 2009; Musa et al., 2006; Phengxay et al., 2005; Unicomb et al., 2018). • Residents living nearby have no choice but to inhale pollutants from these activities.	3	4	12	
			Waste workers (formal and informal)				• Informal waste workers unlikely to wear respiratory protective equipment	3	4	12	LIMIC
Medical waste open burning	Potentially hazardous substances (particularly DRCs)	Atmosphere/inhalation	Population	IRN, NGA, ETH, LAO, BGD	• Open burning is practiced as a method of medical waste disposal throughout LIMICs (Azage and Kumie, 2010; Bassey et al., 2006; Bazrafshan and Kord Mostafapoor, 2010; Mesdaghinia et al., 2009;	• No evidence was found to compare the relative risk of pathogen infection from medical waste with exposure to	• Lack of emissions cleaning in medical waste incinerators in LIMICs (Azage and Kumie, 2010; Bassey et	4	5	20	LIMIC

Activity	Haz.	Pathway	Receptor	Geog.	Evidence and justification for risk assessment	Uncertainty (aleatoric and epistemic)	Receptor vulnerability	L	S	R	Global receptor context
					Musa et al., 2006; Phengxay et al., 2005; Unicomb et al., 2018). • The World Health Organization (2019c), (WHO) still recommends pen burning as a last resort treatment option where there are no alternatives citing it as a 'safe final disposal' method for sharps and infectious waste (World Health Organization, 2015). • The fact that medical waste incinerators are reported to be a source of DRC emissions broadly equivalent to MSW incinerators worldwide (Fiedler, 2007; Quaß et al., 2004), but with considerably less throughput, it is likely that open burning is also a significant source.	hazardous substances from open burning of medical waste.	al., 2006; Bazrafshan and Kord Mostafapoor, 2010; Manyele and Tanzania, 2004; Mesdaghinia et al., 2009; Musa et al., 2006; Phengxay et al., 2005; Unicomb et al., 2018). • Residents living nearby have no choice but to inhale pollutants from these activities.				
			Waste workers (informal)				• Informal waste workers unlikely to wear respiratory protective equipment	4	5	**20**	

Abbreviations: Geographical research context (geog.); likelihood (L); severity (S); risk (R); hazard being assessed (Haz.); high income country (HIC); low income and middle income countries (LIMIC); hepatitis C virus (HCV); hepatitis B virus (HBV); human immunodeficiency virus (HIV); medical waste handlers (MWH); healthcare workers (HCW); dioxins and related compounds (DRC); polyvinyl chloride (PVC).

Table 18: Risk characterisation summary for medical waste hazards during the recovery, treatment and disposal phase: exposure to pathogens.

Haz.	Pathway	Receptor	Geog.	Evidence and justification for risk assessment	Uncertainty (aleatoric and epistemic)	Receptor vulnerability	L	S	R	Global receptor context
							1	4	**4**	HIC
HIV							2	5	**10**	LIMIC
							1	3	**3**	HIC
HBV							4	4	**16**	LIMIC
							2	3	**6**	HIC
HCV	Medical sharps	Population	Global	• Recapping of needles on injection equipment is a common practice across many LIMICs (Enwere and Diwe, 2014; Macaulay and Odiase, 2016; World Health Organization, 2014). • 41% of injections are carried out with reused equipment (Hauri et al., 2004). • The rate of infection from HIV is comparatively low in all regions (Hauri et al., 2004), with the highest prevalence of infection in South East Asia with 200,000 new cases per annum. • In African regions, the rate of HIV infection from used injection equipment is low (Hauri et al., 2004), despite the high numbers of people living with HIV which are up to 20% of the population in some areas (UNAIDS, 2018b). This is partly a result of the low reuse rate (15% to 18%) reported. But, also the fact that HIV transmission risk is just 0.3% compared to HCV which is 3% and HBV which is 33% (Cheng et al., 2017).	•	• Those in receipt of healthcare are unlikely to be aware that injection equipment may have been reused	3	4	**12**	LIMIC
		Informal waste collectors	NPL, PRY, ARG, IND, BGD, NGA			• Informal waste workers are rarely equipped with ballistic protective clothing to mitigate the risk of injury from used injection equipment.	3	5	**15**	
Blood-borne viruses	Medical sharps	Informal medical waste collectors	BGD	• Strong evidence of sharps injury prevalence (3.4% to 61.6%) to informal waste collectors (Afon, 2012; Black et al., 2019; Chokhandre et al., 2017; Cunningham et al., 2012; Parizeau, 2015; Patwary et al., 2011a). • Particular risk to medical waste handling specialists in the informal recycling sector with four sources indicating the practice (Patwary et al., 2011a; Stringer, 2011; Taghipour and Mosaferi, 2009; Unicomb et al., 2018).	• Various methodological issues, such as lack of reporting on sample selection, and differing terminology over the cause of injury. • Risk of virus contraction not calculated. • Limited knowledge about specialists in medical waste reclamation for reuse as the practice is considered illicit in most countries and institutions (Patwary et al., 2011a; Patwary et al., 2011b; Stringer, 2011).	• While medical waste specialist informal waste workers anticipate percutaneous injury, they seldom wear PPE.	4	5	**20**	LIMIC

Abbreviations: Geographical research context (geog.); likelihood (L); severity (S); risk (R); hazard being assessed (Haz.); high income country (HIC); low income and middle income countries (LIMIC); hepatitis C virus (HCV); hepatitis B virus (HBV); human immunodeficiency virus (HIV); medical waste handlers (MWH); healthcare workers (HCW).

7. Conclusions

This systematic review brings together and organises, for the first time in one place, the extensive array of research that exists on the safe management of medical devices and consumables (medical waste) at the end of their engineered life (waste, after-use phase). We summarise the evidence through the conceptualisation of hazard-pathway-receptor combinations; which were subsequently semi-quantitatively assessed and ranked to indicate and enable prioritisation of mitigating actions. These mapped pathways were presented in a series of conceptual flow diagrams based on the phase of waste management / mismanagement, a combination of which is shown in **Figure 25**.

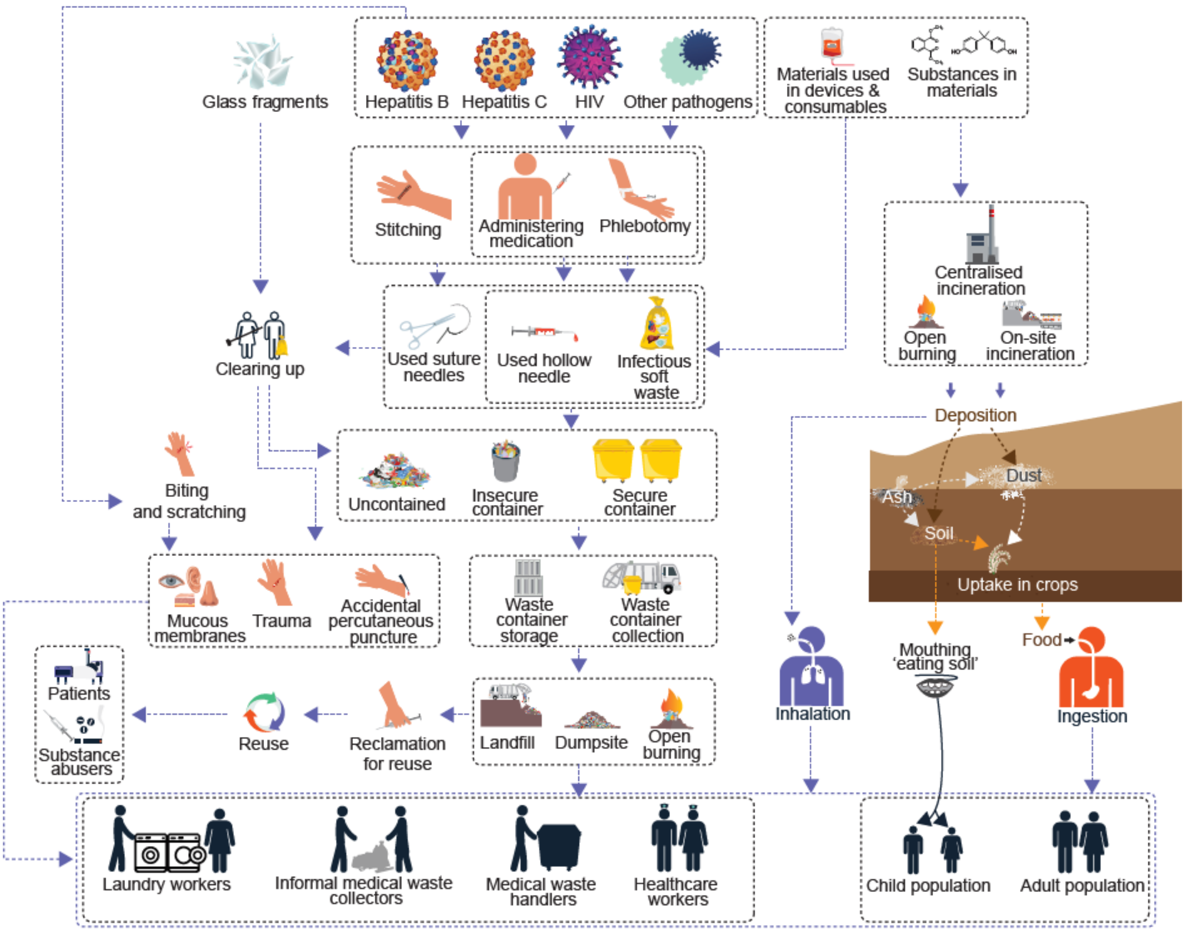


Figure 25: Hazard exposure conceptual model (source–pathway–receptor) for medical waste.

Predominantly, risks were greater in LIMICs where the resource reduces the capability of actors in the system to develop, implement and maintain safe systems of work. Risk to human health during the waste generation phase was almost entirely cantered around the infection of healthcare workers (HCWs) with blood-borne pathogens such as HIV, HBV, and HCV via percutaneous puncture with used injection, suture, or phlebotomy equipment. Several studies exist that determine prevalence, particularly by authors examining the African continent, and these are supported by high quality global burned of disease studies (Prüss-Üstün et al., 2016) that model the potential harm from these types of injury across World Health Organizations regions. The higher rate of transmission for HBV resulted in a high indicative risk according to our semi-quantitative process, particularly, and overwhelmingly centred on LIMICs, but also in Europe. However, in the case of the latter, the cause for concern is lower as the capability to treat patients contracting the disease is greater.

A similar picture is evident for medical waste handlers (MWHs) who, especially in LIMICs, are at considerable risk of contracting HBV as well as other blood borne infections as a result of accidental puncture with sharps that have been stored in non-protective containers. Even in HICs, the rate of percutaneous puncture with used needles was significant amongst MWHs, despite the generally higher standards of waste handling and storage practices.

A deeply concerning practice amongst a specialist group of waste pickers involves the reclamation of used medical equipment to be cleaned and sold for reuse by substance abusers and medical waste providers. Its highlight illicit nature means that the scale of this activity is inherently challenging to quantify, with the few sources of evidence indicating that it is a comparatively small industry. However, the risk to the workers themselves and the potential prevalence of the many materials that might be collected is a serious cause for concern that warrants further research and investigation to establish and quantify the level of risk. Even for those waste pickers who are not engaged in this activity, the risks posed by medical waste are high in countries where it is frequently co-disposed with MSW; both in unprotected, unlocked containers, and also on the dumpsites, landfills and open terrestrial dumps.

An inexorable dilemma is often faced by HCWs and MWHs in some LIMICs in that they must decide between managing potentially infected waste by sending for unprotected land disposal (open dumping or co-disposal with MSW) and open burning or rudimentary incineration. Even the World Health Organization (2015) and (2019c) recommend open burning as a last resort, but the evidence for making such a decision was not revealed in our research. The high content of plastics, particularly PVC, will undoubtedly result in the release of DRCs, which will persist in soil, and enter the atmosphere where they will expose the people tending the combustion process as well as those living within the local area and beyond. A recommendation of this study is that the relative risk of each of these approaches to disposal is urgently quantified to determine the risk and prioritise the activities that mitigate the most potential harm.

Although some methodologically robust studies of specific aspects of medical waste management were revealed in this review, the majority, especially in the parts of the world where harm is most evident, were insufficiently detailed to properly assess and derive a quantitative risk to human health. As with the waste sector as a whole, medical waste management appears not to have received sufficient research attention, being on the margins of an already underfunded sector. The mismanagement of medical waste is somewhat ironic in the context that the waste has been generated, where the imperative is to prevent cure and rehabilitate those who have experienced ill health. When waste is not passed through a system of protective stewardship and ultimately rendered harmless, it poses an ongoing and obvious risk to human health, either through the pathogens contained within or through the emissions released when it is combusted in an uncontrolled fire. Whilst these risks have been considered and demonstrated as being unacceptable to both workers and the society at large, the lack in sufficiently well-resourced research in this field and its low volume unlikely to result in timely and significant reduction in harm.

CRediT author statement

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

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