Taylor & Francis
Taylor & Francis Group

Critical Reviews in Environmental Science and Technology

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/best20

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

Ed Cook, Anne Woolridge, Petra Stapp, Sarah Edmondson & Costas A. Velis

To cite this article: Ed Cook, Anne Woolridge, Petra Stapp, Sarah Edmondson & Costas A. Velis (2023) Medical and healthcare waste generation, storage, treatment and disposal: a systematic scoping review of risks to occupational and public health, Critical Reviews in Environmental Science and Technology, 53:15, 1452-1477, DOI: 10.1080/10643389.2022.2150495

To link to this article: https://doi.org/10.1080/10643389.2022.2150495

CRITICAL REVIEWS IN ENVIRONMENTAL SCIENCE AND TECHNOLOGY
2023, VOL. 53, NO. 15, 1452–1477
https://doi.org/10.1080/10643389.2022.2150495

Taylor & Francis
Taylor & Francis Group

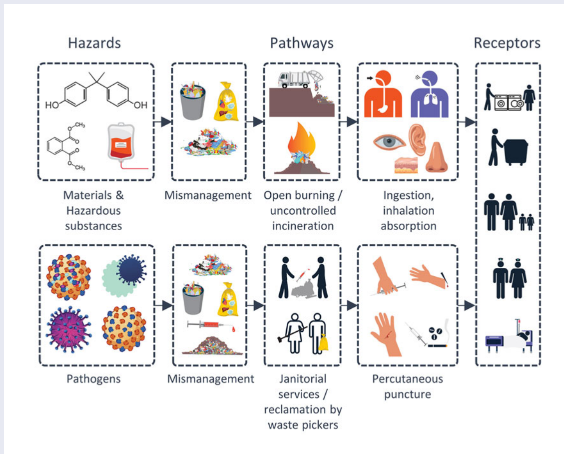
OPEN ACCESS Check for updates

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

Ed Cook[a], Anne Woolridge[b], Petra Stapp[b], Sarah Edmondson[c], and Costas A. Velis[a]

[a]School of Civil Engineering, University of Leeds, Leeds, UK; [b]Independent Safety Services Limited, Sheffield, UK; [c]Somerset, UK

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-income and middle-income countries) such systems, resources and knowhow are lacking; to the extent that medical waste could pose a serious threat to the health, safety and lives of millions of healthcare workers and waste handlers who frequently interact with this category of materials. We present here a novel scope and dimension to investigating specifically the risks and hazards to people who come into contact with medical waste, focusing on activity types and established medical practice. A systematic scoping review of evidence (PRISMA-Scr) was used to critically analyze, compare and summarize data. Prevalent combinations of hazards, exposure and risk are semi-quantitatively scored and ranked. Our results signpost three core topics posing a major risk to human health: (1) Open, uncontrolled burning and rudimentary incineration of medical waste by waste handlers who have to make difficult choices between burning or discarding on land (e.g. in dumpsites) from where it risks pathogen infection; (2) A small but non-negligible trade in reused medical equipment (e.g. hypodermic needles), proliferated by a cohort of waste reclamation specialists (sub-group of waste pickers); and (3) The mismanagement of medical sharps at the point of generation, handling and storage in the Global North and South. A combination of immediate action and further research are recommended to address and inform on these topics which threaten the health and mortality of millions.

Abbreviations: haz: hazard; HBV: hepatitis B virus; HCV: hepatitis C virus; HCW: healthcare workers; HIC: high income countries; HIV: human immunodeficiency virus; L: likelihood; LIC: low income countries; LIMIC: low income and middle income countries; LMC: lower middle income countries; MSW: municipal solid waste; MWH: medical waste handler; NHS: National Health Service (UK); R: risk; S: severity; UMC: upper middle income countries

KEYWORDS Circular economy; health and safety; medical and healthcare waste; open burning; public health; risk

HANDLING EDITORS Jörg Rinklebe and Lena Q. Ma

CONTACT Costas A. Velis c.velis@leeds.ac.uk School of Civil Engineering, University of Leeds, Room 304, Leeds LS2 9JT, United Kingdom.

Supplemental data for this article can be accessed online at https://doi.org/10.1080/10643389.2022.2150495

1. Introduction

Despite extensive global knowledge of the potential hazardousness of medical (healthcare) wastes, there are considerable shortcomings with its management (Singh et al., 2022), particularly in low and middle income countries (LIMICs) where it 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) estimates that approximately 10–25% (wt.) (most recent robust global data) is potentially hazardous to human health, not least due to its potential to harbor pathogens that can subsequently cause infection at multiple points across a complex system.

Medical waste is any object, substance or item that is discarded as a result of healthcare provision. However, a globally unified definition is yet to be agreed (Section S.2.2), meaning that potentially hazardous components may be stored, collected and transported unsafely; exposing medical waste generators, handlers, and treatment and disposal operators to risk (Yoon et al., 2022).

In high-income countries (HIC), systems to neutralize 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 (World Health Organization, 2019c). Infectious material is often incinerated or deposited in specially designed hazardous waste landfills that prevent the risk of interaction with people or, the environment (Hossain et al., 2011; Windfeld & Brooks, 2015). The specialist engineering required and effort undertaken to protect human health and the environment using these approaches is costly. For instance, \$440-620 per tonne (median) for infectious waste treated in the UK in 2015-16 (Royal College of Nursing, 2018) or \$2,360 per tonne in Italy (including management costs) (Vaccari et al., 2018). For healthcare providers in LIMICs, these costs are often prohibitive (World Health Organization, 2020a) and research undertaken by the World Health Organization & the United Nations Children's Fund (2019) indicated that out of 48 countries that at least 15 lacked basic waste management services and one in three healthcare facilities worldwide does not separate hazardous medical waste.

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 & Shekdar, 2001) and Turkey (Ciplak & Kaskun, 2015) amongst others. The World Health Organization has also provided several reviews, including an extensive global review on the safe management of healthcare wastes (World Health Organization, 2014), one that focused on Southeast Asia specifically (World Health Organization, 2017), and another that is dedicated to the safe management of sharps (used injection, phlebotomy and stitching equipment) (World Health Organization, 2019c).

Four reviews with a global geographical scope exist in the academic literature (Caniato et al., 2015; Hossain et al., 2011; Singh et al., 2022; Windfeld & Brooks, 2015). Hossain et al. (2011) reviewed 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 summarized the general legislator approaches in Canada the US and the UK, also very briefly discussing on developing countries. More recently, Singh et al. (2022) reviewed progress and opportunities toward more sustainable medical waste management, and 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. Here, we fill this gap which otherwise 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, the following objectives are to address these challenges, by way of a systematic review. First, we provide an overview of the medical waste system (Section S.1), medical waste composition (Section S.2.1), medical waste generation (Section 3.1) and the healthcare workforce (Section 3.2); and second, we systematically review evidence that indicates hazards associated with medical waste to which receptors can be plausibly exposed through evidenced or conceptually inferred pathways. We focus on medical devices and consumable items, 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. 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 prioritized for further research, innovation and wider interventions.

The scope of the study (further detailed in the Method and Supplemental Information) 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. Given the temporal scope of our study 1977–2019 (with some snowball searching into 2020), papers relating specifically to COVID-19 waste were also intentionally excluded from this study.

2. Methods

2.1. Systematic review

We followed PRISMA-Scr guidelines (Peters et al., 2020) to carry out a systematic scoping review (Checklist in Section S.3.1, Table S2) of evidence obtained from Scopus, Web of Science and Google Scholar, searched for using search terms listed in Section S.3.2. 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 (2020b), Health and Safety Executive (2020; HSE). Titles and abstracts were screened by two reviewers and periodically a third reviewer blind assessed samples to ensure consistency. The screening was carried out according to the inclusion/exclusion criteria listed in Section S.3.3, Table S3 and the system boundary and scope illustrated in Figures S1 and S2 respectively. The criteria were chosen to ensure that all relevant data to the following research questions (RQ) were selected for review:

- **RQ1**: What evidence exists to indicate risk to public and occupational safety posed by medical waste?

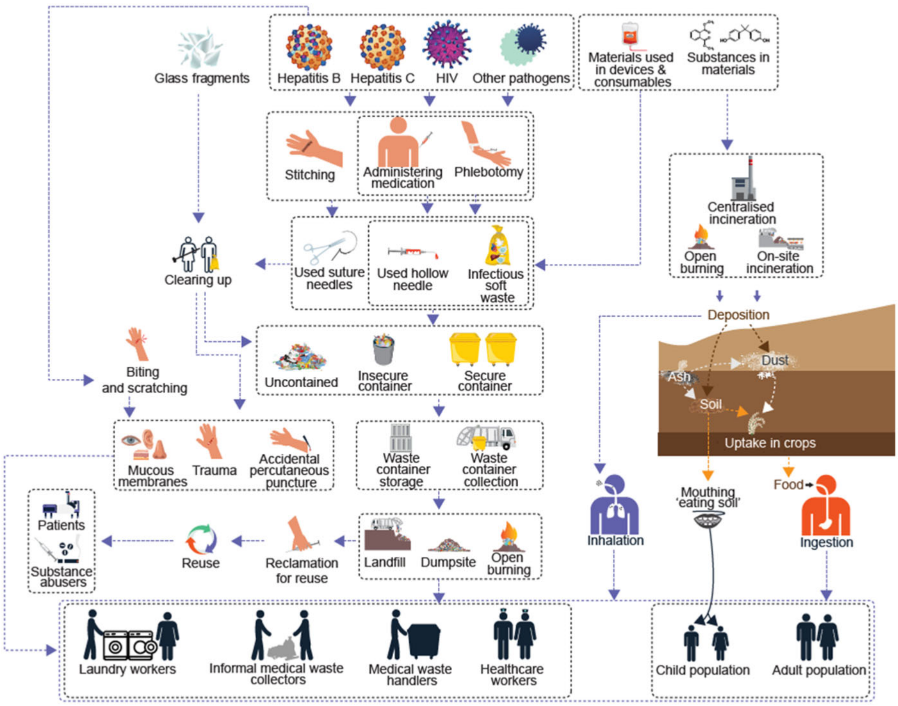


Figure 1. Conceptual overview of the main hazards, pathways and receptors for hazards associated with medical waste.

- **RQ2**: What are the comparative risks to public and occupational safety that arise from the management of medical waste?

Selected studies were coded according to the conceptual categories listed in Section S.3.4, Table S4 and the basic statistical results of the review are presented in Figures S8 and S10.

2.2. Conceptual diagrams

Hazards and risks identified in each source were categorized and grouped according to the pathways through which they might reach receptors, and then arranged into combinations that may be commonly experienced within the healthcare and associated sectors. These combinations were grouped according to three waste system phases, described here as "Challenges" (Sections 3, 5 and 6). For each, a conceptual diagram was created that illustrates the pathways through which receptors are exposed to hazards (Figures S10–S12) and an overarching conceptual diagram in Figure 1 derived from Figure S13.

2.3. Risk based approach

A five step semi-quantitative approach adapted from World Health Organization (2012), Hunter et al. (2003), Kaya et al. (2019) and Burns et al. (2019), was followed (Section S.3.8, Table S5) to assess the likelihood (Table S6) and severity (Table S7) in each hazard-pathway-receptor combination and, assigning an indicative risk score (Table S8) that was used to rank and compare them in the context of the socio-demographic, geographical and receptor vulnerability context (Section S.4, Table S9). This process did not and was not intended to quantify risk in each combination,

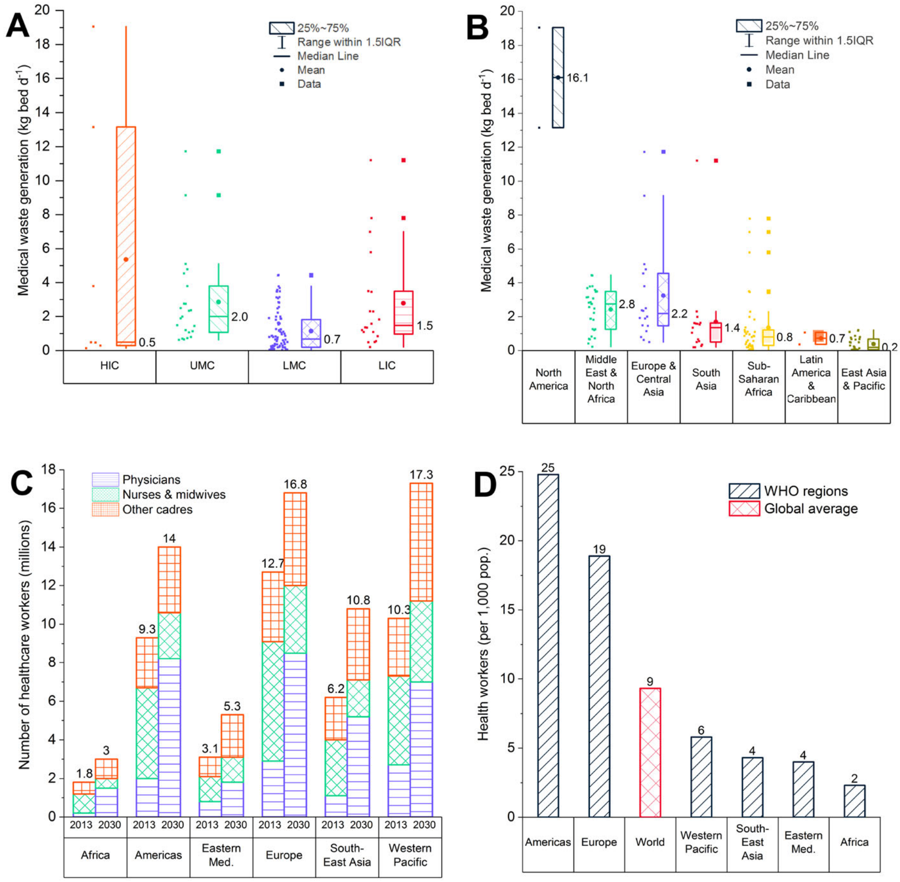


Figure 2. Side by side comparison of central tendency and spread for waste generation rates (n = 136) in medical facilities by **(A)** World Bank income category and **(B)** World Bank region; sources detailed in Table S1. **(C)** Number of healthcare workers by World Health Organization region (Section S.5); data after World Health Organization (2016). 'All other Cadres' refers to the seven other broad categories of the health workforce as defined by the World Health Organization Global Health Workforce Statistics Database, i.e. dentistry, pharmacy, laboratory, environment and public health, community and traditional health, health management and support, and all other health workforce categories. **(D)** Density of healthcare workers by WHO region (World Health Organization, 2006). WHO regions are detailed in Section S.5. Abbreviations: high-income country (HIC); inter-quartile range (IQR); low-income country (LIC); lower middle-income country (LMC); Mediterranean (Med.); upper middle-income country (UMC); World Health Organization (WHO).

but to be used as a decision support method that can be used to inform a future research agenda as suggested by Kaya et al. (2019).

3. Overview of medical waste

3.1. Medical waste generation

Reported rates of medical waste generation in medical facilities vary substantially across the world, with the majority of data-points reported in LIMICs where the median ranged from 0.7-2 kg.bed.d^{-1} (Figure 2A). Just seven data points were reported in HICs where the large range (0.3-19 kg.bed.d^{-1}) is most likely as result of inconsistent definitions and reporting basis (Sections S.2.1 and S.2.4). By World Health Organization region, East Asia and Pacific had the lowest medical waste generation, with a median of 0.2 kg.bed.d^{-1} (Figure 2B). We found a comparative proliferation of studies of medical waste generation in Sub-Saharan Africa (n = 37, Middle East &

North Africa (n = 31) indicates at least a focus of interest in the topic across the regions where medical waste is at higher risk of mismanagement.

3.2. Medical waste sector workforce

There were approximately 43.5 million healthcare workers worldwide in 2013, more than half of whom worked in Europe and the Americas (World Health Organization, 2016; Figure 2C). In 2030 this number is forecasted to rise to 67.3 million, with the largest increases in Western Pacific where population and affluence are anticipated to rise substantially. A very large disparity in the number of healthcare workers between regions is observable, with the Americas having more than double the world average and an order of magnitude more than Africa (Figure 2C).

4. Challenge 1: Medical waste generation phase

4.1. Context

With a few exceptions, most of the studies reviewed here focused 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 & Paterson, 2006). As shown in the conceptual model (Figure S10), 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). Other less common pathogens are reported by NHS Employers (2015) and are summarized in Table S10. 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.

We found that the terms "sharps injury" and "needlestick injury" are 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 and 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 of healthcare workers handling medical waste at the point of generation reported sharps and needlestick injuries on the basis of: 12 month prevalence; lifetime prevalence; and injury rate per 100 person years (Table S11).

A wide variation of reported exposures to sharps and needlestick injuries (range 0.78–284 injuries per 100 person years) was found by Elder and Paterson (2006) who standardized findings from multiple studies and suggested that reporting inconsistencies are the most likely reason. Elder and Paterson (2006) found that 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, 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 & Paterson, 2006), reflecting the level of clinical involvement of each group.

Of the studies that reported 12 month prevalence, that is whether a worker had experienced a single exposure or not over 12 months, the rates of injury were higher by approximately an order magnitude in Africa 35.97% (Confidence interval 95%: 31.15-40.79%) (Auta et al., 2017) and Sri Lanka (54%) (World Health Organization, 2017), compared to in the UK as reported by Mercier (1994; 3.33%, 6.25% and 5.88%). However, two other UK studies (Astbury & Baxter, 1990; Elmiyeh et al., 2004) reported similar or slightly lower rates (38% and 32%) compared to the African studies, suggesting that standards of worker protection may not be so different between higher and lower income country contexts.

An approximate comparison of 12 month injury reporting rates summarized by Auta et al. (2017) with data reported by the same author as well as by Kosgeroglu et al. (2004) in Turkey and Enwere and Diwe (2014) in Nigeria, indicates that prevalence is only 10-20% more over healthcare worker's lifetimes in Africa, suggesting that many workers sustain injuries as frequently as every year or two. Several other correlations can be observed between income level and prevalence of needlestick and sharps injuries among HCWs. For instance, these types of injuries are higher in poorer parts of Africa compared to Southern Africa for instance (Auta et al., 2017). There is also evidence of a reduction in prevalence over time in the first and second decades of the 21st century.

The large difference in prevalence between the study by Mercier (1994) and the other two UK studies (Astbury & Baxter, 1990; Elmiyeh et al., 2004) appears to be a consequence of reporting bias. Mercier (1994) based their analysis on official incident reporting, whereas the other studies elicited their observations from anonymized surveys. In fact, Mercier (1994) acknowledges that the reporting rate is only in the region of 58.3%, an assertion supported by both Cossart and deVries (1994; 22-47%) and Elmiyeh et al. (2004; 51%) (Table S12). The possible 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.

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 localized trauma (NHS Scotland, n.d.). 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 modeled 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).

Prüss-Üstün et al. (2005) reported a very high number potential exposures in the West Pacific region for HBV (Figure S14). These findings result 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 (Table S13), which increases the likelihood of needles containing the pathogen.

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 S14). The number of modeled HIV infections (Figure S15) is broadly proportional to the number of exposures (Figure S14) 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 modeled exposure in the Americas, Eastern Mediterranean and Western Pacific regions. No mention is made of this by Prüss-Üstün et al. (2005) and we suggest that this may be a consequence of a higher rate of prophylactic administration and also vaccination, which historically has been much higher (49% to 93%) than the global average (30% to 85%) since 2000 (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, immunization 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 S16), finding that they were most prevalent in clinical areas, with more than 50% reported on hospital wards. While these data provide a useful indication of where to focus efforts to mitigate the likelihood of future injury, they 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.

Three studies reported the type of activity being carried out when needlestick and sharps injuries took place (Figure S17). The lack of compatibility between the categories makes comparisons challenging, although several patterns can be observed. For instance, World Health Organization (2017), 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 (2017) and Cullen et al. (2006) observed 11% and 4% of injuries taking place after sharps had been discarded, but the studies did not explicitly include medical waste handlers, which may mean downstream injuries were not captured.

Studies of the procedural phase (Figure S18) such as World Health Organization (2017) showed broad alignment with Cullen et al. (2006) and Nagao et al. (2007), showing 45% of injuries occurring during procedures. 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 more recent study by Woode et al. (2014) reported a broadly similar pattern to the other three studies showing 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.

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 S18). We speculate that this difference highlights 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, 2017), in comparison to other procedural phases.

5. Challenge 2: Storage, collection and handling phase

5.1. Context

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 (Figure S11). 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.

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

Of the six studies that reported the prevalence of pathogen exposure to medical waste handlers (MWHs) through sharps and needlestick injuries, four were carried out in Ethiopia, one in Sudan and one in Brazil (Table S14). Lifetime prevalence was reported by five of the authors and ranged from 18.6% to 75%, whereas the 12 month prevalence reported for 126 MHWs surveyed in Ethiopia ranged from 33.3% to 75%. With the exception of the observation of 18.6% by Yizengaw et al. (2018), the ranges were broadly in line with those reported for injury prevalence to HCWs at the point of generation (Table S11). 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 S13). 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).

Only one HIC context study (Blenkharn & Odd, 2008) was identified in which three and a half years of accident and injury records were analyzed from three medical waste collection and storage premises, employing 85 waste handlers collectively. Needlestick and sharps injury frequency was 1 per 29,000 man-hours or 6.45 injuries per 100 person years. Injuries not only occurred to hands (n = 24), but also the legs (n = 11) and bodies of MWHs. 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; 15% of which 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.

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 S19). 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.

Compositional analysis of infective medical waste discarded in sacks (n = 50) in Croatia 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 (Kanisek et al., 2018). The inclusion of these items in soft waste, indicates almost routine non-adherence to safe working practices. 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 S19).

Blenkharn and Odd (2008) found that ballistic protection gloves were not worn in 55% (22/40) of the incidents and Shiferaw et al. (2012) reported found that 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, both finding men less likely to wear gloves than women (Table S15). If this pattern is observed elsewhere it may indicate that men are at greater risk of exposure due to their non-adherence to safe working practices.

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 S20).

Though sharps and needlestick injuries are most prevalent in MWHs, Mol et al. (2016) also found high rates of traffic related injury, fracture or lesion for MHWs in Brazil (Figure S21). 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.

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

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 S22). The study highlighted heterogeneity between the results modeled 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.

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.

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 S12). 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. 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 some groups of people.

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, n.d.). 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 types of localized 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 from waste plants, smaller site-based facilities may be used infrequently or have a low throughput. This results in a requirement for auxiliary fuel to maintain the required combustion temperature and the temperature of 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 municipal solid waste (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. Medical waste often has a high polyvinyl chloride 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 (33R South Asia Expert Workshop, 2006). Thus, when medical waste is combusted, dioxins and related compounds (DRCs) could be released into the air and ash (Table S16).

Modern incinerator plant designs incorporate air pollution control (APC) units that mitigate the emissions to meet strict limits, for instance in Table S17. Many small scale incinerators in LIMICs feature no APC at all (Azage & Kumie, 2010; Bassey et al., 2006; Bazrafshan & Kord Mostafapoor, 2011; Manyele & Tanzania, 2004; Mesdaghinia et al., 2009; Musa et al., 2006; Phengxay et al., 2005; Unicomb et al., 2018).

To provide an indication of the potential emissions from medical waste combustion, a selection of factors are presented in Table S18. 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 by incinerators currently operated in LIMICs.

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 Table 1, as evidenced by seven studies reporting 26-100% of healthcare facilities use this method to treat medical waste. The proportions of medical waste open burned worldwide are unknown, and our evidence presented in Table 1 is not a representative global sample. However, it is estimated that MSW is open burned at a rate of between 13% and 50% across LIMICs (Velis & Cook, 2021), which may provide an indicator of how medical waste is treated in countries in lower income groups.

No specific data were available to quantify emissions from open burning of medical waste; however, the data for its uncontrolled incineration (Table S18) can serve as an indicator. Even if

Table 1. 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 (2011)	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 immunization centers (n = 13)	Injection equipment	Open burning	100%
Azage and Kumie (2010)	ETH	Health centers (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.

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 World Health Organization 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 emissions of dioxins and related compounds 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 World Health Organization'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. Reclamation for reuse or recycling of medical waste

As we will show in this section, the recovery of items from medical waste for reuse or recycling is a deeply concerning practice, not only because of the risk of exposure to infection of patients on whom the items are used, but also for those who collect and process them. The legality of the practice 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; 2011b; Stringer, 2011). The illicit nature of this practice, creates a challenge for researchers when gathering data to estimate the nature and magnitude of the practice as evidenced by criminological research (Feenan, 2002; Rhodes et al., 2003). Nonetheless, we have identified six publications that have investigated the practice in Iran, Nigeria, Bangladesh and Tanzania (Table S19).

The most comprehensive study was by Patwary et al. (2011a) who estimated that a small number of waste pickers were involved with medical waste reclamation, 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. A wide range of medical equipment was being recovered for reuse, including: scalpels, knives, saline drip bags, cotton, and injection equipment. This 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. Taghipour and Mosaferi (2009) found evidence of the practice in serval hospitals in Iran and Stringer (2011) provided multiple photographic examples and personal observations that evidence medical waste reclamation for reuse in Tanzania and Bangladesh.

Evidence of reclamation of items from medical waste for material recycling was also found during the cohort of 20 waste pickers studied by Patwary et al. (2011a) who collected plastics metal and glass for sale 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. No other evidence was found of the practice 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

Over 16 billion injections are administered every year, of which 41% are estimated to be carried out with reused injection equipment (Figure S23), a practice that is normalized across many LIMICs (Enwere & Diwe, 2014; Macaulay & Odiase, 2016; World Health Organization, 2014), for instance in Eastern Mediterranean and Western Pacific Regions (details of World Bank subregions are provided in Table S20), where rates were 70% and 75% respectively. Both NHS Scotland (n.d.) and Watterson (2004) also infer that the practice is normalized in HICs, though the modeling by Hauri et al. (2004) indicated that comparatively, the prevalence was extremely low in Western Europe and North America.

The rates of blood borne virus infection from reused injection equipment is dominated by HBV infections across all regions, with comparatively large numbers of infections across Western Pacific and South East Asia regions (Hauri et al., 2004; Figure S24). As with the global burden of disease modeling of risks to HCWs carried out by (Prüss-Üstün et al., 2005), the modeled exposure presented by Hauri et al. (2004; Figure S24) is not always proportional to the rate of infection (Figure S23).

The rate of infection from HIV is 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 modeled to be low, despite the high numbers of people living with HIV which is up to 20% of the population in some areas (UNAIDS, 2018). 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 unexpectedly while searching for other valuable materials in municipal solid waste (Zolnikov et al., 2019). We found evidence form six countries in South Asia, South America and West Africa indicating that the risk of injury to informal waste workers may be geographically widespread (Table S21). Lifetime prevalence of exposure ranged from 10% (Parizeau, 2015) to 61% (Afon, 2012). In Nepal, a 12 month prevalence of 3.4% was observed by Black in a comparatively large survey of waste pickers, in contrast to the 35% prevalence over 6 months reported by Chokhandre et al. (2017) for dumpsite waste pickers in India, albeit for both glass laceration and needlestick within the same category. Comparability between studies is challenging as the bases of each study are incongruous. Despite the large sample, Black et al. (2019) did not report the location or context where the survey respondents carried out their activities. 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. 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.

Based on the evidence reviewed here, 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.

7. Risk characterization and discussion

7.1. Challenge 1: Risk characterization 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 2. The assessment is based largely on data already

Table 2. Risk characterization summary for medical waste hazards.

Haz.	Pathway	Receptor	Geog.	Evidence and justification for risk assessment	Uncertainty (aleatoric and epistemic)	Receptor vulnerability	L	S	R	Global receptor context
Waste generation phase										
HIV HBV HCV	Medical sharps	HCW	LKA, TUR, NGA, GBR, all Africa global	Prevalence of sharps and needlestick injuries strongly evidenced in HICs and LIMICs (Astbury & Baxter, 1990; Auta et al., 2017; Cossart & deVries, 1994; Elder & Paterson, 2006; Elmiyeh et al., 2004; Enwere & Diwe, 2014; Kosgeroglu, et al., 2004; Mercier, 1994; World Health Organization, 2017). Exposure and infection rate modeled 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 & 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 2 2 4 2 3	4 5 3 4 3 4	4 10 6 16 6 12	HIC LIMIC HIC LIMIC HIC LIMIC
Collection, storage and handling phase										
HIV HBV HCV	Medical sharps	MWH	ETH, BRA, SDN, GBR, LBY, Global	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 & 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 & 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.	Evidence that many reported needlestick exposure events are underestimated (Cossart & deVries, 1994; Elmiyeh et al., 2004; Mercier, 1994)	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)	1 2 2 4 2 3	4 5 3 4 3 4	4 10 6 16 6 12	HIC LIMIC HIC LIMIC HIC LIMIC
Blood-borne viruses	Infectious soft waste	MWH	ETH	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).			na 3	na 4	na 12	HIC LIMIC

(continued)

Table 2. Continued.

Haz.	Pathway	Receptor	Geog.	Evidence and justification for risk assessment	Uncertainty (aleatoric and epistemic)	Receptor vulnerability	L	S	R	Global receptor context
Recovery treatment and disposal phase: 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. Polyvinyl chloride is used extensively in single use medical products (33R South Asia Expert Workshop, 2006) which results in a high chlorine content and thus higher dioxins and related compounds 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 & Kumie, 2010; Bassey et al., 2006; Bazrafshan & Kord Mostafapoor, 2011; Manyele & 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 & Cooper, 1992) which are far greater than the emissions thresholds in Europe and the US (World Health Organization, n.d.).	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 suggest 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, n.d.).	1	2	2	HIC
						Lack of emissions cleaning in medical waste incinerators in LIMICs (Azage & Kumie, 2010; Bassey et al., 2006; Bazrafshan & Kord Mostafapoor, 2011; Manyele & 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	LIMIC
		Waste workers (formal and informal)				Informal waste workers unlikely to wear respiratory protective equipment	3	4	12	
Recovery treatment and disposal phase: medical waste open burning										
Potentially haz. 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 & Kumie, 2010; Bassey et al., 2006; Bazrafshan & Kord Mostafapoor, 2011; Mesdaghinia et al., 2009; Musa et al., 2006; Phengxay et al., 2005; Unicomb, et al., 2018). The World Health Organization (2019c) still recommends open 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).	No evidence found to compare the relative risk of pathogen infection from medical waste with exposure to hazardous substances from open burning of medical waste.	Lack of emissions cleaning in medical waste incinerators in LIMICs (Azage & Kumie, 2010; Bassey et al., 2006; Bazrafshan & Kord Mostafapoor, 2011; Manyele & 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.	4	5	20	LIMIC
		Waste workers (informal)		As medical waste incinerators are reported to be a source of dioxins and related compound 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.		Informal waste workers unlikely to wear respiratory protective equipment	4	5	20	

(*continued*)

Table 2. Continued.

Haz.	Pathway	Receptor	Geog.	Evidence and justification for risk assessment	Uncertainty (aleatoric and epistemic)	Receptor vulnerability	L	S	R	Global receptor context
Recovery treatment and disposal phase: exposure to pathogens										
HIV	Medical sharps	Population	Global	Recapping of needles on injection equipment is a common practice across many LIMICs (Enwere & Diwe, 2014; Macaulay & 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, 2018). This is partly a result of the low reuse rate (15% to 18%) reported. But, also because 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	1	4	4	HIC
							2	5	10	LIMIC
HBV							1	3	3	HIC
							4	4	16	LIMIC
HCV							2	3	6	HIC
							3	4	12	LIMIC
Blood-borne viruses	Medical sharps	Informal waste collectors	NPL, PRY, ARG, IND, BGD, NGA	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).	Various methodological issues, such as lack of reporting on sample selection, and differing terminology over the cause of injury.	Informal waste workers are rarely equipped with ballistic protective clothing to mitigate the risk of injury from used injection equipment.	3	5	15	LIMIC
		Informal medical waste collectors	BGD	Specific risk to medical waste handling specialists in the informal recycling sector with four sources indicating the practice (Patwary et al., 2011a; Stringer, 2011; Taghipour & Mosaferi, 2009; Unicomb, et al., 2018).	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; 2011b; Stringer, 2011).	While medical waste specialist informal waste workers anticipate percutaneous injury, they seldom wear PPE.	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); personal protective equipment (PPE).

modeled 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. Despite evidence of high rates of sharps injury in HICs, we assess risks to their workers as 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.

7.2. Challenge 2: Risk characterization during storage, collection and handling

Rather than a reflection of the rate of in jury, the risks to MWHs from sharps in jury is based largely on the rate of infection during this phase (Table 2). The low rates of infection amongst the populations of HICs have resulted in a low risk of pathogen transmission particularly for HIV where the risk of transmission from needlestick injuries is just 0.3%. 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.

7.3. Challenge 3: Risk characterization during the reuse recovery, treatment and disposal

Strict regulation and enforcement of air pollution control systems in HICs results in a very low risk from medical waste incineration in HICs despite its comparatively high chlorine content (Table 2). By contrast, in LIMICs incineration of medical waste was categorized as medium high risk as facilities are less likely to incorporate emissions cleaning. We found substantial evidence that suggests open burning or rudimentary incineration are widely practiced as a form of treatment for medical waste in LIMICs. The high content of plastics, particularly chlorinated plastics, indicates that emissions from this uncontrolled combustion are likely to be extremely hazardous, resulting in high scores for this risk category.

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 recommends open burning as a last resort, but the evidence for making such a decision was not revealed in our research.

As there is a high reported rate of needle recapping in many LIMICs, we found a high risk of infection from HBV to their populations from reused injection equipment and a medium risk from HBC, partly driven by the rates of infection amongst the population.

Perhaps most concerning is the evidence related to a specialist group of waste pickers who reclaim used medical equipment to be cleaned and sold for reuse by substance abusers and medical waste providers. The highly illicit nature of this practice means that the scale of this activity is inherently challenging to quantify, with a handful 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 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. 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 3. Major topics revealed and highlighted in this review and recommendations for future research.

Topic		Recommended research	Rationale
T1	The open burning of medical waste in open uncontrolled fires or rudimentary incinerators.	Systematic review of the prevalence of medical waste open burning behavior, with a specific focus on the Global South where it is through to be most prevalent. Observational research to determine prevalence.	The prevalence of combustion practices for disposing of medical waste is not well understood. Understanding this is key to targeting cost-effective interventions.
		Quantitative assessment of risk to human health as a result of emissions from the open burning or rudimentary incineration of medical waste, focusing on workers in close proximity and the wider local, national and global populations.	Although our approach considered exposure on a qualitative basis, it was more strongly driven by potential hazards, particularly on dioxins and related compounds that are inevitably produced when medical waste is combusted at low temperatures. It is critical that our assumptions are validated through a quantitative approach.
		Innovation research to investigate cost-effective air pollution control equipment suitable for implementation in resource scarce contexts such as parts of the Global South.	Clearly open burning or rudimentary incineration is carried out as a cost-saving measure – therefore innovating to improve the practice cheaply would limit the harmful effects.
T2	The reclamation of medical waste for recovery by the informal sector	Global review of illicit trade in medical waste, focusing on the buyers rather than the informal sector suppliers.	This highly prevalent trade is driven by the market, therefore mitigation efforts necessitate an understanding of the trade, actors, mechanisms and centers of power.
T3	The mismanagement of medical sharps at the point of generation, handling and storage	Focus research aimed at prevention of harm: Behavioural change. Innovation of cost-effective devices to prevent reuse of items likely to transmit infection if reused.	The existence and prevalence of the practice and the risks that it poses to human health in the Global North and South are well established, therefore focus on direct prevention is recommended.

8. Limitations and prospects

Our review has several limitations. Firstly, we encompassed a very broad topic with the intention of summarizing and indicatively ranking aspects of medical waste that pose a substantial risk to human health. Our semi-qualitative approach was intended to signpost future researchers and implementers of change toward the topics which would have the greatest impact in mitigating these risks. As stated, we did not fully quantitatively assess risk, and our findings should not be treated as such. Having indicated the topics that are most important (ranked in Table S9), we recommend that three general topics are investigated in more detail, and have suggested potential avenues of research in Table 3.

Secondly, given the global paucity of data presented for each the three “Challenges” (Sections 3, 5 and 6), over-generalizing should be avoided—for example, we did not identify any data that directly quantify emissions from the open burning of medical waste and we do not understand its prevalence nor its quantitative risk to human health. Our evidence is largely hazard based, but it is critical that assumptions are validated through a quantitative approach based on new primary data collection (Table 3).

9. Conclusions

Mismanagement of medical devices and consumable items (medical waste) at the end of their engineered life is endemic throughout the Global South: from the moment they are discarded by healthcare workers, throughout the storage, collection and transport phases through to their disposal. It is somewhat ironic that, despite the potential for medical waste to transmit pathogens and potentially toxic substances, the healthcare sector itself does not always implement safe systems of work to protect its own members from potentially fatal hazards. The lack of monetary resources and knowledge may partly explain this phenomenon in parts of the Global South; yet, we find that in some highly developed parts of the Global North, poor handling of sharps at the point of generation has prevalence that is almost equivalent with some of the poorest countries in Africa.

As with the waste sector as a whole, our research indicates that medical waste management appears not to have received sufficient research attention, being on the margins of an already underfunded sector. 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 open, uncontrolled fire. These risks are far beyond what would be considered acceptable in most societies, yet the low volume of robust, quantitative evidence is not always strong enough to effectuate the resource allocation or policy change necessary to mitigate them.

We recommend that the relative risk of each of these approaches to disposal, particularly open burning, is urgently quantified to more accurately determine the risks and prioritize activities that could 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. Whereas research and evidence will always be required to justify interventions, there is already sufficient evidence to take converted and timely action to mitigate poor practice in almost all of the topics covered in this review.

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.

Acknowledgements

We are grateful to the Technical Advisory Board of the Engineering X Safer End of Engineered Life programme, of the Royal Academy of Engineering for their steering and insightful feedback, especially on early versions of this research and manuscript. We thank the Programme Board, chaired by Professor William Powrie FREng & the Academy staff, especially Hazel Ingham and Shaarad Sharma who provided support throughout the process. Ad hoc advice, guidance and criticism was provided by multiple stakeholder representatives, as listed in the relevant Engineering X report. We are grateful to Nick Rigas, (D-Waste) for the presentation of infographics. The research communicated and opinions expressed here are authors' alone.

Funding

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

ORCID

Ed Cook http://orcid.org/0000-0003-3902-7705
Costas A. Velis http://orcid.org/0000-0002-1906-726X

Data availability statement

All data associated with this review can be found within the main manuscript and the Supplementary Material, and original sources are stated.

References

3R South Asia Expert Workshop. (2006). *Promoting reduce, reuse, and recycle in south Asia: Synthesis report of 3R south Asia expert workshop: Kathmandu, Nepal, 30 August – 1 September 2006*. Asian Development Bank, Institute for Global Environmental Strategies & United Nations Environment Programme. https://iges.or.jp/en/publication_documents/pub/policyreport/en/454/intro.pdf

Afon, A. (2012). A survey of operational characteristics, socioeconomic and health effects of scavenging activity in Lagos, Nigeria. *Waste Management & Research: The Journal of the International Solid Wastes and Public Cleansing Association, ISWA*, *30*(7), 664–671. https://doi.org/10.1177/0734242X12444894

Akpieyi, A., Tudor, T. L., & Dutra, C. (2015). The utilisation of risk-based frameworks for managing healthcare waste: A case study of the National Health Service in London. [Article]. *Safety Science*, *72*, 127–132. https://doi.org/10.1016/j.ssci.2014.08.014

Ali, M., Wang, W., Chaudhry, N., & Geng, Y. (2017). Hospital waste management in developing countries: A mini review. *Waste Management & Research: The Journal of the International Solid Wastes and Public Cleansing Association, ISWA*, *35*(6), 581–592. https://doi.org/10.1177/0734242X17691344

Al-Momani, H., Obaidat, M., Khazaleh, A., Muneizel, O., Afyouni, N. M., & Fayyad, S. M. (2019). Review of medical waste management in Jordanian health care organisations. *British Journal of Healthcare Management*, *25*(8), 1–8. https://doi.org/10.12968/bjhc.2019.0041

Amsalu, A., Worku, M., Tadesse, E., & Shimelis, T. (2016). The exposure rate to hepatitis B and C viruses among medical waste handlers in three government hospitals, southern Ethiopia. *Epidemiology and Health*, *38*, e2016001-e2016001. https://doi.org/10.4178/epih/e2016001

Anagaw, B., Shiferaw, Y., Anagaw, B., Belyhun, Y., Erku, W., Biadgelegn, F., Moges, B., Alemu, A., Moges, F., & Mulu, A. (2012). Seroprevalence of hepatitis B and C viruses among medical waste handlers at Gondar town health institutions, northwest Ethiopia. *BMC Research Notes*, *5*(1), 55. https://doi.org/10.1186/1756-0500-5-55

Arafa, A., & Eshak, E. S. (2020). Medical waste handling and hepatitis B virus infection: A meta-analysis. *American Journal of Infection Control*, *48*(3), 316–319. https://doi.org/10.1016/j.ajic.2019.08.011

Astbury, C., & Baxter, P. J. (1990). Infection risks in hospital staff from blood: Hazardous injury rates and acceptance of hepatitis B immunization. *Occupational Medicine*, *40*(3), 92–93. https://doi.org/10.1093/occmed/40.3.92

Auta, A., Adewuyi, E. O., Tor-Anyiin, A., Aziz, D., Ogbole, E., Ogbonna, B. O., & Adeloye, D. (2017). Health-care workers' occupational exposures to body fluids in 21 countries in Africa: systematic review and meta-analysis. *Bulletin of the World Health Organization*, *95*(12), 831–841F. https://doi.org/10.2471/BLT.17.195735

Azage, M., & Kumie, A. (2010). Healthcare waste generation and its management system: the case of health centers in West Gojjam Zone, Amhara Region, Ethiopia. *Ethiopian Journal of Health Development*, *24*(2), 121–126. https://doi.org/10.4314/ejhd.v24i2.62960

Bassey, B. E., Benka-Coker, M. O., & Aluyi, H. S. A. (2006). Characterization and management of solid medical wastes in the Federal Capital Territory, Abuja Nigeria. *African Health Sciences*, *6*(1), 58–63. https://doi.org/10.5555/afhs.2006.6.1.58

Batterman, S. (2004). *Findings on an assessment of small-scale incinerators for health-care waste*. World Health Organization. https://www.who.int/water_sanitation_health/medicalwaste/en/smincinerators.pdf

Bazrafshan, E., & Kord Mostafapoor, F. (2011). Survey of medical waste characterization and management in Iran: a case study of Sistan and Baluchestan Province. *Waste Management & Research: The Journal of the*

International Solid Wastes and Public Cleansing Association, ISWA, *29*(4), 442–450. https://doi.org/10.1177/0734242X10374901

BBC Urdu. (2013). *Medical waste illegally sold off from Pakistan hospital* (S. Jaffery (Ed.)). BBC.

Benzaken, A. S., Girade, R., Catapan, E., Pereira, G. F. M., Almeida, E. C. d., Vivaldini, S., Fernandes, N., Razavi, H., Schmelzer, J., Ferraz, M. L., Ferreira, P. R. A., Pessoa, M. G., Martinelli, A., Souto, F. J. D., Walsh, N., & Mendes-Correa, M. C. (2019). Hepatitis C disease burden and strategies for elimination by 2030 in Brazil. A mathematical modeling approach. *The Brazilian Journal of Infectious Diseases*, *23*(3), 182–190. https://doi.org/10.1016/j.bjid.2019.04.010

Black, M., Karki, J., Lee, A. C. K., Makai, P., Baral, Y. R., Kritsotakis, E. I., Bernier, A., & Fossier Heckmann, A. (2019). The health risks of informal waste workers in the Kathmandu Valley: A cross-sectional survey. *Public Health*, *166*, 10–18. https://doi.org/10.1016/j.puhe.2018.09.026

Blenkharn, J. I., & Odd, C. (2008). Sharps injuries in healthcare waste handlers. *The Annals of Occupational Hygiene*, *52*(4), 281–286. https://doi.org/10.1093/annhyg/men010

Burns, C. J., LaKind, J. S., Mattison, D. R., Alcala, C. S., Branch, F., Castillo, J., Clark, A., Clougherty, J. E., Darney, S. P., Erickson, H., Goodman, M., Greiner, M., Jurek, A. M., Miller, A., Rooney, A. A., & Zidek, A. (2019). A matrix for bridging the epidemiology and risk assessment gap. *Global Epidemiology*, *1*, 100005. https://doi.org/10.1016/j.gloepi.2019.100005

Canadian Centre for Occupational Health & Safety. (2020). Needlestick and Sharps Injuries. Retrieved 2020, from https://www.ccohs.ca/oshanswers/diseases/needlestick_injuries.html.

Caniato, M., Tudor, T., & Vaccari, M. (2015). International governance structures for health-care waste management: A systematic review of scientific literature. [Review]. *Journal of Environmental Management*, *153*, 93–107. https://doi.org/10.1016/j.jenvman.2015.01.039

Cheng, V. C.-C., Chan, J. F.-W., Hung, I. F.-N., & Yuen, K.-Y. (2017). Viral Infections, an overview with a focus on prevention of transmission. In S. R. Quah (Ed.), *International encyclopedia of public health* (2nd ed. , pp. 368–377). Academic Press.

Chokhandre, P., Singh, S., & Kashyap, G. C. (2017). Prevalence, predictors and economic burden of morbidities among waste-pickers of Mumbai, India: a cross-sectional study. *Journal of Occupational Medicine and Toxicology*, *12*(1), 30. https://doi.org/10.1186/s12995-017-0176-3

Ciplak, N., & Kaskun, S. (2015). Healthcare waste management practice in the West Black Sea Region, Turkey: A comparative analysis with the developed and developing countries. *Journal of the Air & Waste Management Association (1995)*, *65*(12), 1387–1394. https://doi.org/10.1080/10962247.2015.1076539

Cogut, A. (2016). *Open burning of waste: A global health disaster*. Switzerland. https://bit.ly/37At6id

Cooper, C., Booth, A., Varley-Campbell, J., Britten, N., & Garside, R. (2018). Defining the process to literature searching in systematic reviews: a literature review of guidance and supporting studies. *BMC Medical Research Methodology*, *18*(1), 85. https://doi.org/10.1186/s12874-018-0545-3

Cossart, Y. E., & deVries, B. (1994). Needlestick injury in medical students. *The Medical Journal of Australia*, *160*(7), 398–400. https://doi.org/10.5694/j.1326-5377.1994.tb138262.x

Cullen, B. L., Genasi, F., Symington, I., Bagg, J., McCreaddie, M., Taylor, A., Henry, M., Hutchinson, S. J., & Goldberg, D. J. (2006). Potential for reported needlestick injury prevention among healthcare workers through safety device usage and improvement of guideline adherence: expert panel assessment. *The Journal of Hospital Infection*, *63*(4), 445–451. https://doi.org/10.1016/j.jhin.2006.04.008

Cunningham, R. N., Simpson, C. D., & Keifer, M. C. (2012). Hazards faced by informal recyclers in the squatter communities of Asunción. *International Journal of Occupational and Environmental Health*, *18*(3), 181–187.

Elder, A., & Paterson, C. (2006). Sharps injuries in UK health care: a review of injury rates, viral transmission and potential efficacy of safety devices. *Occupational Medicine (Oxford, England)*, *56*(8), 566–574. https://doi.org/10.1093/occmed/kql122

Elmiyeh, B., Whitaker, I. S., James, M. J., Chahal, C. A. A., Galea, A., & Alshafi, K. (2004). Needle-stick injuries in the National Health Service: a culture of silence. *Journal of the Royal Society of Medicine*, *97*(7), 326–327. https://doi.org/10.1258/jrsm.97.7.326

Enwere, O. O., & Diwe, K. C. (2014). Knowledge, perception and practice of injection safety and healthcare waste management among teaching hospital staff in south east Nigeria: an intervention study. *The Pan African Medical Journal*, *17*, 218. https://doi.org/10.11604/pamj.2014.17.218.3084

European Commission. (2008). *Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives*. https://eur-lex.europa.eu/legal-content/FR/TXT/?uri=OJ:L:2008:312:TOC

Feenan, D. (2002). Legal issues in acquiring information about illegal behaviour through criminological research. *British Journal of Criminology*, *42*(4), 762–781. https://doi.org/10.1093/bjc/42.4.762

Fiedler, H. (2007). National PCDD/PCDF release inventories under the Stockholm convention on persistent organic pollutants. *Chemosphere*, *67*(9), S96–S108. https://doi.org/10.1016/j.chemosphere.2006.05.093

Franka, E., El-Zoka, A., Hussein, A., Elbakosh, M., Arafa, A., & Ghenghesh, K. (2009). Hepatitis B virus and hepatitis C virus in medical waste handlers in Tripoli, Libya. *The Journal of Hospital Infection*, *72*(3), 258–261. https://doi.org/10.1016/j.jhin.2009.03.019

Hagenmaier, H., Kraft, M., Brunner, H., & Haag, R. (1987). Catalytic effects of fly ash from waste incineration facilities on the formation and decomposition of polychlorinated dibenzo-p-dioxins and polychlorinated dibenzofurans. *Environmental Science & Technology*, *21*(11), 1080–1084. https://doi.org/10.1021/es00164a006

Harhay, M. O., Halpern, S. D., Harhay, J. S., & Olliaro, P. L. (2009). Health care waste management: a neglected and growing public health problem worldwide. *Tropical Medicine & International Health: TM & IH*, *14*(11), 1414–1417. https://doi.org/10.1111/j.1365-3156.2009.02386.x

Hauri, A. M., Armstrong, G. L., & Hutin, Y. J. F. (2004). The global burden of disease attributable to contaminated injections given in health care settings. *International Journal of STD & AIDS*, *15*(1), 7–16. https://doi.org/10.1258/095646204322637182

Health and Safety Executive. (2020). Information and services. Retrieved October 13, 2020, from https://www.hse.gov.uk/.

Hossain, M. S., Santhanam, A., Nik Norulaini, N. A., & Omar, A. K. (2011). Clinical solid waste management practices and its impact on human health and environment-A review. *Waste Management (New York, NY)*, *31*(4), 754–766. https://doi.org/10.1016/j.wasman.2010.11.008

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

International Labour Organization. (2020). ILOSTAT: The leading source of labour statistics. Retrieved October 13, 2020, from https://ilostat.ilo.org/.

Israel Deneke, H., Mohamed Aqiel, D., Biruck Desalegn, Y., & Hanibale Atsbeha, Z. (2010). Assessing the management of healthcare waste in Hawassa city, Ethiopia. *Waste Management & Research*, *29*(8), 854–862. https://doi.org/10.1177/0734242X10379496

Jiang, C., Ren, Z., Tian, Y., & Wang, K. (2012). Application of best available technologies on medical wastes disposal/treatment in China (with case study). *Procedia Environmental Sciences*, *16*, 257–265. https://doi.org/10.1016/j.proenv.2012.10.036

Kanisek, S., Gmajnić, R., & Barać, I. (2018). Risk of potential exposure incident in non-healthcare workers in contact with infectious and municipal waste. *Zdravstveno Varstvo*, *57*(2), 65–71. https://doi.org/10.2478/sjph-2018-0009

Kaya, G. K., Ward, J. R., & Clarkson, P. J. (2019). A framework to support risk assessment in hospitals. *International Journal for Quality in Health Care: Journal of the International Society for Quality in Health Care*, *31*(5), 393–401. https://doi.org/10.1093/intqhc/mzy194

Kaza, S., Yao, L., Bhada-Tata, P., & Van Woerden, F. (2018). *Country level dataset* [Data set]. Retrieved July 26, 2019, from https://datacatalog.worldbank.org/dataset/what-waste-global-database

Kerdsuwan, S., & Laohalidanond, K. (2015). Efficiency improvement for medical waste management. In J. Yan (Ed.), *Handbook of Clean Energy Systems*. https://doi.org/10.1002/9781118991978.hces196

Khan, B. A., Cheng, L., Khan, A. A., & Ahmed, H. (2019). Healthcare waste management in Asian developing countries: A mini review. *Waste Management & Research: The Journal of the International Solid Wastes and Public Cleansing Association, ISWA*, *37*(9), 863–875. https://doi.org/10.1177/0734242X19857470

Kosgeroglu, N., Ayranci, U., Vardareli, E., & Dincer, S. (2004). Occupational exposure to hepatitis infection among Turkish nurses: frequency of needle exposure, sharps injuries and vaccination. *Epidemiology and Infection*, *132*(1), 27–33. https://doi.org/10.1017/S0950268803001407

Lau, W. W. Y., Shiran, Y., Bailey, R. M., Cook, E., Stuchtey, M. R., Koskella, J., Velis, C. A., Godfrey, L., Boucher, J., Murphy, M. B., Thompson, R. C., Jankowska, E., Castillo Castillo, A., Pilditch, T. D., Dixon, B., Koerselman, L., Kosior, E., Favoino, E., Gutberlet, J., … Palardy, J. E. (2020). Evaluating scenarios toward zero plastic pollution. *Science (New York, NY)*, *369*(6510), 1455–1461. https://doi.org/10.1126/science.aba9475

Macaulay, B. M., & Odiase, F. M. (2016). Medical waste management practices in developing countries: A case study of health facilities in Akure, Nigeria. *International Journal of Environment and Waste Management*, *17*(2), 103–127. https://doi.org/10.1504/IJEWM.2016.076756

Manyele, S. V., & Tanzania, V. (2004). Effects of improper hospital-waste management on occupational health and safety. *African Newsletter on Occupational Health and Safety*, *14*(2), 30–33.

Mercier, C. (1994). Reducing the incidence of sharps injuries. *British Journal of Nursing (Mark Allen Publishing)*, *3*(17), 897. https://doi.org/10.12968/bjon.1994.3.17.897

Mesdaghinia, A., Naddafi, K., Amir Hossein, M., & Saeedi, R. (2009). Waste management in primary healthcare centres of Iran. *Waste Management & Research: The Journal of the International Solid Wastes and Public Cleansing Association, ISWA*, *27*(4), 354–361. https://doi.org/10.1177/0734242X09335693

Mitchell, E. J. S., Cottom, J. W., Phillips, D., & Dooley, B. (2019). *A review of the imapct of domestic combustion on UK air quality*. HETAS. https://www.hetas.co.uk/scientific-review-casts-doubt-on-impact-of-domestic-burning/

Mol, M. P. G., Gonçalves, J. P., Silva, E. A., Scarponi, C. F., Greco, D. B., Cairncross, S., & Heller, L. (2016). Seroprevalence of hepatitis B and C among domestic and healthcare waste handlers in Belo Horizonte, Brazil. *Waste Management & Research: The Journal of the International Solid Wastes and Public Cleansing Association, ISWA*, *34*(9), 875–883. https://doi.org/10.1177/0734242X16649686

Musa, O. I., Parakoyi, D. B., & Akanbi, A. A. (2006). Evaluation of health education intervention on safe immunization injection among health workers in Ilorin, Nigeria. *Annals of African Medicine*, *5*(3), 122–128. http://www.bioline.org.br/request?am06029

Nagao, Y., Baba, H., Torii, K., Nagao, M., Hatakeyama, K., Iinuma, Y., Ichiyama, S., Shimokata, K., & Ohta, M. (2007). A long-term study of sharps injuries among health care workers in Japan. *American Journal of Infection Control*, *35*(6), 407–411. https://doi.org/10.1016/j.ajic.2006.03.015

National Research Council (US) Committee on Health Effects of Waste Incineration. (2000). *Waste incineration & public health*. National Academies Press (US).

NHS Employers. (2015). *Managing the risks of sharps injuries*. The NHS Confederation Company Ltd. https://www.nhsemployers.org/-/media/Employers/Documents/Retain-and-improve/Health-and-wellbeing/Managing-the-risks-of-sharps-injuries-v7.pdf

NHS Scotland. (n.d.). *Needle stick injuries: sharpen your awareness*. https://www.sehd.scot.nhs.uk/publications/Nisa/nisa.pdf

Pandelova, M., Stanev, I., Henkelmann, B., Lenoir, D., & Schramm, K.-W. (2009). Correlation of PCDD/F and PCB at combustion experiments using wood and hospital waste. Influence of (NH4)2SO4 as additive on PCDD/F and PCB emissions. *Chemosphere*, *75*(5), 685–691. https://doi.org/10.1016/j.chemosphere.2008.12.043

Parizeau, K. (2015). Re-representing the city: waste and public space in Buenos Aires, Argentina in the late 2000s. *Environment and Planning A: Economy and Space*, *47*(2), 284–299. https://doi.org/10.1068/a130094p < Go

Patil, A. D., & Shekdar, A. V. (2001). Health-care waste management in India. [Article]. *Journal of Environmental Management*, *63*(2), 211–220. https://doi.org/10.1006/jema.2001.0453

Patwary, M. A., O'Hare, W. T., & Sarker, M. H. (2011b). Assessment of occupational and environmental safety associated with medical waste disposal in developing countries: a qualitative approach. *Safety Science*, *49*(8–9), 1200–1207. https://doi.org/10.1016/j.ssci.2011.04.001

Patwary, M. A., O'Hare, W. T., & Sarker, M. H. (2011a). An illicit economy: Scavenging and recycling of medical waste. [Article]. *Journal of Environmental Management*, *92*(11), 2900–2906. https://doi.org/10.1016/j.jenvman.2011.06.051

Peters, M. D. J., Marnie, C., Tricco, A. C., Pollock, D., Munn, Z., Alexander, L., McInerney, P., Godfrey, C. M., & Khalil, H. (2020). Updated methodological guidance for the conduct of scoping reviews. *JBI Evidence Synthesis*, *18*(10), 2119–2126. https://doi.org/10.11124/jbies-20-00167

Phengxay, S., Okumura, J., Miyoshi, M., Sakisaka, K., Kuroiwa, C., & Phengxay, M. (2005). Health-care waste management in Lao PDR: a case study. *Waste Management & Research: The Journal of the International Solid Wastes and Public Cleansing Association, ISWA*, *23*(6), 571–581. https://doi.org/10.1177/0734242X05059802

Prüss-Üstün, A., Rapiti, E., & Hutin, Y. (2005). Estimation of the global burden of disease attributable to contaminated sharps injuries among health-care workers. *American Journal of Industrial Medicine*, *48*(6), 482–490.

Prüss-Üstün, A., Wolf, J., Corvalán, C., Bos, R., & Neira, M. (2016). *Preventing disease through healthy environments: a global assessment of the burden of disease from environmental risks*. World Health Organization.

Quaß, U., Fermann, M., & Bröker, G. (2004). The European dioxin air emission inventory project––final results. *Chemosphere*, *54*(9), 1319–1327. https://doi.org/10.1016/S0045-6535(03)00251-0

Rhodes, S. D., Bowie, D. A., & Hergenrather, K. C. (2003). Collecting behavioural data using the world wide web: considerations for researchers. *Journal of Epidemiology and Community Health*, *57*(1), 68–73. https://doi.org/10.1136/jech.57.1.68

Rice, B. D., Tomkins, S. E., & Ncube, F. M. (2015). Sharp truth: health care workers remain at risk of bloodborne infection. *Occupational Medicine (Oxford, England)*, *65*(3), 210–214. https://doi.org/10.1093/occmed/kqu206

Royal College of Nursing. (2018). *Freedom of information follow up report on management of waste in the NHS*. https://www.rcn.org.uk/-/media/royal-college-of-nursing/documents/publications/2018/february/pdf-006683.pdf?la=en

Secretariat of the Stockholm Convention on Persistent Organic Pollutants. (2008). *Open burning of waste, including burning of landfill sites*. United Nations Environment Program (UNEP). http://www.pops.int/Implementation/BATandBEP/BATBEPGuidelinesArticle5/tabid/187/ctl/Download/mid/21090/Default.aspx?id=217&ObjID=1516

Shiferaw, Y., Abebe, T., & Mihret, A. (2012). Sharps injuries and exposure to blood and bloodstained body fluids involving medical waste handlers. *Waste Management & Research: The Journal of the International Solid Wastes and Public Cleansing Association, ISWA*, *30*(12), 1299–1305. https://doi.org/10.1177/0734242X12459550

Singh, N., Ogunseitan, O. A., & Tang, Y. (2022). Medical waste: Current challenges and future opportunities for sustainable management. *Critical Reviews in Environmental Science and Technology*, *52*(11), 2000–2022. https://doi.org/10.1080/10643389.2021.1885325

Stringer, R. (2011). *Medical waste and human rights: Submission to the UN Human Rights Council Special Rapporteur*. Health Care Without Harm. https://noharm-europe.org/sites/default/files/documents-files/1684/MedWaste_Human_Rights_Report.pdf

Taghipour, H., & Mosaferi, M. (2009). Characterization of medical waste from hospitals in Tabriz, Iran. [Article]. *The Science of the Total Environment*, *407*(5), 1527–1535. https://doi.org/10.1016/j.scitotenv.2008.11.032

The World Bank. (2020). *World Bank Open Data: Free and open access to global development data* [Data set]. Retrieved December 14, 2020, from https://data.worldbank.org/

Trozzi, C., Nielsen, O.-K., Hjelgaard, K., Sully, J., & Woodfield, M. (2016). *EMEP/EEA air pollutant emission inventory guidebook 2016*. European Environment Agency. https://www.eea.europa.eu/ds_resolveuid/WQ7UPR94CF

UNAIDS. (2018). HIV prevalence. Retrieved 2020, from https://aidsinfo.unaids.org/.

Unicomb, L., Horng, L., Alam, M.-U., Halder, A. K., Shoab, A. K., Ghosh, P. K., Islam, M. K., Opel, A., & Luby, S. P. (2018). Health-care facility water, sanitation, and health-care waste management basic service levels in Bangladesh: Results from a nation-wide survey. *The American Journal of Tropical Medicine and Hygiene*, *99*(4), 916–923. https://www.ajtmh.org/content/journals/10.4269/ajtmh.18-0133

Vaccari, M., Tudor, T., & Perteghella, A. (2018). Costs associated with the management of waste from healthcare facilities: An analysis at national and site level. *Waste Management & Research: The Journal of the International Solid Wastes and Public Cleansing Association, ISWA*, *36*(1), 39–47. https://doi.org/10.1177/0734242X17739968

Velis, C. A., & Cook, E. (2021). Mismanagement of plastic waste through open burning with emphasis on the global south: A systematic review of risks to occupational and public health. *Environmental Science & Technology*, *55*(11), 7186–7207. https://doi.org/10.1021/acs.est.0c08536

Walker, B. L., & Cooper, C. D. (1992). Air pollution emission factors for medical waste incinerators. *Journal of the Air & Waste Management Association*, *42*(6), 784–791. https://doi.org/10.1080/10473289.1992.10467030

Watterson, L. (2004). Monitoring sharps injuries: EPINet surveillance results. [Review]. *Nursing Standard (Royal College of Nursing (Great Britain): 1987)*, *19*(3), 33–38. https://doi.org/10.7748/ns2004.09.19.3.33.c3701

Wilson, D. C., Rodic, L., Modak, P., Soos, R., Rogero, A. C., Velis, C., … Simonett, O. (2015). *Global waste management outlook*. U. N. E. Programme. https://wedocs.unep.org/bitstream/handle/20.500.11822/9672/-Global_Waste_Management_Outlook-2015Global_Waste_Management_Outlook.pdf.pdf?sequence=3&amp%3BisAllowed=

Windfeld, E. S., & Brooks, M. S.-L. (2015). Medical waste management–A review. *Journal of Environmental Management*, *163*, 98–108.

Woode, O. M., Wellington, E., Rice, B., Gill, O. N., & Ncube, F., contributors. (2014). *Eye of the needle: United Kingdom surveillance of significant occupational exposures to bloodborne viruses in healthcare workers*. Public Health England. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/385300/EoN_2014_-_FINAL_CT_3_sig_occ.pdf

World Health Organization and the United Nations Children's Fund. (2019). *WASH in health care facilities. Global Baseline Report 2019*. Geneva: https://www.unwater.org/publications/wash-in-health-care-facilities-global-baseline-report-2019/#:~:text=The%202019%20global%20baseline%20report,sub%2Dstandard%20in%20every%20region.

World Health Organization. (2020a). *Reducing UPOPs and mercury releases from the health sector in Africa*. Geneva. https://greenhealthcarewaste.org/wp-content/uploads/2020/12/Decision-Tree-for-the-treatment-of-COVID-19-Healthcare-Waste.pdf

World Health Organization. (2006). *World Health Report: Health Workers: a global profile*. World Health Organization. https://www.who.int/whr/2006/06_chap1_en.pdf

World Health Organization. (2012). *Rapid risk assessment of acute public health events. WHO/HSE/GAR/ARO/2012.1)*. World Health Organization. https://www.who.int/csr/resources/publications/HSE_GAR_ARO_2012_1/en/

World Health Organization. (2014). *Safe management of wastes from health-care activities. 978 92 4 154856 4)*. World Health Organization. https://wash.unhcr.org/download/safe-management-of-wastes-from-health-care-activities-2nd-ed-who/

World Health Organization. (2015). *Water, sanitation and hygiene in health care facilities: status in low and middle income countries and way forward*. World Health Organization. https://apps.who.int/iris/bitstream/handle/10665/154588/9789241508476_eng.pdf;jsessionid=6BD30175CC3AC7FAC997ABC1DCC8773A?sequence=1

World Health Organization. (2016). *Global strategy on human resources for health: Workforce 2030*. World Health Organization. https://apps.who.int/iris/bitstream/handle/10665/250368/9789241511131-eng.pdf

World Health Organization. (2017). *Report on health-care waste management (HCWM) status in countries of the south-east Asia region (SEA Region)*. World Health Organization. https://apps.who.int/iris/rest/bitstreams/1087970/retrieve

World Health Organization. (2019a). Hepatitis B (HepB3): Immunization coverage estimates by WHO region. *Global Health Observatory data repository*. https://apps.who.int/gho/data/view.main.81300

World Health Organization. (2019b). Number of people (all ages) living with HIV Estimates by WHO region. *Global Health Observatory data repository*. https://apps.who.int/gho/data/view.main.22100WHO?lang=en

World Health Organization. (2019c). *Overview of technologies for the treatment of infectious and sharp waste from health care activities* 978 92 4 151622 8). https://apps.who.int/iris/bitstream/handle/10665/328146/9789241516228-eng.pdf?sequence=1&isAllowed=y

World Health Organization. (2020b). *World health data platform* [Data set]. Retrieved October 13, 2020, from https://www.who.int/data

World Health Organization. (n.d.). *Module 16: Incineration of healthcare waste and the Stockholm Convention guidelines*. World Health Organization. https://www.who.int/water_sanitation_health/facilities/waste/training_modules_waste_management/en/

Yizengaw, E., Getahun, T., Geta, M., Mulu, W., Ashagrie, M., Hailu, D., & Tedila, S. (2018). Sero-prevalence of hepatitis B virus infection and associated factors among health care workers and medical waste handlers in primary hospitals of North-west Ethiopia. *BMC Research Notes*, *11*(1), 437. https://doi.org/10.1186/s13104-018-3538-8

Yoon, C.-W., Kim, M.-J., Park, Y.-S., Jeon, T.-W., & Lee, M.-Y. (2022). A review of medical waste management systems in the Republic of Korea for hospital and medical waste generated from the COVID-19 pandemic. *Sustainability*, *14*(6), 3678. https://doi.org/10.3390/su14063678

Zolnikov, T. R., Ramirez-Ortiz, D., Moraes, H., Nogueira, V. R. C., Dominguez, A., & Galato, D. (2019). Continued medical waste exposure of recyclable collectors despite dumpsite closures in Brazil. *Journal of Health & Pollution*, *9*(23), 190905. https://doi.org/10.5696/2156-9614-9.23.190905