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EngineeringX

Global Review on Safer End of Engineered Life

Royal Academy of Engineering

Lloyd's Register Foundation

This Global Review was commissioned as part of the Engineering X Safer End of Engineered Life programme which is 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.

The Engineering X Safer End of Engineered Life programme seeks to improve safety and reduce harm caused by the decommissioning, dismantling and disposal of engineered products, artefacts, and structures at the end of their life.

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A research project carried out and coordinated by the University of Leeds in partnership with the International Solid Waste Association (ISWA) D-Waste and Independent Safety Services Ltd.

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Global Review on Safer End of Engineered Life

Waste picker harvests materials from Bantargebang landfill, Jakarta, Indonesia; © Rumbo a lo desconocido (2019).

Professor William Powrie FREng

Foreword

Professor William Powrie FREng, Chair of the Engineering X Safer End of Engineered Life programme

The decommissioning, dismantling and disposal of products and structures at the end of their life can damage the environment and squander scarce resources if not carried out responsibly. These processes can also be dangerous and harmful to those people involved in them, especially as the waste and processes in question are often displaced to parts of the world least able to manage them safely.

The Engineering X Safer End of Engineered Life programme seeks to address these challenges and improve safety globally by: understanding and applying practical interventions; building diverse international communities to share evidence, knowledge, and good practice; and raising awareness and a broader understanding of the global challenges of dealing safely and ethically with the billions of tonnes of end-of-life materials, artefacts and structures that humanity produces each year.

The programme focused initially on improving safety in the decommissioning of offshore structures and ships globally, a notoriously difficult and dangerous task in some contexts. We then commissioned this Global Review to look at other categories of engineered materials and products and the safety of associated disposal and decommissioning practices. These were plastic, medical, electronic, construction and demolition waste. Methods of land disposal were also investigated. We hoped to map waste flows, identify good practice, and understand the most critical safety issues worldwide and on which the programme should focus going forward.

What became clear was that our efforts should be centred not on the types of materials and products – as for ships and offshore structures – but the processes employed in their disposal.

The research identified the harm caused by uncontrolled burning and dumping worldwide, particularly for those most exposed in the informal recycling sector. This is not just a technical issue – economics and human need also play a part. In preparing the report, we have been reminded repeatedly that we must strive to create appropriate solutions that work in local contexts to reduce harm and not to assume that we have all the answers. We must listen to all voices as we seek to address these complex global challenges.

This report provides a rigorous and valuable evidence base. I would like to thank the authors from the University of Leeds and their partners for their substantial work, as well as members of the Technical Advisory Group for their invaluable insights and unstinting efforts in reviewing earlier drafts. I also thank Lloyd's Register Foundation, our funding partner for the programme and co-founder of Engineering X.

We hope this review will help bring attention to the most pressing and underdiscussed challenges concerning the end of engineered life that threaten the safety and wellbeing of millions of individuals worldwide. We have identified priority areas that the Safer End of Engineered Life programme seeks to address, starting with the burning of waste. We hope the international community will mobilise to collaboratively address this urgent global challenge and invite you to join us.

Dr Ruth Boumphrey

Foreword

Dr Ruth Boumphrey, Director of Research, Lloyd's Register Foundation

When we published our Insight work on Global Safety Challenges we identified a range of safety problems that arise when engineered assets – large and small – reach the end of their lives. From ships and oil rigs to medical and electronic items, we are seeking to understand and address the safety problems associated with the 'end of engineered life'.

We want to make responsible and sustainable interventions, and these must be driven by evidence. Lack of evidence can slow and misdirect efforts. This Global Review takes an important step in reviewing the evidence in this field. It fills an important gap that is often overlooked: the safety issues surrounding mismanaged waste, and the resulting dire consequences for many around the world.

Now is the time for collective action: it is unacceptable that in today's world we do not have a proper understanding of how to safely and responsibly manage the waste from engineered items. While important conversations on circular economy and Industry 4.0 steam ahead we must also shine a spotlight on the reality of the situation today for many people, especially in the world's poorest countries. By undertaking a systematic review, whose initial focus was specific waste streams, the report's authors have identified the most pressing safety issues which relate to open burning of waste, to dumpsites, and to the waste pickers who make their livings in the waste economy.

Lloyd's Register Foundation is an independent global charity with a mission to engineer a safer world. We know that global challenges need global solutions. They cannot be tackled by working alone. So together with the Royal Academy of Engineering we founded Engineering X bringing together a global community to tackle some of the greatest challenges of our age.

We hope that this report will shine a spotlight on these long-neglected issues and help us build new partnerships that lead to action. We are seeking out collaborators who share our deepest values and strong social purpose to help us bring change by lending their voices and energy to this mission. Join us.


Dr Costas Velis

On behalf of the authors

An Introduction by Dr Costas Velis, University of Leeds

Our planet's resources are finite and thus valuing and preserving the resources we use in our engineered materials, products and structures is the only long-term and sustainable way forward. We can and should treat our end-of-life engineered objects as resources within a circular economy.

Some 200 years ago, the so called 'sanitation era' saw humanity start to use science and engineering to manage substantially increased quantities of solid waste in order to protect human health. Today, our technological and managerial successes in this direction are well celebrated and, with the benefit of new and emerging knowledge and expertise, we continue to make improvements with a positive impact on public health.

However, in the intervening years, and particularly in the affluent Global North, we have somehow lost sight of the link between the mismanagement of end-of-life engineered resources ('waste' or 'after-use' products) and the risks posed to human life and health. Yet such threats remain a reality for tens of millions of informal waste sector workers (waste pickers, informal sector recyclers) and their communities in the low- and middle-income countries, largely in the Global South. Here, the risks from exposure to such things as the open, uncontrolled burning of waste are far higher, with the highest risk occurring in and around open dumpsites where there are few, if any, protective measures in place.

In this Global Review on Safer End of Engineered Life, we take a long overdue and systematic look at the scientific evidence around waste and resources management and the impact on human health and life. Surprisingly, this research appears to be the first of its kind anywhere in the world. We offer suggestions for immediate corrective action that should be taken and identify where engineering solutions could mitigate and prevent harm to human life and health. We also suggest where further research is required into the nature and magnitude of the problem.

We hope our work will not only address the world's immediate challenges regarding solid waste and end of engineered life but also provide a stepping stone toward the development of circular economies worldwide that explicitly and fundamentally value human health and safety. In this way, we may also find we have progressed towards achieving many other important Sustainable Development Goals, such as poverty alleviation, clean air, climate change mitigation, sustainable consumption and production, and prevention of plastic pollution. Surely, it's worth a shot?

Heavily polluted river in Sierra Leone; © Amanda Ingram – WasteAid (2018).

Executive summary

Nearly a billion tonnes of waste threaten the health and wellbeing of billions of people worldwide

Dumpsite on fire in The Gambia; © WasteAid (2017).

In contemporary society, few engineered products and structures will last indefinitely, either by design, or through technical, functional or stylistic obsolescence. These products and structures can be said to have completed the use phase, reached the end of their engineered life, or become, for legal purposes, solid waste.

Of all the municipal solid waste (MSW) generated on earth, 24% (half a billion tonnes) is not collected, and a further 27% is mismanaged following collection[1] **(Section 3.1)**. This means that close to a billion tonnes of waste is at risk of interaction with the natural environment: on land, in water and in the air when waste is burned in open fires.

'Solid waste' describes products and structures that have completed the use phase or reached the end of their engineered life. When solid waste management emerged as a structured concept in the mid-1800s, the main motivation was public health[2-4]. Today, with much of this imperative achieved in affluent countries, considerations such as resource recovery and climate change have taken precedence. These new priorities are reflected in contemporary solid waste management research, in the form of resources recovery from waste and the wider circular economy. The result has been a partial dilution of focus away from public and occupational health and safety.

Meanwhile, in low-income and middle-income countries (LIMICs), competing priorities have impeded municipal governments' ability to provide comprehensive solid waste collection services and subsequent management[5]. Consequently, people have to make difficult choices about how to manage their own solid waste by dumping it on land, burning, burying, or depositing into rivers and coastal waters. In this context, waste materials, the chemical substances within them, and those that are produced when they are transformed, are free to interact with the environment and humans.

Possibly 1 billion tonnes of waste is burned in open, uncontrolled fires every year; ending this practice will require an enormous increase in waste management infrastructure and services

Systematic review

This report comprises seven systematic reviews, [162, 163, 164, 165, 166, 167, 168] each focusing on aspects of solid waste that either present significant challenges to occupational and public safety; but also for which no formal, global reviews have been carried out within the scope presented here **(Figure 1)**.

Analysis of the scientific evidence in the seven reviews, through the lens of hazard-pathway-receptor combinations, indicates a convergence around three cross-cutting and interconnected 'overarching themes': open burning, dumpsites and waste pickers.

Overwhelmingly, the evidence indicates that the risk to populations and workers from solid waste are higher in LIMICs compared to high-income countries (HICs). People in LIMICs suffer greater exposure to solid waste and its derivatives and have less capacity and capability to protect themselves from potential hazards: they are more vulnerable.

Open burning

Open (uncontrolled) burning of solid waste results in a hazardous cocktail of emissions being released into the atmosphere and onto land, posing risk to populations, workers and the environment **(Section 2.3)**. While the open burning of waste is thought to be common practice throughout LIMICs, the scientific evidence for that assertion is lacking. Likewise, the scientific basis for many of the emission factors used in modelling is also not available **(Section 2.2)**. It is certain that waste fires emit potentially hazardous substances and pose a risk to human health and the environment, and this report strongly recommends cessation of the activity **(Section 2.4.1)**. However, the scarcity of mass and emission data make it almost impossible to reliably quantify the local and overall impact of these fires on human health and the environment, a gap in the research that should be urgently filled.

The scale of the response needed is likely to be considerable. If current estimates of open burning are to be believed, ending the practice could result in a requirement to treat and dispose of close to a billion tonnes of solid waste worldwide **(Section 2.4.1)**. Open burning provides tremendous perceived or actual benefits to those who carry out the practice and it is critical that these are understood so that alternative management can be provided; and that resources to mitigate the activity can be cost-effectively targeted. Here, for the first time, a review of these motivating factors is presented, which reveals how people, governments and business have come to rely on open burning for a wide range of reasons **(Section 2.1)**.

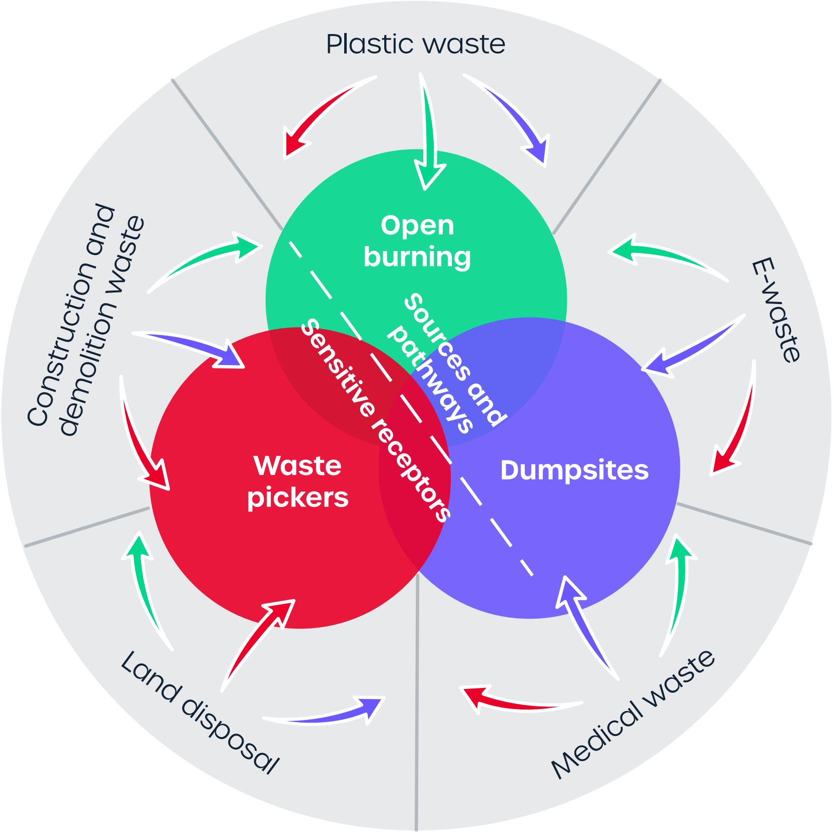


Figure 1: The five thematic areas (outer circuit) distilled to three cross-cutting and interconnected themes (inner Venn diagram).

Open burning of uncollected waste on the main road pavement in Kibera, Nairobi, Kenya; courtesy of Costas Velis (2017).

In several circumstances, the benefits and drawbacks of the open burning of waste require more detailed assessment, which is recommended in this report **(Section 2.4.2)**. For example, medical waste contains both PVC and potentially fatal pathogens, and in the absence of alternative treatment, advice is sometimes to generate harmful dioxins by burning PVC rather than risk infection from a blood-borne virus[6, 7]. This review was unable to find evidence to support such a decision, a conspicuous shortcoming in scientific literature, also requiring urgent attention.

Dumpsites

The practice of dumping concentrated, mixed waste on land is the oldest method of disposal[8] and is still predominant throughout many LIMICs **(Section 3.1)**. In the short term, it is the single most cost-effective management approach in comparison to other forms of treatment and disposal, which is part of the reason it persists as a waste management option.

While access to land disposal sites in HICs is largely restricted, in LIMICs, the high pathogenic load in these facilities results in a considerable infection risk for workers who interact closely with the waste, particularly those in the informal waste reclamation sector (also termed waste pickers, informal recycling sector) **(Section 3.3.1)**. Coupled with frequent agitation and heat, biological material is easily aerosolised on dumpsites, exposing those in proximity through inhalation. The lack of engineering method and simplistic management inherent in dumpsites results in a high rate of occupational accidents, many of which are undocumented **(Section 3.3.2)**.

Tragically, this review has revealed that more than 31 people have died each year since 1992 due to recorded waste-slope failures on dumpsites. These are caused when overwhelming quantities of waste become mobile as shear stability breaks down at the interface between the sub-soil and the waste matrix **(Section 3.3.4)**. It is recommended that urgent action is taken to eliminate the risk of this entirely avoidable phenomenon. Firstly, by identifying the sites that are at risk, quantifying that risk, and then taking steps to remove it, by relocating those at risk of exposure, or implementing engineering response to prevent structural instability of the threatening mass **(Sections 3.4.1** and **3.4.2)**.

Waste pickers

It is estimated that 11 million waste pickers collect more that 90 million metric tonnes (Mt) of waste for recycling each year worldwide **(Section 4.2)**. Located almost entirely in LIMICs, this army of entrepreneurs supports the global circular economy, working on dumpsites, in streets and as traders working door-to-door. Despite the fact that they provide essential functionality to 'prop-up' insufficient formal systems, informal waste workers are often stigmatised and even criminalised for their activities.

Waste pickers are exposed to a large number of hazards that result in ill health, high fatality rates and lower life expectancy compared to their formal counterparts **(Section 4.3)**. The high level of interaction with wastes of unknown chemical and physical composition, coupled with a lack of protective equipment and structured safety regime, drastically increases the vulnerability of waste pickers to hazard exposure.

Several specialist activities lead to a very high level of risk to waste pickers. Medical waste is collected for reuse by a small number of informal recyclers and sold for use by substance abusers and mainstream healthcare providers; exposing both the users and reclaimers to percutaneous pathogen infection **(Section 4.3.2)**. E-waste reclamation specialists often use heating, combustion or acid/alkali leaching to recover metals and components, exposing them to considerable quantities of potentially hazardous substances that are released during these processes **(Section 4.3.1)**.

Safety outcomes for waste pickers must be improved through inclusion and integration rather than exclusion and prohibition

Improving safety conditions for informal waste workers is a complex undertaking. Past efforts by governments and businesses have often focused on exclusion and prohibition, leaving some of the world's poorest and most marginalised people without the materials that they rely upon for income **(Section 4.4.1)**. Evidence from previous research advocates for the efforts of informal waste workers to receive greater recognition through their inclusion and integration into formal, municipal solid waste management plans[9, 10]. If successful, inclusion and integration can result in improved safety outcomes for informal waste workers as their income is stabilised, and wider stakeholders (for example municipalities) also take an interest in their overall wellbeing as critical service providers.

Managed access to land disposal sites has been reported as a successful intervention in South Africa, where waste pickers are permitted controlled access to sites in exchange for adherence to health and safety protocols[11, 12] **(Section 4.4.1)**.

Where this is not possible, exclusion from the most hazardous areas in dumpsites and landfills, such as the operational front, have also proved successful. However it is critical that this is carried out in collaboration with the workers to ensure that they can maintain access to the material they rely upon for income. Providing safe working spaces and infrastructure to store, sort and bale material as demonstrated in Brazilian cooperatives and in North Macedonia[13] can enable improvements to safety, however there is also some evidence that new challenges to safety and wellbeing have arisen in some contexts[14].

Recommendations

This review makes 11 recommendations for urgent action and 18 recommendations for further research that are detailed throughout the report, summarised in **Section 5** and briefly referred to in **Table 1** and **Table 2**.

It is intended that these recommendations will be considered in more detail by relevant organisations such as official development assistance providers and those managing research and innovation agendas.

They should be actioned with urgency to prevent further harm to human health and wellbeing as a result of products, object and structures when they reach the end of their engineered life.

Table 1: Summary of 11 urgent responses to mitigate harm.

Open burning	Dumpsites	Waste pickers
Manage waste so that populations do not have to manage their own by open burning	Reduce the amount of material deposited in dumpsites	Restrict access to hazardous environments in close collaboration with the informal waste workers
Managed continuation of open burning by providing guidance on carrying out safer combustion	Transform existing dumpsites through a series of cost-effective transitional steps	Facilitate managed access to land disposal sites
Remove or substitute selected substances (for instance, catalytic metals or bromine compounds) used in the product system in areas where open burning is prevalent	Identify, assess and evacuate sites at risk of waste-slope failure	Restrict supply chain for certain items and materials (e-waste and medical waste)
Remove or substitute selected materials (for instance, halogenated plastics or polystyrene) used in the product system in areas where open burning is prevalent		Integrate waste pickers into municipal solid waste management plans

Table 2: Summary of 18 recommendations for further research and innovation.

	Open burning	Dumpsites	Waste pickers
Global systemic implications and benchmarking	**ALL three areas:** Research and innovation on the local to global scale and nature of the phenomena and their implications, and system wide challenges and opportunities, including benchmarking and global observatories supported by standardised quantified evidence		
Risk, health implications and emissions quantification	Collect primary data on prevalence	Identification of dumpsites (location, extent, nature)	Develop standardised reporting criteria to establish causality controlling for confounding factors
	Link prevalence (above) with management practices	Carry out assessment of the risk of slope failure	Carry out high-quality, comparable and actionable research that quantifies risk
	Develop reliable emission factors	Develop guidance to mitigate the risk of slope failure	Link epidemiological observations to risk exposure evidence in global burden of disease type studies
	Link observed atmospheric concentrations to source		
Long term research and innovation for solutions to eliminate risks	Risk comparison between emissions and pathogen elimination	Standards for controlled, managed disposal alongside guidance and monitoring of transitionary steps to achieve it	Training packages on the risks involved and the mitigation needs and opportunities
	Develop transition practices/guides to work to eliminate hazards		Empower waste pickers to get organised at greater extents and move from high exposure activities (dumpsite front) to least exposure activities (collection of source separated clean recyclables)
	Assess the benefits and motivations for open burning	Guidance to mitigate the risk of slope failure	Innovation on PPE and use that can be usable/ acceptable/affordable by waste pickers

Informal dumpsite in Malawi; © WasteAid (2017).

1 Introduction

Waste collection vehicle unloads at a dumpsite; © Mohamed Abdulraheem.

1.1 Context

Alongside a growing population and ever-increasing economic prosperity, the amount of solid waste being generated on Earth has increased steadily since the start of human civilisation, and is now estimated at between 10 and 20 billion metric tonnes per annum; of which, two billion tonnes is generated at the municipal level[15]. When managed properly, solid waste can be converted into a resource, or disposed of in ways that pose little threat to human health or the environment.

However, when it is mismanaged, solid waste can result in the emission of substances and materials that interact negatively with people and the environment.

In contemporary society, few engineered products and structures will last indefinitely, either by design, or through technical, functional or stylistic obsolescence. These products and structures can be said to have completed the use phase, reached the end of their engineered life, or become, for legal purposes, solid waste.

Commissioned by Engineering X, an international collaboration, founded by the Royal Academy of Engineering and Lloyd's Register Foundation, the aim of this research is to provide global insights into the occupational, community and public health and safety aspects of complex materials, items and infrastructure as they are managed at the end of their engineered life. The research followed five pre-prescribed thematic areas:

- Plastic waste.
- Construction and demolition waste (CDW).
- Medical devices and consumables (hereafter, medical waste).
- Electronics and electrical waste (hereafter, e-waste).
- Landfills and dumpsites (hereafter, land disposal sites).

These thematic areas were chosen for two reasons: first, because no formal comprehensive global review of the safety challenges associated with them exists; and second, because each has the potential to cause harm to people (and the environment) through the way that they are managed. Three research questions were used in this research to achieve the core aim:

- **RQ1:** What evidence exists across each of the thematic areas to indicate risk to public and occupational safety?
- **RQ2:** What are the comparative risks to public and occupational safety that arise from the management of end of engineered life products, structures and materials?
- **RQ3:** What research could be carried out that would have the greatest impact on harm reduction across the five thematic areas?

Initially it was anticipated that **RQ3** would highlight one of the five thematic areas that would become the focus of a future funding call. Instead, the risk assessment **(RQ2)**, indicated three cross-cutting and interconnected safety challenges that emerged as presenting the greatest risk to human health **(Section 1.5)**, and it is these three overarching themes that form the basis of this report as follows:

- **Open burning of waste -** uncontrolled combustion **(Section 2)**.
- **Dumpsites -** uncontrolled land disposal **(Section 3)**.
- **The informal waste sector (Waste pickers)** - sensitive receptors **(Section 4)**.

Each of these overarching themes is supported by a suite of seven systematic reviews that answer **RQ1** and **RQ2**. These have been published and are available to view[162, 163, 164, 165, 166, 167, 168] in a pre-print repository and submitted for peer review in academic journals.

The link between risk to human health and solid waste – after-use engineered items – has been partly neglected in modern scientific research priorities

Waste picker carries baled recyclate at a landfill near Cimahi, West Java, Indonesia; © motorclassic (2005).

1.2 Solid waste and the safer end of engineered life

A best order of magnitude estimate suggests that, possibly around 12 to 20 million people are employed in formal municipal solid waste management worldwide. In addition, a further 10 to 20 million may work informally as waste pickers/entrepreneurs, who supplement or sustain their livelihoods by reclaiming materials and items discarded by others[16].

The nature of waste, such as its unpredictable composition, mode of occurrence, high heterogeneity, (sometimes) hazardous properties, and its processing and interaction with the environment, may contribute to an increased level of risk experienced by those who manage it, in comparison with other employment sectors. Solid waste management may be one of the most hazardous occupations per worker, with its heavy machinery operation, vehicle movement, working in the elements, and often long and unsociable working hours. For example in the UK, a well-regulated and monitored environment, approximately seven waste management sector workers per 100,000 are killed every year, around 16 times more than the average across all industries[17]. A further 4.5% of the workforce experience ill health, significantly higher than the 3.1% in average across all industries[18].

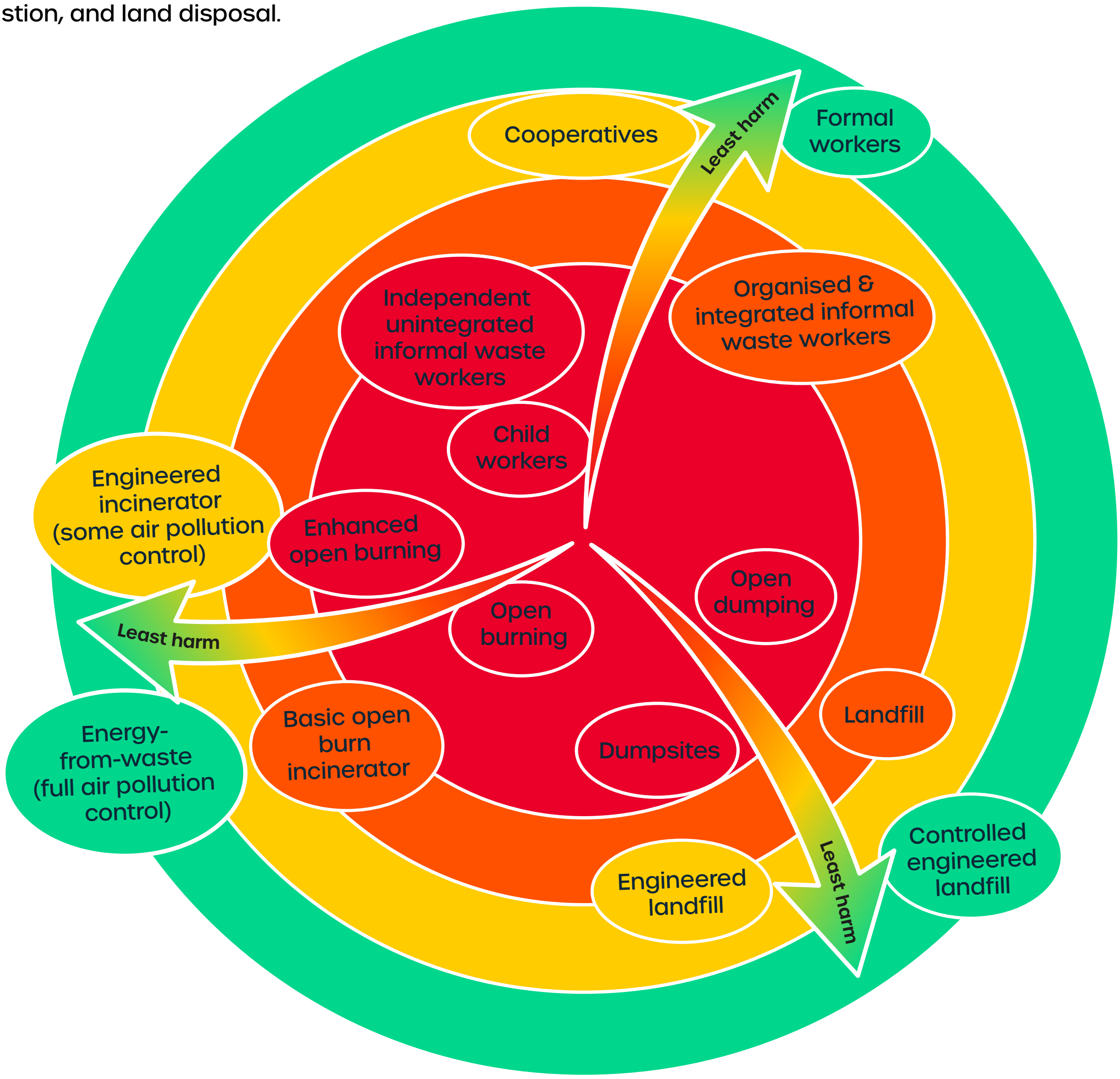
During the middle of the 19th century, the protection of public health drove the creation of modern waste management[2]. However, in recent decades, other considerations have diluted this priority (for example resource recovery and climate change imperatives), as public health protection has been largely achieved in the affluent west. Governments are also more easily swayed towards progression in waste management practices by the lure of job creation or economic amelioration. Therefore, the link between risk to human health and solid waste has arguably been neglected in the modern scientific research priorities[19], despite the huge outstanding issues persisting in low-income and middle-income countries (LIMICs), and the tremendous overall advances in the scientific community's ability to conduct relevant research, including relevant progress in the Global South.

However, in LIMICs injuries from solid waste management activities are often undocumented and though deaths are recorded they are rarely monitored and often not reported on. The International Labour Organization[20] manages a repository of occupational health data collected over the last decade, but the reporting standards are different across countries, leading to high variability and limited confidence in the data.

There is no comprehensive data collection at a national level on the occupational health status of informal waste workers who carry out a significant proportion of waste management activities in many countries, supplementing the lack of comprehensive services provided by their municipalities[21]. Decoupling negative health outcomes from the general living conditions and background environment of waste pickers and identifying causal links with specific hazards is complex and challenging given the vast array of factors that could contribute to their ill health and morbidity[22]. Moreover, many studies that assess or review the health of the informal recycling sector may not be methodologically robust[23].

Whether solid waste workers are employed formally or are informal entrepreneurs, there is a lack of research specifically exploring the interactions between the end of engineered life complex materials/ items/ structures handled by them, as they become waste. The current evidence base on interactions and resultant negative impact upon human health is detailed in this report.

Figure 2: Progression of harm reduction alongside socio-techno evolution for waste workers, waste combustion, and land disposal.



1.3 Waste management practice: progression towards safer working conditions

Globally, waste management practices vary tremendously as does the use of terminology for different technologies, activities, materials, and substances. In **Figure 2** the terminology used to describe the technical and social evolution of **waste workers, waste combustion,** and **land disposal** is shown in the context of the potential harm that each practice may cause to human health and the environment. This review covers all of these steps, however the focus is on the practices in the centre of the diagram that are most likely to result in harm to human health and the environment. This diagram is intended as a guide only, and it is acknowledged that the progression between each step is gradated and overlapping and there are likely to be contexts where some of the steps can be swapped.

1.4 What this study doesn't do

While this study focused on the five thematic areas described in **Section 1.1**, it was not intended to be a generic and broad assessment of occupational and public health in the waste sector overall, and there are already several reviews that do this[24-27]. Instead, the study specifically excluded the wider comparison of safety challenges across the waste sector as a whole by focusing on the specific themes. This means that certain activities that would normally be considered waste safety challenges were not covered, such as mixed municipal solid waste (MSW) collection, mixed materials sorting, composting and anaerobic digestion, and mixed MSW incineration (energy from waste) plants. Undeniably, some scope overlap exists with these broader categories: excluding them from the scope of this study's investigation reveals particular hazards that could otherwise be over-shadowed.

Abbreviations: Air Pollution Control (APC).

Overwhelmingly the risks to occupational and public safety from waste are greater in low-income and middle-income countries

1.5 Cross-cutting and interconnected safety challenges

Rather than indicate a specific group of materials, the categorisation of hazard-pathway-receptor (H–P–R) combinations resulted in three emerging themes **(Figure 3)**. Firstly, analysis of activity context indicated a considerable number of high and high-medium H–P–R combinations that involved uncontrolled combustion **(open burning)**. A second indicative pattern emerged when the risks were categorised by receptor, with the **informal waste sector** being represented in slightly more high and high-medium H–P–R combinations compared to other receptors.

Overwhelmingly H–P–R combinations focused on activities and contexts in LIMICs, where the resources to provide safe working conditions are limited, and the regulatory and enforcement frameworks are often insufficiently robust to comprehensively protect public and occupational health and safety. The emergence of **open burning** and the **informal waste sector** as a high-risk activity and receptor group respectively, is also salient because of the interaction between the two. Participants in the informal waste sector often cause open burning, but the informal workers and their communities, for example in informal settlements, are also most vulnerable to exposure from the associated emissions.

The third cross-cutting theme that emerged as a priority area in this study was **dumpsites**, which was chosen partly because of several H–P–R combinations that scored high or medium high, but also because dumpsites are core places where both **open burning** and the **informal waste sector** interact. In combination, the three themes chosen for further analysis exemplify the majority of H–P–R combinations identified in this research.

Sections 2, 3, and **4** describe the key safety challenges associated with each of these three themes, discuss the urgent action that could be taken to reduce harm and highlight the specific future research need that could be undertaken to address them.

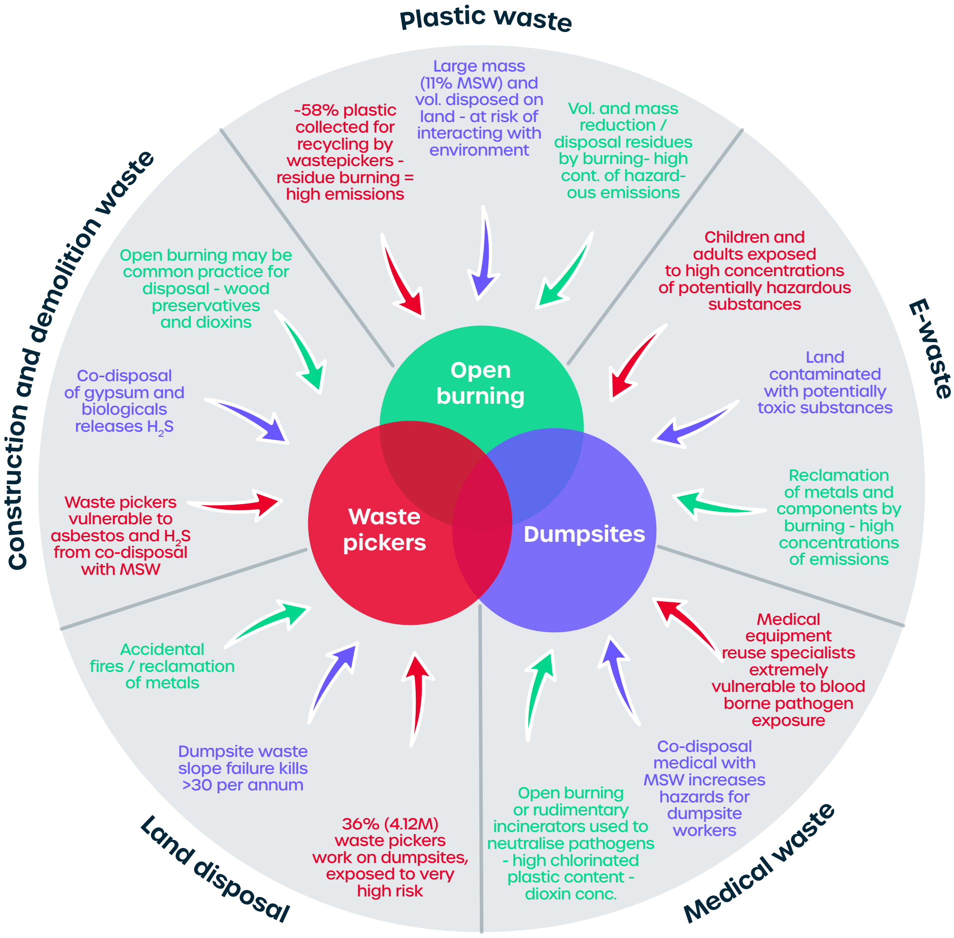


Figure 3: The five thematic areas (outer circuit) distilled to three cross-cutting and interconnected themes (inner Venn diagram).

2 Open burning

2.1 The motivation for open burning

Across the world, waste is openly burned as a method of volume and mass reduction, particularly in areas where waste collection services are not comprehensively provided[15, 32]. As well as this, burning waste decreases its bioactivity[33], meaning that scavenging animals are less likely to feed, breed and transmit pathogens, and minimises unsavoury odours[33]. There are even reports that the open burning of waste is carried out to repel mosquitos, which transmit malaria[34].

Open burning reduces and destroys many pathogens in waste that may otherwise pose a risk to those encountering them[6].

For example, medical waste is often sterilised by combustion in controlled incinerators[35]. Where these are unavailable or prohibitively expensive to operate, more rudimentary facilities may be used, followed by open burning as a last resort as it is still perceived to be the next best option for reducing pathogen load[7, 36-42].

Figure 4: The motivation for and benefits (perceived or actual) of open burning.

Participants in the informal recycling sector use open burning as a method of materials reclamation, removing combustible materials so that they can access metals without having to spend time disaggregating complex piles of material[32, 43, 44]. This is a prevalent practice among informal e-waste recycling workers who do it to recover copper from electrical cables as well as components from larger electrical and electronic waste products[45-47].

While open burning of waste is often carried out by members of the public, there is also evidence that it is used as a method of treatment by municipal authorities.

For instance Pansuk et al.[48] interviewed municipal officials (n = 96) and householders (n = 4,300) across Thailand, finding that approximately 2.5% of material was collected by local authorities and subsequently burned in open piles as a cost-effective method of treatment. In another study, Garfi et al.[32, 161] reported that the waste of 70,000 to 80,000 Saharawi refugees (Algeria) use open burning as the sole method of waste management.

In a perverse sense, open burning may offer a range of perceived or actual benefits to people who are fundamentally disadvantaged by not having access to waste collection, and treatment or disposal services and infrastructure (accounted at approximately 2 billon and approximately 3 billion worldwide, respectively, in 2012)[15], because it effectively mineralises biological waste and reduces its biohazard potential at virtually no cost **(Figure 4)**. From the perspective of many people, openly burning solid waste makes it disappear – an out of sight out of mind solution – however, in reality, open burning of waste results in emissions of a wide array of potentially hazardous substances that pose a considerable risk to human health (along with contributing to dispersed environmental pollution).

Most open burning evidence is based on expert assumptions and survey data, with very little robust evidence of prevalence

Child sifting through dumpsite on fire in Bangladesh; © Azim Khan Ronnie (2019).

2.2 Prevalence of open burning

Estimates of the mass of municipal solid waste that is open burned range from 1% to 50% (weight), with a large variability by geographical location and rurality **(Table 3)**. The majority of these studies base their estimates on assumptions[49-54], while others rely on interviews with officials and experts[48, 55], residential survey data[56, 57], and in one case, transect surveys to observe prevalence in the streets of Indian cities[50].

One highly cited study, by Wiedinmyer et al.[49] estimated global atmospheric emissions from open burning. The model included a basic estimate of prevalence, concluding that 41% of all MSW is open burned worldwide. However, due to the lack of available empirical data, the model used an assumption from an Intergovernmental Panel on Climate Change report[58] based on expert elicitation.

Evidence for the mass of waste open burned on dumpsites is extremely limited. Many studies refer to anecdotal observations of open burning on dumpsites[15, 32, 43, 44, 51] and this review also found film footage[59-61] and news articles[62, 63] that provide indicative evidence. Only two studies, Wiedinmyer et al.[49] and the National Environmental Engineering Research Institute (NEERI)[55] in India, provide mass / proportion estimates, but neither has empirical basis. Deep-seated fires in HICs, so called 'landfill fires', are more commonly reported[64-66], though the metric is as a discrete occurrence rather than on the basis of the mass combusted.

Table 3: **Summary of estimates for the mass of solid waste open burned (Velis and Cook)**[163].

Denominator	Context	Proportion
All municipal solid waste	LIMIC	1 - 50%
	HIC (Rural)	25 – 32 %
Household solid waste	LIMIC	2 - 66%
Uncollected waste	LIMIC	2 - 60%
	HIC	13%
Dumpsite waste	LIMIC	60%
	HIC	13%
Landfilled waste[a]	LIMIC	10%
Collected waste	LIMIC	2.5%

[a] the definition of landfill in this context is not specified and is likely that the sites described would be classified as an open dumpsite.

The prevalence of medical waste open burning is better evidenced, and six studies indicated a range of between 26% and 100% across LIMICs in Africa, Central, South and Southeast Asia **(Figure 5)**.

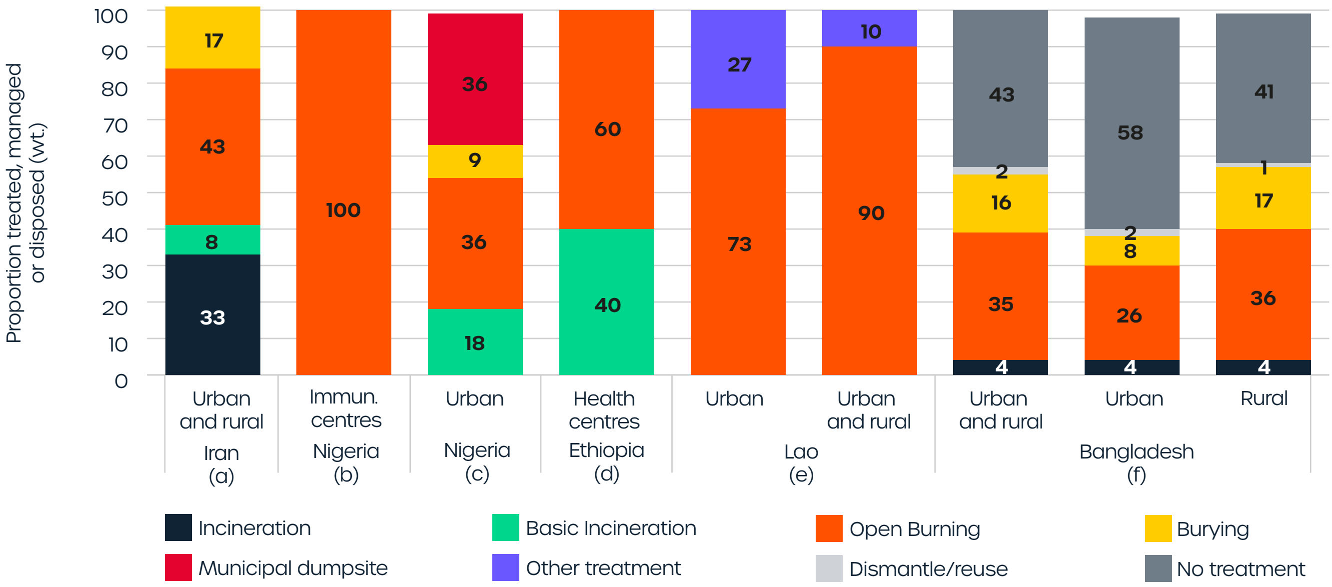
In several examples, the combustion of medical waste in rudimentary, brick-built incinerators was reported. While these devices improve combustion temperature in comparison to open burning, they lack auxillary fuel sources to maintain a sufficiently high temperature and do not incorporate emissions (air pollution) control technology. The image on the right, exemplifies one of the shortcomings of this type of semi-controlled combustion whereby the fire has been left to smoulder and the flue is not generating an updraft.

As a method of secondary resources reclamation, open burning is practised widely by e-waste recyclers to recover copper from electrical cabling[45-47] and bound components from electrical and electronic equipment[67-69, 162]. No evidence was found to indicate the prevalence of this activity, as studies tend to focus on the occurrence of potentially hazardous substances in biotic receptors and environmental compartments. **(Figure 6)**.

There is a similar lack of research to evidence the open burning of construction and demolition waste, despite several authors[70-72] assertions that the activity is widespread. Speculatively, open burning of construction and demolition waste is likely to exist with the same prevalence as any other waste in a country where waste mismanagement is also prevalent, as it is a cost-free solution to dispose of unwanted timber and plastics. Though as with other types of waste, it is unlikely that disposal is always the preferred pathway if material has value, as suggested by Dania et al.[73] who inferred that in Nigeria, timber is likely to be sold for firewood, given its high value as a fuel in energy-impoverished communities.

Small brick incinerator used for medical waste in Southern Africa; courtesy of Professor Linda Godfrey (2019).

Figure 5: **Comparison of medical waste management methods in selected countries; data after: (a)[38]; (b)[36]; (c)[40]; (d)[39]; (e)[41]; (f)[42] (See Section E.2.4.2 for full review). Some columns do not sum to 100% due to rounding.**



Several studies found elevated levels of lead (Pb) in the blood of children living on e-waste reclamation sites

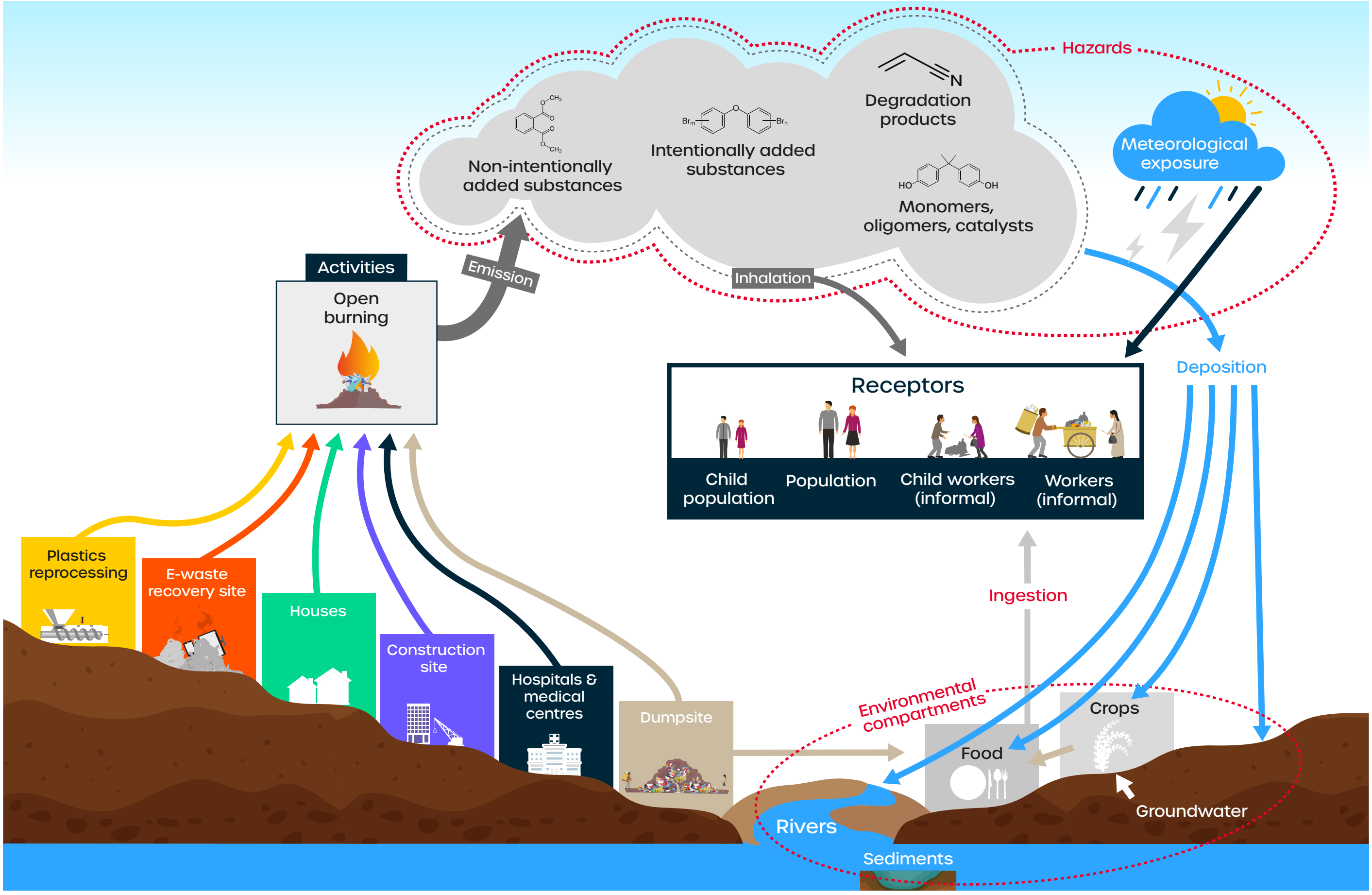


Figure 6: Hazard exposure conceptual model (source – pathway – receptor) associated with open (uncontrolled) burning (from substances contained and combustion products).

2.3 Safety challenges from open burning

2.3.1 Hazardous substance release during combustion

The open burning of waste, in its multiple formats, results in the emissions of a wide range of potentially hazardous substances, volatilised and transformed under heat and through mutual interaction[163]. These substances may be directly inhaled, or distributed through the environment and subsequently ingested, up-taken by crops or absorbed through the skin of fauna **(Figure 6)**.

Many of these potentially hazardous substances exist in near ubiquity throughout the anthroposphere at concentrations where there is limited evidence to suspect harm. However, this review finds evidence of emissions of several substances from open burning that are classed as persistent organic pollutants (POPs), as well as those which are carcinogenic, mutagenic, cause immunological and developmental impairments, and may lead to reproductive abnormalities[162, 163, 166, 168].

To understand the potential hazard exposure from open burning activities, it is first necessary to characterise and quantify the potential emissions generated in various global contexts. Open burning is a disparate activity, carried out in a multiplicity of different situations, where it is sometimes classed as illegal and socially unacceptable, but not necessarily. Therefore, the evidence to indicate the magnitude and nature of hazardous emissions from open burning does not provide a complete picture and has to be collated by identifying substances of interest in a range of environmental compartments and receptors in the context of various activities.

When materials are heated, unbound substances within them become excited and migrate to the surface from where they may be released into the atmosphere as droplets or gases. This review highlighted plastics as an important and potentially major source of some of these groups of substances, which include brominated flame retardants (BFRs), potentially toxic elements (PTEs), phthalates, and bisphenol A (BPA)[163, 168]. In addition, wood preservatives such as chromated copper arsenate (CCA), which were historically used in construction timber, were linked to high concentrations of arsenic, chromium and copper in the atmosphere and ash around construction waste burning sites[74].

Materials present in complex item assemblies may also be volatilised when heated, for example in informal e-waste recycling where metallic and non-metallic bonding agents, such as solder and thermoset plastics are heated and combusted to reclaim components and metals for recycling[162].

This review has identified a growing body of research that has determined the concentrations of these potentially hazardous substances in environmental compartments near to plastics and e-waste open burning activities, such as in the atmosphere, soil, sediments, dust and water[162-163]. In addition, several studies identified high concentrations of many of these substances in the blood, urine and hair of those involved with open burning of e-waste, and plastics, as well as those who live in close proximity[162-163]. It is alarming that several studies found elevated levels of lead in the blood of children (biologically vulnerable receptors) who live on e-waste recycling sites in China[75, 76], as well as very high levels in the blood of child workers who burn e-waste in Uruguay[77]. This evidence should be also interpreted in the context of wider intrinsic vulnerability of child receptors, who may have no choice but to endure such an exposure, a sole survival strategy or anticipated contribution to family income.

Informal worker recovers metals and components by burning away plastics in Agbogbloshie waste reclamation site, Accra, Ghana; © Aline Tong (2016).

2.3.2 Interactions and transformation during combustion

Emissions from open burning not only result from substances within and on the surface of materials, but because of interactions and transformations within the combustion zone. Open burning takes place at relatively low temperatures in comparison to controlled combustion incineration/energy from waste plants[163]. Even when open fires reach a high temperature at their peak combustion point, a priori data suggests that there will be periods at the start, end, and in areas on the periphery of the fire where incomplete combustion takes place.

The result is the production of a range of substances that may cause serious harm to human health if inhaled including polycyclic aromatic hydrocarbons (PAHs), dioxins and related compounds (DRCs), particulate matter (PM) and a range of volatile organic compounds (VOC)[162-163]. As well as the potential carcinogenicity of some of these substances when inhaled, deposition from the atmosphere onto surfaces, soils and sediments places them at risk of being ingested directly, ingested with food, or up-taken by crops and ingested as part of food.

Low temperature combustion is inherent in open fires, resulting in the formation and release of a range of substances that can cause serious harm to human health

Children carry water next to smouldering waste, which is routinely burned in uncontrolled fires in Douala, Cameroon; © WasteAid (2019).

Fifteen of twenty nine hazard-pathway-receptor combinations assessed as 'high risk' in this study involved the open burning of waste, of which 'inhalation' was the route of exposure in eight [162-168]. Medical waste in particular scored very highly due to its high content of chlorinated plastics that form dioxins during combustion[164]. Informal waste workers were also highlighted as some of the highest risk receptors due to their vulnerability to exposure from proximity to open burning and lack of protective equipment **(Section 4.3)**.

2.3.3 Quantification of risk

The semi-quantitative risk assessment provided in the present study was intended to provide an indication of focus for the research agenda rather than a quantified risk to human health **(Appendix A)**. However, there are a handful of studies that have carried out quantitative assessments of the population level risks to human health from open burning based on measured concentrations and modelled exposure. The most recent is Williams et al.[78] who built on a study by Kodros et al.[79] and the Institute for Health Metrics and Evaluation (IHME) Global Burden of Disease database[80] to estimate at between 270,000 and 270,500 premature deaths per year as a result of the open burning of waste. Another model by Shivani et al.[81] estimated that 'plastic and waste burning' (combined) contributes 13.5% of the PM2.5 (mass per cubic metre of air of particles with a size (diameter) generally less than 2.5 micrometres) and 5.1% of lung cancer cases (5,000 per million pop.) or 255 cases per million in Indian cities. These studies focus on atmospheric inhalation of PM. However, there are a number of notable substances, highlighted in this review, that have been reviewed at a local and regional scale near to e-waste burning facilities, showing very high risks to those living in and around the sites[162].

A notable uncertainty in open burning studies that base findings on concentrations in environmental compartments, is the ability to attribute them to one source or another. For example, in several investigations of e-waste sites, the authors were ambiguous about the activity that was being undertaken, often vaguely referring to 'e-waste recycling' without specifying the type, location and magnitude of activities[162]. Although unhelpful to future reviewers, this ambiguity is understandable as gathering data on the detailed activities of informal workers is time-consuming and surveillance of these activities is fraught with complications, not least the potential reticence of those engaged in the activity who may be aware of its illegality, potentially affecting the results of the study.

The vulnerability of those who are directly involved or living nearby is one of the key reasons for open burning being scored highly in the semi-qualitative risk assessment **(Appendix A)**. The exposure of children has already been discussed and this group of receptors is particularly vulnerable to substances such as lead and cadmium that may interfere with their development, and in the case of younger children, because they eat more soil than older children and adults.

2.4 Priority recommendations for action to reduce harm from open burning

2.4.1 Urgent responses required to address key challenges

Avoid unintended consequences

Without improved data to determine the impact of open burning in the context of other environmental, public and occupational safety concerns, it is challenging to identify urgent responses to mitigate its harmful effects, as to do so could risk negative or unintended consequences. For example if Wiedinmyer et al.[49] are correct in estimating that 41% of the world's MSW is open burned, then a cessation of the practice could potentially result in an environmental disaster, with close to one billion tonnes of waste requiring treatment or disposal. The urgent response toward the mitigation of harmful effects of open burning is therefore to find ways to manage safely the world's solid waste using the most cost-effective methods available.

A combination of interventions

Recent offerings by Lau et al.[16] indicate that the amount of plastic waste being generated on earth is rising faster than the capability of global municipal authorities to manage. This suggests that, without intervention by 2040, the solid waste management crisis will result in significantly more material entering the aquatic environment. The research suggests that no single waste management intervention will be sufficient to mitigate the ever-increasing mass of material being generated; and that a combined suite of interventions is necessary to result in a reduction. This should include increasing the mass of plastic recycled, reducing the mass of plastic produced, and increasing the mass of material collected. The detailed pathway toward achieving these interventions was not determined in the research, as it was aimed at establishing the high-level economic implications of the scenarios investigated. However, the same suite of interventions is likely to be just as effective when applied to the challenge of reducing open burning.

Restrict the use of substances in product streams in high-risk areas

The Secretariat of the Stockholm Convention[82] highlights several substances that should be avoided in open fires to reduce the risk of harm to human health. For instance, the report recommends the avoidance of materials containing catalytic metals such as iron, copper, aluminium, and chromium as well as those containing bromine compounds (such as brominated flame retardants) used in e-waste. It is recommended that where there is a high risk of open burning taking place, manufacturers, brand owners and governments take steps to exclude these substances from the product stream to protect human health.

Replacement or removal of materials in product streams in high-risk areas

Several materials could be considered for exclusion from the product stream in areas where open burning is likely to take place. For instance, the Secretariat of the Stockholm Convention[82] recommends that polyvinyl chloride (PVC) and other chlorinated plastics are avoided in open fires because of dioxin formation. Polystyrene (PS) is also of concern because of high particulate emissions compared to other plastics[83, 163]. Given that packaging is a major component of MSW and therefore at high risk of being open burned in some areas, PVC and PS packaging could be considered for exclusion from the system as a precaution to protect human health. To an extent, the use of these two plastics in packaging has already been reduced in Europe, although open burning was not the motivation.


Waste is burned in an uncontrolled fire as a form of disposal in Kiev, Ukraine; © KAY4YK (2020).

Replacement of conventional plastics with other materials such as coated paper (and card) or 'bioplastics' has also been discussed, for instance by Lau et al.[16]. Although the study was intended to focus on aquatic debris emissions, the principles could also be considered for reducing the risks to human health from open burning. Metals, wood and glass could also be considered as alternative materials, but while it is beyond the scope of this research to assess the implications of a change in material type, it is recommended that the potential emissions of alternative products are investigated before intervening in this way. For instance, a study by Yasahura et al.[84] found that DRC emissions from burning paper were greater than those from some plastics in one study.

Astonishingly, only one study modelled the mass of material being open burned based on empirical field observations

Large waste fire burns on an unknown dumpsite; © WitthayaP .

2.4.2 Evidence needs, research gaps and foresight

Quantities openly burned

Surprisingly little is known about the mass of waste that is open burned in different parts of the world, particularly in dumpsites and e-waste processing areas where there is no empirical research to decisively evidence and support the assumptions used in relevant accounting/modelling efforts to date[163, 165]. While there is some evidence that waste management practices are improving across the world alongside economic prosperity, the level of societal progression toward a world without open burning is unknown. It is likely that open burning practices are highly variable depending on different cultural and behavioural norms.

Unsurprisingly, there is evidence to indicate that the practice is more prevalent in areas where waste is not comprehensively collected[56]. However, the data are scant and often based on speculation, witness estimates, or incidental rather than systematic and methodologically controlled expert judgement, which cannot lead to reliable quantification[165]. This conspicuous research gap restricts progress along a critical research pathway that urgently requires investigation to understand the atmospheric and terrestrial emissions from open burning in all contexts.

Astonishingly, only one study[50] was identified during this review that modelled the mass of material being open burned on a robust basis of empirical field observations. The researchers carried out terrestrial transect analysis, combined with a survey and estimates to determine the mass of material being combusted in selected urban areas in Indian cities. Alternative data collection methods could include the use of drones, satellite imagery or aeroplane photography, validated with ground truthing and calibrated against survey, data and waste characterisation studies. It is a recommendation of this study that significant field research is carried out to attempt to determine the prevalence of open burning including the development of standardised methodologies for data collection, interpretation and analysis. Alongside these efforts, it is recommended that details of the waste management practices implemented in the study area are documented, so that they can be compared and correlated with the observed behaviour, providing evidence that can be applied to predictive models in other contexts.

It should be noted that there is a potential risk that a study of open burning may influence the results, the Hawthorne effect[85], and therefore any study would need to be designed to avoid this from happening. For instance, a municipality that openly burns waste to save landfill space may cease its activity for the duration of the project, knowing its activities are illegal or unacceptable.

Quantification of emissions

Substance emission factors from open burning exist for many materials, as reported by both Lemieux et al.[72] and Wiedinmyer et al.[49], the latter of whom has provided the most comprehensive global characterisation and quantification. The present review has identified several further sources of emission factors that will prove useful in future modelling of emissions from combustion of plastic waste[86-91], e-waste[92, 93], and for house fires (useful for construction and demolition waste) including PVC[94]. However, there is also a need to assess and quantify emissions on a more granular and case-specific basis, such as in dumpsites where co-disposed waste may smoulder for many years; for e-waste, which contains high concentrations of PTEs, BFRs and DRCs; and for medical waste, which has a high chlorinated plastic content. A particular concern highlighted here is that the factors that are used to calculate emission profiles do not necessarily replicate the heterogeneous temperature, air flow and feedstock composition of an informal, uncontrolled waste fire. Therefore, it is a recommendation of this report that further research is carried out to develop more reliable emission factors that replicate open burning conditions, in particular on land disposal sites.

Students burn waste from their school in a barrel in Kwa-Muhia, Kenya; © WasteAid (2011).

Source apportionment

Many of the concentrations of potentially hazardous substances identified by researchers in environmental compartments and receptors are problematic to apportion to a source in the context of confounding factors such as transport, domestic heating and cooking, demolition and industry. Guttikunda et al.[95] made considerable efforts towards this endeavour by apportioning sources of PM2.5 in 20 Indian cities, concluding that 10.5% (range: 4-20%) are as a consequence of open burning of waste. One solution to source apportionment is through the identification of chemical markers, as elaborated by Fu and Kawamura[96] who were able to use 1,3,5-triphenylbenzene as an identifier to determine causality between BPA emissions and open burning of waste. The identification of further markers could potentially assist with apportioning the disaggregation of confounding factors in future studies. It is a recommendation of this study that further research is conducted to understand the contribution of open burning in the context of other confounding sources, including the identification of chemical marker species that can be used to assist with modelling this apportionment.

Difficult choices

Despite the considerable shortcomings of open burning, there are circumstances where it may be or is currently perceived as the safest option for disposal of wastes **(Section 2.1)**. For instance, in the case of potentially infected medical waste, open burning offers a cost-free method of neutralising pathogens, which could otherwise threaten the health of those who encounter it post disposal. As discussed in[164], the World Health Organization (WHO) recommends open burning as a last resort treatment option where there are no alternatives[7], citing it as a 'safe final disposal' method for sharps and infectious waste[6]. Whether or not the WHO has quantitatively assessed the relative risk of emissions from open burning in comparison to the risk of infection from medical waste that has been buried or open dumped is not clear, and no published evidence was found to substantiate the advice. The fact that medical waste incinerators are reported to be a source of DRC emissions broadly equivalent to MSW incinerators worldwide[97, 98], but with considerably less throughput, indicates that open burning is also a significant source. It is therefore recommended that further research is conducted to assess the evidence for the WHO's advice in more detail to ascertain whether it is still up-to-date given the current state of knowledge in this area.

Understanding the motivation for open burning is critical to mitigating the activity

Informal worker burns away PVC insulation from electrical wires to recover copper in Agbogbloshie waste reclamation site, Accra, Ghana; © Aline Tong (2016).

The motivation for open burning

Open burning brings tremendous benefits (perceived or actual) to people who have no access to solid waste management, such as the reduction in mass and volume, malarial mosquito control, and the reduction of odour and bioactivity **(Section 2.1)**. Moreover, for people and organisations that cannot dispose of their hazardous waste by any other method, open burning offers the opportunity to neutralise pathogens before they can infect people further[164]. The present study has reviewed some of these benefits, but it is noteworthy that the majority of studies that include narratives of open burning focus attention on the negative outcomes. While these are important to highlight, developing an understanding of the benefits open burning brings to those who carry it out is vital for designing interventions to mitigate the negative effects of the practice or reduce its prevalence.

Therefore, it is a recommendation of this research that further studies are carried out to understand better the reasons why open burning is carried out by different actors so that response interventions can be tailored toward the mitigation of this practice.

Develop transition practices

The current suspected high prevalence of the open burning of waste indicates a substantial challenge in reducing and ultimately eliminating the culture. It is recommended that a set of evidence-based practice frameworks and guides are developed to assist policymakers, governments and businesses with the protocols and steps towards the managed reduction and elimination of the practice, combining behavioural change theory with risk assessment and targeting areas where prevalence is high.

2.4.3 Best practice

Open burning

Guidance on open burning tends to recommend prohibition, alternative treatment or waste avoidance in places where open burning practices are commonplace. Only one document from the Secretariat of the Stockholm Convention[82] acknowledges the potential benefits of open burning as a last resort and provides best practice guidance for those who have no choice but to undertake the activity. The report strongly discourages open burning; however, where it is necessary, for instance to manage pathogen-infected medical waste, the guidance encourages practitioners to maintain temperature, airflow and careful control of feedstock, which should avoid halogenated plastic content as well as BFRs and other POPs.

Uncontrolled incineration

For incinerators that operate without effective emissions mitigation technology, a multitude of engineering controls exist that effectively abate emissions. In Europe, an exhaustive list of these ‘best available techniques’, compiled by the Joint Research Centre[99], assist operators and facility designers with engineering decisions to ensure compliance with the Industrial Emissions Directive 2010/75/EU[100].

3 Dumpsites


Tracked vehicle manoeuvres waste on a dumpsite; © Kalyakan.

3.1 Context

Depositing unwanted material onto land is the oldest method of waste disposal, practised for millennia[8]. Even today, land disposal is practised throughout HICs and LIMICs, as it is both simple and cost-effective relative to other methods of waste treatment, at least in the short term.

Historically, land disposal involved placing waste directly onto the ground or into natural or artificial depressions in the land, and this uncomplicated method sufficed for many centuries. The contemporary term for this type of facility is the 'dumpsite'. However, as the historical population density increased alongside individual consumption, many historical dumpsites became overwhelmed. As the mass of waste increased, many land disposal sites became anoxic, creating ideal conditions for anaerobic microbes to flourish and produce methane. As rainwater trickled through these piles of waste, dissolved substances and suspended biological material (leachate) were washed into surface and groundwater. Plastics and paper blew across the land. Something had to be done.

The logical response to these environmental transgressions was the engineered landfill. Thick multi-layer liners were designed to capture leachate, and networks of pipes were installed to capture gas before it escaped to the atmosphere. Landfills were covered: first with nets and sheets and later with soil and minerals.

Today, waste in the best-managed landfills is covered daily to prevent the escape of light material onto the surrounding land and to prevent animals from accessing it for food. These are known as 'sanitary landfills'.

However, despite these advances, landfills continue to exhibit many shortcomings. Landfill liners are not expected to last more than 200 years, and possibly 10% to 20% of the methane generated is often uncaptured. Consequentially, in HICs such as in Europe, Korea and Japan, as well as China, landfills are being replaced with other methods of treatment and disposal, such as incineration with energy recovery, recycling, composting, and anaerobic digestion.

3.2 The persistent dumpsite

Sanitary landfills are a comparatively cheap method of disposal with combined CAPEX (capital expenditure) and OPEX (operating expenditure) ranging from $15 per tonne in low-income countries (LICs), to $80 per tonne of waste deposited in HICs compared to the cost of modern incineration with air pollution control and energy capture, which is circa $120 per tonne[5]. Yet for many LIMICs these costs remain out of reach in a context of competing priorities to provide healthcare, housing and food for their citizens.

The boundary between 'dumpsite' and 'engineered landfill' is a gradated progression rather than a binary denotation. At its most basic, a dumpsite exists as a concentrated pile of waste on the surface of the land where additional material is deposited and left by collection vehicles in a place of their choosing.

Medical waste is co-disposed with municipal solid waste on a dumpsite in Malawi; © WasteAid (2020).

Managed dumpsites may be more organised, with officials directing new deposits to certain areas, and mechanical plant to compact and shift incoming piles of material to make the best use of space. Sometimes waste is burned deliberately as a method of volume reduction, with some fires burning for many years. Liners may be added but no cover and visa-versa. The lack of defined barrier between dumpsite and landfill leads to inconsistent reporting that can interfere with efforts to intervene to improve sites that present safety challenges. While acknowledging these inconsistencies, the estimated proportions of waste treated and disposed of by different methods is reported by Kaza et al.[101], who have published the most comprehensive dataset on global waste management **(Figure 7)**.

Dumpsites (open dumps) are the predominant form of solid waste disposal in LIMICs, accounting for just over 400 Mt of waste in deposits annually; 20% of all MSW generated. Uncollected waste represents approximately 490 Mt, and much of this will also be deposited on land. However, important as these deposits are, this research focuses on larger concentrated 'facilities', dumpsites, and their associated risks. It should also be noted, that many of the LIMIC sites reported by Kaza et al.[101] as 'landfills', are also likely to be indistinguishable from dumpsites in appearance and management as highlighted by Lau et al.[16], who posits that plastic is free to escape form many sites in LIMICs.

3.3 Safety challenges on dumpsites

Large concentrations of waste that are piled onto the land represent a range of cross-cutting and interconnected safety challenges that affect people working and living in proximity, as well as the surrounding environmental systems. The challenges posed by open burning have already been discussed in **Section 2.3** and the risks of harm to waste pickers from e-waste and H2S emissions from co-disposal of gypsum and putrescible waste will be discussed in **Section 4.3.** Therefore, to avoid repetition this section will focus on the remaining, significant hazards reviewed by Maalouf et al.[165].

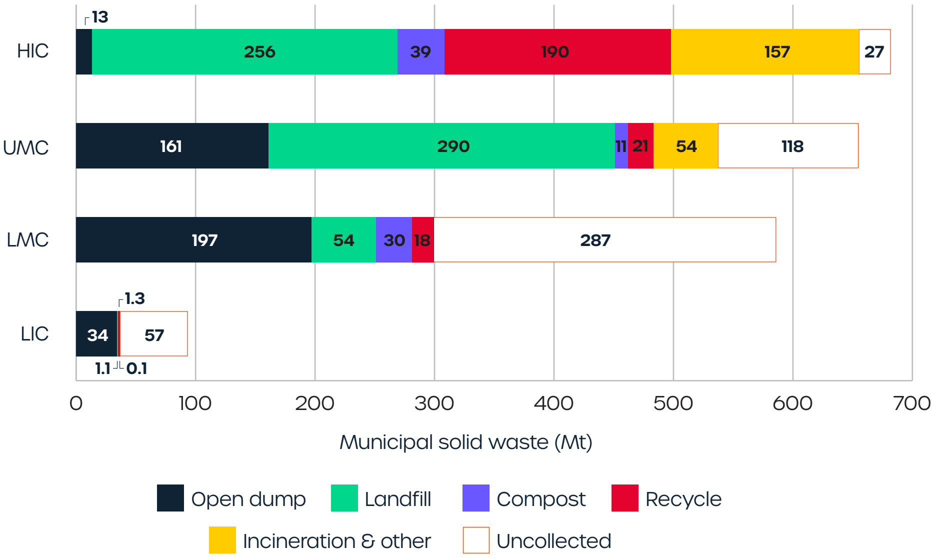


Figure 7: Mass of municipal solid waste by management method; data after Kaza et al.[101]

A high prevalence of sharps injuries is experienced by waste pickers, exposing them to hepatitis, AIDS, tetanus, and other life-threatening diseases

3.3.1 Aerosolised and non-aerosolised biological material

The warm and wet conditions alongside deposits of pet faeces, food waste, diapers (nappies), and human waste[102] create ideal conditions for microbes to flourish on land disposal sites. This high pathogenic load results in a considerable infection risk to those who work and live on land disposal sites, especially waste pickers, who come into close contact with waste and who rarely wear protective equipment[165].

Cointreau[103] reported notable increased morbidity associated with waste-picking activities on land disposal sites while acknowledging a range of confounding conditions that may result in illness and infection **(Figure 8)**. These potential confounding effects are important to note, partly because waste pickers often experience issues related to poverty such as poor nutrition or a lack of protected water supply, but also because the necessity to participate in the profession may indicate other extraneous life events that could affect their health. Whereas the pathogenic load on land disposal sites presents a risk to workers from ingestion associated with bare-handed sorting and deliberate ingestion of food, significant concentrations of biological material have also been reported in the ambient air by multiple authors[165]. The deleterious health implications of bioaerosol inhalation are a subject of ongoing research because of the inconsistent and insufficient quantitative evidence[104-107]; yet, at least one author[104] suggests that there is enough evidence to indicate that a precautionary approach should be adopted to reduce the risk of inhalation of aerosolised biological matter.

3.3.2 Accidents

As well as suffering considerable exposure to biological (infectious) material (microorganisms), waste pickers experience frequent accidents during the course of their work[165]. Typically, they have no access to protective equipment and may perceive the use of gloves negatively, as a factor that reduces their dexterity and therefore productivity[108]. Furthermore, they may lack awareness of the extraneous factors that could expose them to risk, including respiratory problems, skin problems, musculoskeletal problems and injuries from sharp objects that in one survey affected 96% of respondents at a South African dumpsite[109]. Injuries from medical sharps have been reported with a prevalence of between 43% and 60%[110-112], potentially exposing victims to hepatitis, AIDS, tetanus, and other life-threatening diseases[111].

3.3.3 Meteorological exposure

The nature of outdoor work also exposes waste pickers and formal workers to the elements, and in particular hot and sunny weather that can lead to a range of deleterious effects, which may increase with advancing climate change. The implications of hot weather outdoors on the health of waste-pickers is discussed by Maalouf et al.[165], with effects including headaches, heat stress, dehydration, sunburn, excessive sweating, and difficulties concentrating.

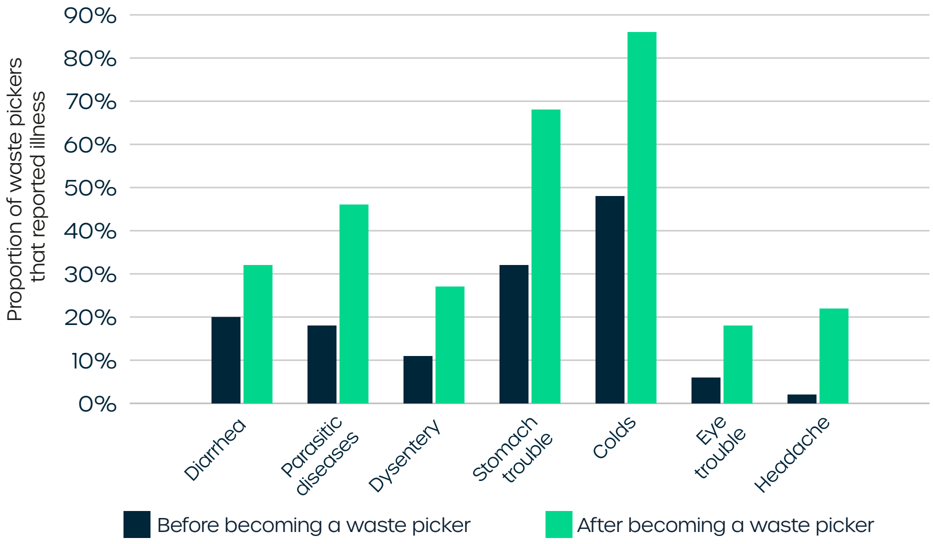


Figure 8: Incidences of morbidity reported by waste pickers before and post occupational exposure to waste; after Cointreau.[103]

Structural slope failure has resulted in at least 866 confirmed fatalities (approximately 31 per annum) since 1992

3.3.4 Waste-slope failure

Perhaps the most concerning risk presented by poorly managed land disposal sites is that of structural slope failure that has resulted in at least 866 confirmed fatalities (approximately 31 per annum) since 1992 **(Figure 9)**. This review found 28 incidents of waste-slope failure reported since 1977, although speculatively this is unlikely to be a comprehensive record as many of these types of incident may go unreported in cases where no fatalities or injuries take place, thus raising the incident profile[165]. The underlying reasons for waste-slope failure often combine a range of factors, all of which involve too much waste being deposited in a pile. As moisture builds up within the waste matrix, the pore pressure increases. However, it is the interface between the sub-soil surface and the waste that may be the most important factor as indicated by Keolsch et al.[113] who carried out forensic analysis of the catastrophic failure at Bandung dumpsite in 2005, which claimed 147 lives and destroyed 71 houses. Koeslch et al. indicated that a deep-seated fire had damaged waste particles that reinforce shear stability. Combined with high water pressure at the waste sub-soil interface, the pile became mobile.

The activities of the informal recycling sector have also been suggested as a cause of slope instability, created because of participants' efforts to 'mine' valuable materials from the waste matrix[114]. This suggestion is entirely anecdotal; however, it may present a topic for future research into slope failure mitigation.

Although there are examples of waste-slope failure in HICs, virtually all cases and all of the deaths reported take place in LIMICs. Although a detailed analysis was not carried out here, the large numbers of deaths appear to affect the poorest people who either work on dumpsites or live very close by.

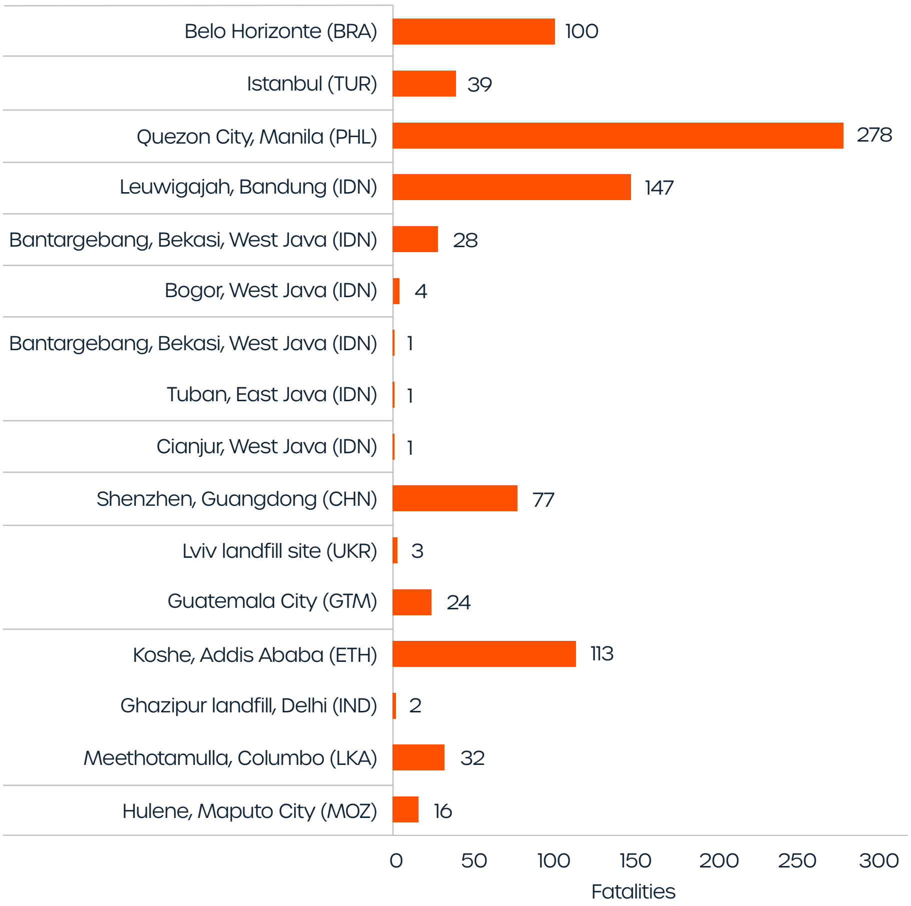


Figure 9: Number of confirmed fatalities at reported waste-slope failures on land disposal sites since 1992[165].

Waste-slope failure at Payatas Dumpsite, Philippines; courtesy of SM Merry (2005).[115]

3.4 Priority recommendations for action to reduce harm

3.4.1 Urgent responses required to address key challenges

Reduce the amount of material deposited in dumpsites

Given the large number of deaths and the devastating impact of waste-slope failure in recent years alongside other harm associated with dumpsites, it is recommended that urgent action is taken to reduce the future likelihood of these preventable incidents occurring. The simplest immediate response is to stop delivering waste to all dumpsites. While this will not prevent failure of previously constructed waste structures, it is likely to prevent risk from increasing. Diverting material to other forms of cost-effective treatment is one approach explored in **Section 3.4.3**, particularly organics, which make up more than 50% of MSW in LIMICs and dry recyclates that are already collected in large quantities by the informal recycling sector. However, the remaining material will need to be disposed of somewhere and the lack of available resources in the context of multiple competing priorities will continue to be a challenge for many municipal governments in LIMICs; many of whom are bankrupt and unable even to borrow (for example, from the World Bank) to fund construction.

The transitionary dumpsite

If the resources were available to construct engineered landfills or other alternative treatment then they would have been constructed already, so it is suggested here that it may be counterproductive to continue with this aspiration. Instead, it is proposed that a series of transitionary steps between dumpsite and engineered landfill could be implemented to reduce the harm from future waste deposits by introducing management methods including: basic organisation of waste; management of waste inflow; separate cells; intermediate and daily cover; liners; and caps. These steps could be applied to existing or new sites according to availability of land and funds, and could be prioritised in order of risk mitigation potential specific to the locale.

Identify, assess, and evacuate

Where other options are not able to be implemented in short timeframe and in all cases where waste that has already been deposited exhibits risk of slope failure, action must be taken to urgently protect life. Of course this would also come at a cost, so it is important that the highest risk sites are prioritised. In many cases, the risk is visually obvious, because of the steep or vertical slopes and large material mass. However, despite the obvious hazard, action has not been taken and the risks persist. It is suggested here that the only logical response is urgent, coordinated international action to identify and assess the most vulnerable sites to determine sheer stability, followed by evacuation of those living and working in proximity to the hazards.

Providing the informal waste sector with direct access to source separated material generated in households could reduce significantly quantities of material on dumpsites

3.4.2 Evidence needs, research gaps and foresight

Two comprehensive reviews of waste-slope failure have been carried out by Blight[116] and Lavigne et al.[117] as well as multiple individual assessments and forensic investigations reviewed by Maalouf et al.[165]. The present study has updated the two existing reviews and found an alarming number of incidents reported in recent years. Slope-shear stability is well understood and strategies for prevention have virtually eradicated the phenomenon in many HICs. Given the large quantity of waste being deposited in dumpsites, it seems likely that it is only a matter of time before another catastrophic failure claims the lives of some of the world's poorest people. It is therefore recommended that urgent research be carried out in three key areas:

- Identification of dumpsites
- Assessment of the risk of slope failure
- Guidance to mitigate the risk of slope failure

Identification of dumpsites

While the International Solid Waste Association (ISWA) has already identified some of the world's largest dumpsites. The location of the majority is unknown to the international community who may be able to provide assistance to municipalities harbouring high-risk facilities. However, identification of these sites could be extremely time-consuming, involving communication with a large range of actors in many countries.

A first step could be to engage with ISWA's international network to identify known, high-risk sites and manage the data in a central repository; an initial attempt already exists in the Waste Atlas database[118]. Whereas this would provide data on known sites, it would not constitute a comprehensive assessment. Therefore, it is suggested that a research programme is conducted using algorithms to identify the locations of the largest sites from aerial (satellite or aeroplane) imaging. The data could be used to profile sites according to topology, climatic conditions and size, to develop a shortlist of sites.

Assessment

With the sites identified, it is proposed that a global team of geotechnical experts in waste-slope failure be deployed to selected sites to assess the risk to the workers and the local population. The team's findings would enable quantified risk to populations that would provide the justification for funding and further action/evacuation.

Guidance to assess and mitigate risk of waste-slope failure

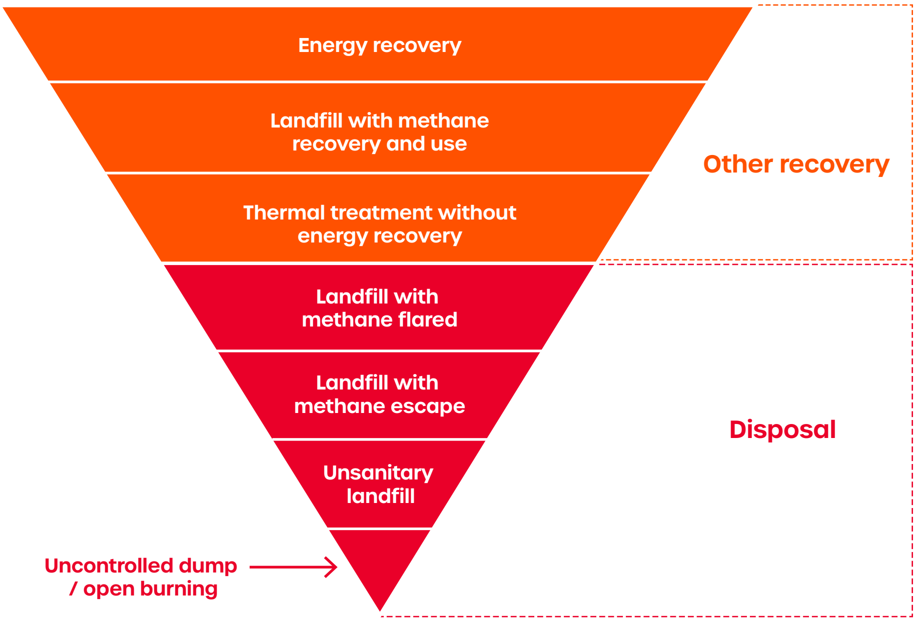
Alongside identification of dumpsites and assessment of risk, it is recommended that guidance is produced to enable cost-effective action by municipalities as well as international funders and NGOs to both assess the risk of slope failure and carry out action to mitigate it.

Guidelines for preventative measures to reduce risk on dumpsites

Produce minimum standards for low-cost 'controlled land disposal' in LIMICs that recognise the challenges associated with implementation in the context of scarce financial resources.

Supplement with guidance and monitoring protocols that support the transitionary steps towards harm reduction and eventual sanitary landfill.

Figure 10: Extended waste hierarchy; adapted from a combination of Wilson et al.[15]; Oteng-Ababio et al.[120] and Kaufman and Themelis.[121]



Waste pickers watch while a collection vehicle unloads its material at a dumpsite; © Kalyakan.

3.4.3 Best practice

The response in Europe to the multiplicity of safety challenges posed by dumpsites was to develop and apply the Waste Hierarchy[119], which has enabled policymakers to implement interventions under its simplistic guiding principles. While there are considerable contemporary criticisms of the ongoing usefulness of the Waste Hierarchy for making waste management decisions[15], these tend to be related to the upper tiers that many LIMICs have yet to reach. Whereas ideally solutions should work towards greater resource recovery from waste and support for the informal sector as discussed in **Section 4**, the resources to do so in many LIMICs are unlikely to be sufficient. The Extended Waste Hierarchy **(Figure 10)** adapted from a combination of illustrations by Wilson et al.[15]; Oteng-Ababio et al.[120] and Kaufman and Themelis[121] includes more granularity and extends below the 'disposal' rung, which is at the bottom of the European standard version. It is proposed here that for LIMICs that have not yet developed the capacity to manage waste so that it no longer interacts with the environment, this structure provides sufficient guiding principles to make cost-effective management choices in the context of scarce resources and competing priorities.

Reducing the mass of deposits can also be achieved by alternative and cost-effective treatment and by diverting recyclate for reprocessing. For instance, in LIMICs more than 50% (by weight) of MSW generated is food and yard (aka green or garden) waste. Providing basic facilities to separate this from other wastes alongside local treatment and valorisation projects could drastically reduce the mass deposited in dumpsites as well as many of the negative effects of the biological waste deposited there. Furthermore, supporting and integrating the informal recycling sector into waste management plans **(Section 4.4)**, providing them with access to material before it reaches the most dangerous parts of the dumpsite could reduce significantly quantities of material that currently present a risk to those with whom it interacts.

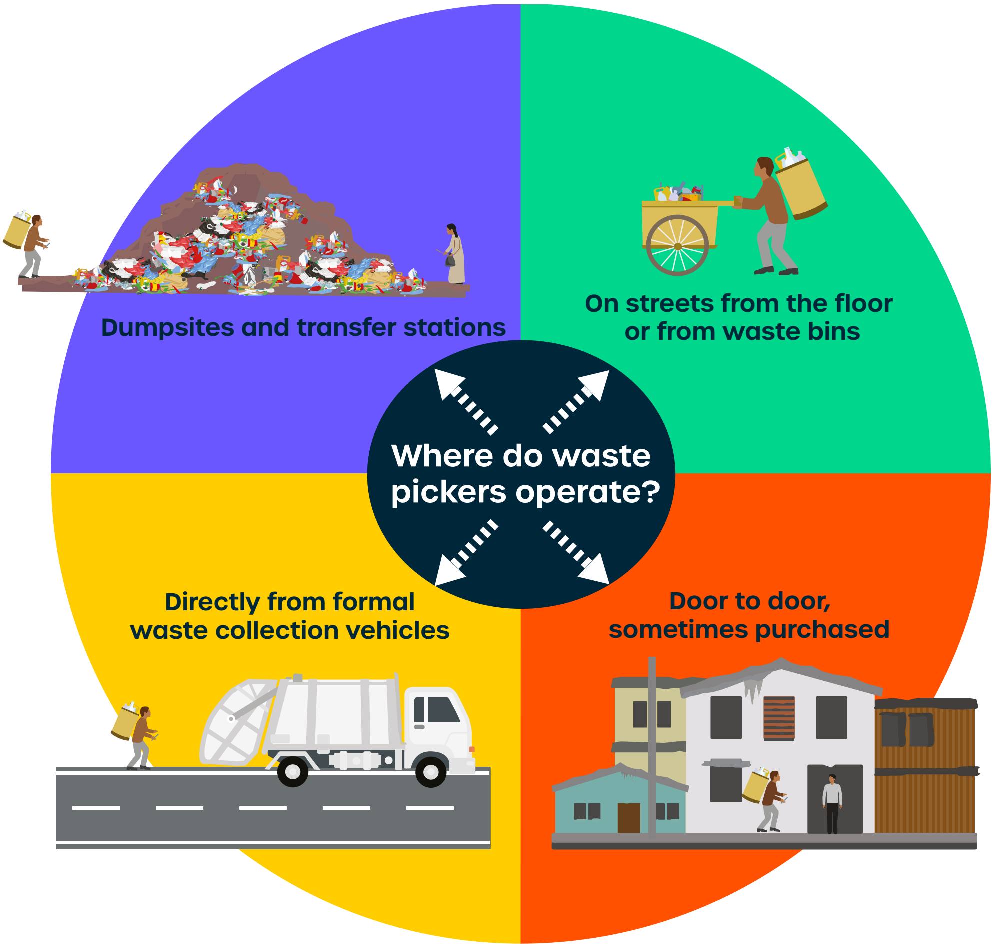
4 The informal waste sector

4.1 Waste pickers: an informal workforce fulfilling critical global functionality

Throughout the world, a large workforce of individual and organised entrepreneurs carries out a critically important waste management function that mitigates environmental pollution from debris and reduces the requirement to extract and refine raw materials and thus the pressure on ecological systems. Informal waste workers (in roles of collection of mixed waste, collection for recycling and sorting, and waste processing; but for simplicity referred to hereafter as 'waste pickers') operate primarily in LIMICs, partly because of economic imperative, but also because the opportunity exists in countries that lack comprehensive state-organised waste management and resource recovery systems. The informal waste sector exploits this opportunity, while providing essential functionality where formal systems fail to deliver. Waste pickers collect material for recycling (informal recycling sector (IRS)) in a variety of contexts, including from dumpsites, formal waste collection vehicles, door to door, and the litter or waste containers on the streets **(Figure 11).** They may operate independently or be organised in a form of cooperative, association or community-based organisation.

In addition, the informal waste sector operates in several other specialist contexts identified in this review. For instance, e-waste recyclers are known to operate in several countries worldwide, notably in Ghana, West Africa and China. Additionally, a small group of specialist medical waste reclamation and reuse specialists has been documented in Bangladesh, Iran, Nigeria, and Tanzania[164].

Figure 11: Contexts where waste pickers operate to collect recyclable materials (informal recycling sector).



The informal waste sector is a highly productive labour force across the global materials markets; collecting more than 88 Mt waste (after-use items) for recycling each year

Children search for waste to reclaim at Kingtom dumpsite, Freetown, Sierra Leone; © Amanda Ingram – Waste Aid (2018).

4.2 Size and contribution of the informal waste sector

Estimates of the number of participants in the informal waste sector vary depending on location, but have been variously reported to be in the region of 10 to 20 million people worldwide[15]. Linzner and Lange[122] provided a comprehensive review that report estimated numbers of participants as a proportion of the urban population in 19 countries, mainly across LIMICs. The median proportion engaged in waste-picking activities was approximated at 0.33% for lower middle-income countries (LMCs) and 0.41% for upper-middle income countries (UMCs), enabling an estimate of potential numbers operating in different income categories **(Figure 12)**. These numbers are substantially uncertain, because waste pickers themselves have few reasons to keep records of their activities and may not have the capability to do so[122].

To assist with understanding the relative exposure to hazards experienced by waste pickers, the four categories illustrated in **Figure 11, Section 4.1** can be divided into two simplified groups: (i) those who work on dumpsites and (ii) those who do not (described hereafter as working on the 'streets'). This is useful because in this research, the risk exposure to waste pickers was found to be generally much higher on dumpsites in comparison to other contexts.

A more sophisticated description and typology of the service delivery mode and interaction with waste management stakeholders can be found elsewhere[123].

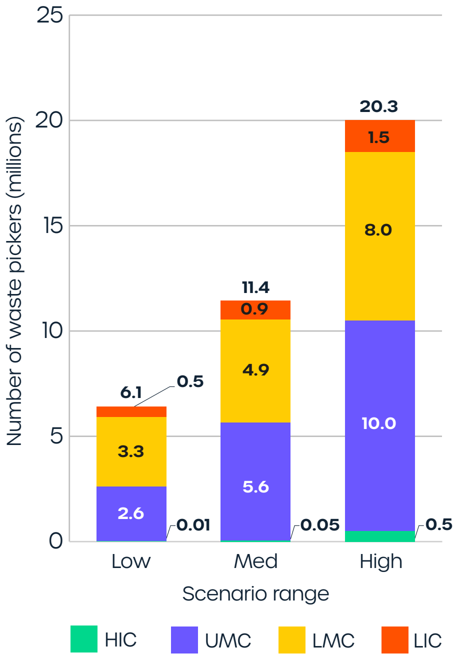


Figure 12: Estimated number of waste pickers operating worldwide (numbers above columns are total mass); data after Lau et al.[16]

There is very little reported data on the proportion of waste pickers who work in each context, although Lau et al.[16] provide a best order of magnitude estimate based on a few data points and expert opinion **(Figure 13)**. The basic assumption by Lau et al. is that in LICs, where virtually all land disposal is in dumpsites, 50% of waste pickers will work on them. As dumpsites are replaced with engineered controlled landfills, where access to the public is restricted in LMCs and UMCs, proportionally fewer waste pickers will work on dumpsites, being forced to look for material on the streets of towns, cities and villages. Very little information is available to establish the number of waste pickers operating in HICs, and comparatively, it is likely to be small as waste collection and treatment services reach close to 100% coverage. Therefore, the number of waste pickers is estimated by Lau et al. at approximately 0.005% of the urban population, with none working on dumpsites.

The informal sector is a highly productive force across the global materials markets. Based on a combination of Lau et al.[16] and several other studies[124-128], a conservative estimate indicates that waste pickers collect more than 88 Mt of recyclate each year **(Figure 14)**.

To put these figures in context, the total mass of material collected for recycling in Europe (mainly from the formal sector) across the same categories was 76.3 Mt (7.5 Mt for MSW plastic in 2019[129]; 55 Mt for paper and card in 2018[130]; 3.2 Mt for metallic packaging in 2017[131]; and 10.6 Mt for glass packaging in 2017[131]). Despite the considerable uncertainty with the estimates provided here for the waste-picker productivity, even if the accurate quantities are somewhat lower, their activities are still likely to represent a considerable contribution towards the global mass of material being recycled and reused.

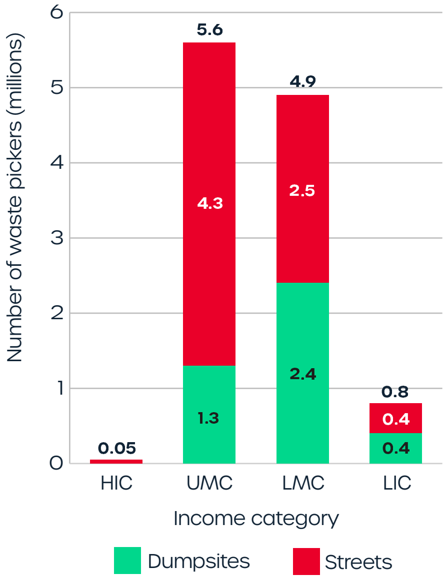


Figure 13: Estimated number of waste pickers working on streets and dumpsites by World Bank income category (numbers above columns are total mass); data after Lau et al.[16]

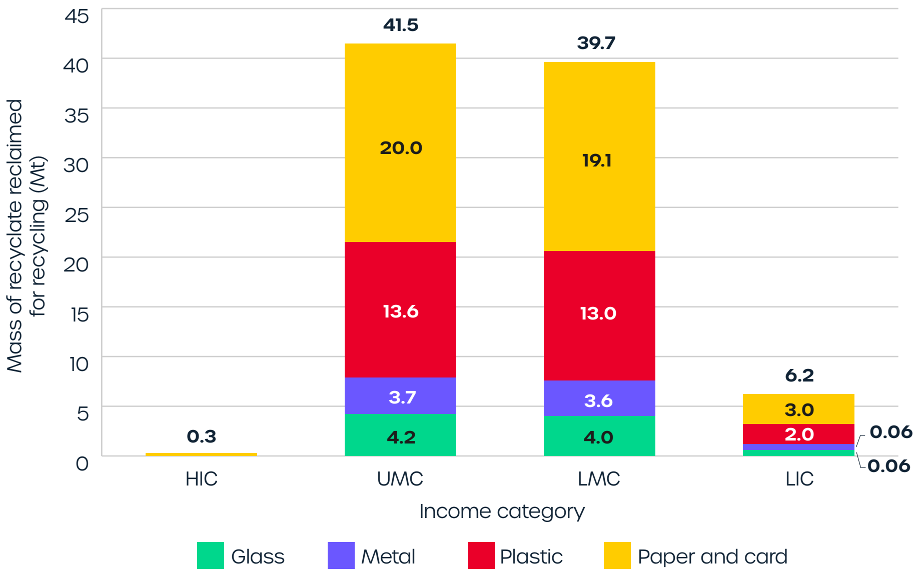


Figure 14: Estimated mass of recyclate reclaimed for recycling by waste pickers in each income category (numbers above columns are total mass); mass data after Lau et al.[16]; composition taken as the mean of compositional data reported by Ibáñez-Forés [124], Hayami et al.[125], Vergara et al.[126], Majeed et al.[127] and Chen et al.[128]

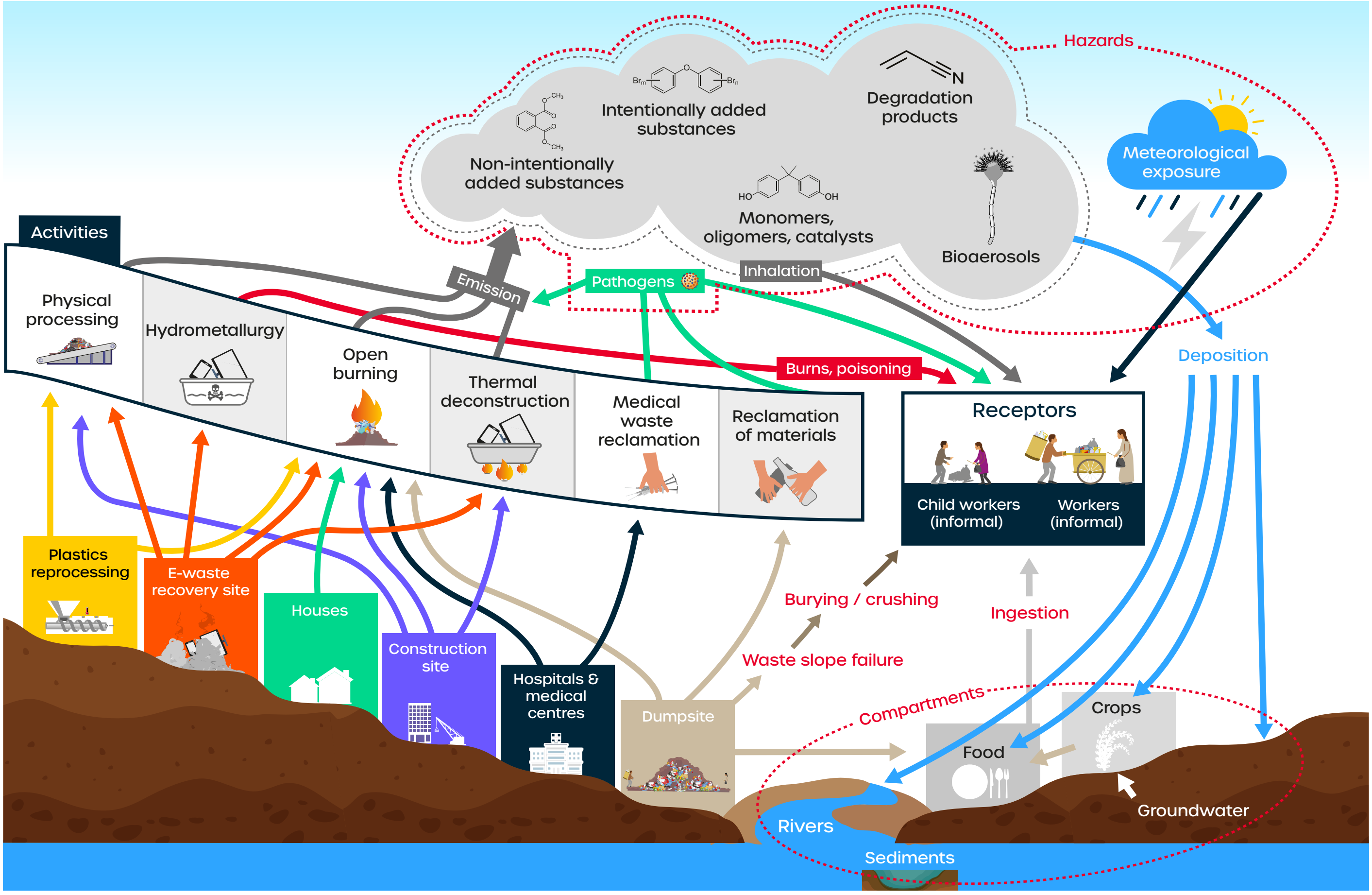


Figure 15: Hazard exposure conceptual model (hazard–pathway–receptor) for risk scenarios experienced by waste pickers.

4.3 Safety challenges faced by informal waste sector

The nature of the work, and the environment in which they work, exposes waste pickers to a range of hazards that have the potential to reduce the quality and length of life for those who work in the sector[132]. For example, a study in Mexico City found that the life expectancy of waste pickers on one dumpsite was just 39 years, and another in India reported child morbidity to be 2.5 times greater than the national average[133]; child labour is endemic among many waste-picker communities[15, 134]. In a study of workers in a Brazilian waste picking cooperative, Gutberlet et al.[14] observed a range of deeply concerning safety challenges experienced by workers alongside dissatisfaction with oppressive, hierarchical and sexist social structures. While these observations were related to cooperatives, many of the findings were also identified in the present study, including exposure to chemical, biological, physical, and ergonometric hazards **(Figure 15)**. In particular, this review identified the inhalation of aerosolised and gaseous substances to represent a series of high risks to informal waste workers[162, 163, 165].

Many studies that related directly to waste pickers were not included in this review, as their findings were often vague, non-specific and insufficiently evidenced/not supported by methodologically robust approaches; a status quo also reported by Wilson et al.[23]. Without sufficient detail to evidence a complete causal relationship between the hazard–pathway–receptor (H-P-R), in some cases, this review has relied on a combination of substance concentrations measured in environmental media and the blood, urine and hair of receptors; inferred hazard generation factors; and theoretically justifiable pathways to indicate risk.

Informal recyclers are highly unlikely to have access to or wear protective equipment

Waste pickers were the receptor in 36 of the H–P–R combinations assessed in this research[162-168]. Of these, the most prevalent high-risk activity was uncontrolled combustion, accounting for 53% of all H–P–R combinations considered. Inhalation was also the main pathway through which informal waste workers were exposed to higher risk hazards, such as DRCs, BFRs, phthalates, PTEs, PM, PAHs, and PCBs. Percutaneous puncture with pathogen-infected medical waste was the source of 12% of all H–P–R combinations, as was the case with dermal contact.

4.3.1 E-waste recovery

The practice of reclaiming materials from e-waste for recycling is a lucrative endeavour in LIMICs, yielding high value metals such as copper, that e-waste workers in India reported to trade for approximately $6,730 per tonne in 2012[135]. However, in some cases, the methods used to dismantle electrical and electronic items can result in emissions of substances that endanger the health and wellbeing of those who carry out the practice as well as people living nearby[162, 166].

In contrast to some other thematic sections, this review found a large research base of studies that determined concentrations of hazardous substances released from e-waste dismantling activities into the surrounding environment, as well as identified in the bodies of informal waste workers and people living in proximity to these activities[162, 166]. Three broad categories of activity were considered to understand the level of hazard and risk exposure: physical dismantling; thermal recovery and disposal; and hydrometallurgical treatment or acid/alkali washing.

Remnants of partially combusted medical waste that has been burned in an open, uncontrolled fire; © frank60.

High concentrations of BFRs and PTEs, particularly lead, chromium and arsenic, have been found in soils, dust and sediments near to e-waste processing activities, providing a strong indication that informal e-waste reclamation is the source[162, 166]. Although many of the studies reviewed here were able to describe the types of activities taking place, these were not always clear. In at least one example, concentrations of BFRs and PTEs were attributed to dismantling activities. However, the author also observed high concentrations of DRCs, which can only have been produced by open burning activities. In several HIC examples[136-138], significant emission of BFRs have been evidenced, providing proof-of-concept that mechanical processing results in emissions of these substances.

In virtually all cases, regardless of activity, informal workers (including child workers in one study) were determined to suffer from the greatest risk of exposure to potentially hazardous substances, scoring high or medium high in the majority of H–P–R combinations. Underpinning this is the intrinsic vulnerability of these workers who often live and work in the same areas[162, 166], therefore suffering prolonged exposure to the emitted substances. Furthermore, informal recyclers are highly unlikely to have access to or wear protective equipment[139], especially if not organised, and often have poorer access to hygiene[140] increasing the risk of exposure through respiration and ingestion.

4.3.2 Exposure to pathogens from medical waste

Unless neutralised, the pathogens that are present in some types of medical waste can present a serious risk to those who encounter them[164]. Throughout many LIMICs, medical waste is routinely collected alongside MSW, dumped in the open, or buried in the grounds of medical facilities[164].

Of the 1.25 million people who are expected to suffer from asbestos-related cancer in the coming years, more than half will be in India where the market for asbestos continues unhindered

Manual demolition of a house in Mumbai, India; © rkl_foto (2015).

Medical waste is also generated in people's homes, and there is evidence that 'self-care' medical treatment may increase over the coming decades[164]. Interviews with waste pickers have revealed that they experience a lifetime exposure prevalence to used medical sharps of between approximately 10% and 60% while they forage for other valuable materials[164]. These largely unexpected encounters not only expose waste pickers to potentially life-threatening pathogens such as hepatitis C (HCV), hepatitis B (HBV) and human immune deficiency virus (HIV), but they result in psychological trauma because of the uncertainty associated with potential infection[141].

A small number of waste pickers are known to seek medical waste purposefully, with the intention of reclaiming it for reuse, either by themselves or for onward sale to recreational drug users or medical establishments[164]. Evidence suggests that a wide range of medical equipment is reclaimed for reuse including scalpels, knives, saline drip bags, cotton, and injection equipment. The risks of these activities are considerable, and posed to not only the reclamation workers who are at risk of accidental infection, but also to the patients and drug users whom they supply – even more so as the latter may be unaware of the risks to which they are being exposed.

The practice of medical waste co-disposal with MSW, and the illicit trade in reused medical devices and consumables, is considerably less common in HICs as these types of material are tightly controlled under enforced legislation. In LIMICs, resources are often insufficient to enable similar controls, and therefore approaches that are more rudimentary are sometimes adopted, such as open burning or basic brick-built incineration that both neutralise pathogens and render medical consumables and devices unusable[164]. The decision whether to safeguard actors engaged in downstream foraging or mitigate atmospheric emissions of hazardous substances from uncontrolled combustion is challenging. The WHO[7, 6] alludes to this dilemma, cautiously recommending open burning if there is no other option (covered in more detail in **Section 2.4.1**).

4.3.3 Plastic waste

This research has highlighted the considerable risks experienced by informal waste workers who are acutely exposed to emissions from the open burning of waste plastics[163]. As discussed in **Section 2.3**, open burning of plastic waste results in the release of many thousands of chemical substances, many of which are potentially hazardous to human health. In particular, evidence for exposure from PAHs, DRCs, PM, and BFRs was identified and attributed high risk scores for informal workers, who are exposed to considerable concentrations on dumpsites and during residue burning activities[163]. Phthalate and BPA exposure were also reviewed here, and although both decompose during complete combustion[142, 143], low temperatures in open burning fires are a source of emissions of these two endocrine disruptors[96, 81, 144].

4.3.4 Construction and demolition waste

While it is likely that informal waste workers encounter construction and demolition waste, the sector was barely mentioned in any studies reviewed here[167]. Risks to the health of informal sector workers from exposure to construction and demolition waste can be inferred from a priori data, although it would be disingenuous to attempt to infer the magnitude of harm in the context of so little information.

Informal worker pauses while reclaiming waste at a dumpsite in Cimahi, West Java, Indonesia; © motorclassic (2005).

As many of the risks cross-cut with those discussed under other sub-headings, just two construction and demolition waste-specific risks, asbestos and gypsum, are highlighted here, with further detail provided in[167].

The most concerning H–P–R combination is exposure to asbestos, which may claim as many as 233,000 workers lives annually worldwide[145]. Whereas many of these deaths take place in HICs, where asbestos activity has been most prevalent in the last 70 years, it has been estimated that approximately 58,000 of these take place in LIMICs[167]. Moreover, asbestos is still being produced at a rate of 1.1 Mt per annum and consumption continues in 39 counties worldwide[146]. Asbestos poses a considerable risk when it becomes friable and unless stringent safety precautions are implemented, the risk of inhalation is considerable. In particular, it has been predicted that of the 1.25 million people who are expected to suffer from asbestos-related cancer in the coming years, more than half will be in India[147].

The co-disposal of gypsum plasterboard was highlighted as a potentially serious concern because the combination of carbon and sulphate ions leaching from the mineral provide ideal conditions for sulphate-reducing bacteria to proliferate and produce H_2S[167]. Although no specific evidence was indicated, the likelihood of this co-disposal on dumpsites in LIMICs may be significant, and exposure to the gas has been implicated in the deaths of landfill workers in Japan[148] and a suite of morbidities associated with its exposure[148-150].

4.3.5 Land disposal sites

Dumpsites (and engineered landfills not operated to the controlled standards) provide the work context for 4.19 million (36%) **(Figure 14)** of the 11.4 million **(Figure 13)** waste pickers estimated to be operating worldwide. As well as the hazards discussed in other sections, such as open burning, asbestos and hydrogen sulphide gas exposure, waste pickers working on dumpsites are exposed to a range of additional hazards, discussed in detail in[165].

To avoid repetition, these hazards are summarised in **Section 3.3**.

4.4 Priority recommendations for action to reduce harm

4.4.1 Urgent responses required to address key challenges

The contribution of the waste pickers to global resource recovery from waste is significant **(Section 4.2)** and at present, the majority of its participants operate without any government support, being vulnerable to a multiplicity of hazards due to a range of environment, self-induced and extraneous factors. Reducing the magnitude of harm experienced by this sometimes disparate community will require a combination of improved research and carefully targeted interventions. However, given the severity of some of the challenges, it is recommended that several responses are implemented with some urgency to reduce critical risks to human health. Several relevant actions are proffered in **Sections 2.4.1** and **3.4.1**, so have been excluded from this section to avoid repetition.

Restrict access to hazardous environments in close collaboration with the informal waste workers

Restricting or denying access for waste pickers to land disposal sites significantly reduces hazard exposure, but also access to material that the participants in the sector rely upon for their livelihoods.

Government policies in India[151], Brazil[152] and other parts of South and Central America[153] to restrict access to landfills and open dumps have met with varying success depending on the level of inclusion afforded to the informal sector in decision-making.

Provision of safe working spaces for waste pickers with access to waste handling equipment has been successful in reducing the risk of harm and increased their income

Brazil has two to three decades worth of experience in the development of workers cooperatives, many of which have been set-up concurrently alongside landfill access restrictions. Where inclusion and integration with the formal municipal authorities is successful, waste bound for the landfill is first deposited in a sorting area (shed) where recyclates can be reclaimed on tables or conveyor belts in much safer conditions.

Collaboration with waste pickers is imperative when deciding to exclude them from land disposal sites, without which their activities are either displaced or their ability to obtain income is destroyed, leading to poverty.

It is worth noting that although many of these replacement schemes have been successful, some authors[154, 14] have reported that replacement activities have not always been successful with continuing complex issues and morbidities reported by many waste pickers that have not necessarily improved the livelihoods of those involved.

Facilitate managed access to land disposal sites

Managed access to landfills **(Section 4.4.3)** has been implemented by some operators in South Africa[11] with some success, and is promoted by both ISWA[12] and the United Nations Environment Programme (UNEP)[155] as a critical intervention that can improve safety of informal workers. While many operators may be reluctant to increase their risk profile by allowing unsafe activities for which they are liable, in cases where the activity is essentially uncontrollable, managed access may represent a safer alternative, alongside the moral imperative to allow people to make an income.

Waste picker selects material for recycling at a dumpsite in Porto Seguro, Brazil; © Joa Souza (2008).

It is therefore recommended that interventions are implemented to compel municipal authorities the world over to recognise informal waste workers in municipal waste management plans and integrate them into the value chain.

Restrict supply chain for certain items and materials

The illicit trade in medical sharps is a worrying activity that raises the risk of pathogen transmission across every aspect of the value chain that touches it, including the collectors themselves, the subsequent handlers, or buyers as well as the drug users and patients who unwittingly allow these used devices to puncture their skin. According to Unicomb et al.[42] 2% of facilities in Bangladesh admitted selling single-use medical devices for reuse, a trade also evidenced by several other authors[156, 157]. While it is near impossible to control the activities of these specialist medical waste collectors, making efforts to restrict supply is an intervention that could dramatically reduce the risk for all those who may be potentially affected.

Inclusion and integration of informal waste reclaimers

Evidence indicates that inclusion and integration of informal waste workers into municipal solid waste management planning may improve the health and safety and wellbeing of its participants[23, 158, 159]. Many of the steps towards facilitating this integration **(Section 4.4.3)** are relatively cost-free and therefore this report recommends that municipalities throughout the world begin the process as a matter of urgency to begin to mitigate the harm caused to this vulnerable population.

Waste pickers search for materials in Bantargebang landfill, Jakarta, Indonesia; © Rumbo a lo desconocido (2019).

4.4.2 Evidence needs, research gaps and foresight

Develop standardised reporting criteria to establish causality

Considerable evidence exists to indicate potentially serious risk to the health of informal waste workers from e-waste reclamation activities. Much of the evidence is based on concentrations determined in environmental compartments and in the bodies of those engaged in the activities as well as those who live nearby. However, many of these studies lack sufficient descriptive narrative to confidently establish the specific activities that constitute emissions sources that remain confounded. It is suggested here that future studies develop a reporting criteria that require researchers to report the context of the research in a standardised framework alongside reporting environmental concentrations. In doing so, this could ensure that future studies can attribute harm to receptors and concentrations in environmental compartments to the source activity, enabling policymakers to intervene in a more strategic and logical evidential basis.

Carry out high-quality, comparable and actionable research that quantifies risk

The general quality of research into the safety of the informal waste sector has presented challenges in this study. Overwhelmingly, literature on waste pickers is qualitative, non-technical and un-actionable with a focus on philanthropic poverty alleviation and anecdotal evidence or reporting of individual experiences. The types of data collected often lack critical information that is presented inconsistently across studies and while these insights assist with general understanding, they do not enable measured and targeted intervention.

One exception is for informal e-waste workers, where several authors have calculated and reported the 'hazard index' and 'hazard quotient' associated with exposure to substances encountered during their activities[162, 166]. Similar approaches were taken with formal medical waste handlers[164], but overall, very few studies quantify risk into participants in the informal waste reclamation sector. Given their intrinsic vulnerability to exposure, and the number of global participants in the sector, it is recommended that the risk of exposure to harm is quantitatively assessed across a range of potential hazards.

Global burden of disease

Development of studies to quantify risk as mentioned in the previous section, will enable quantification of risk on a global scale. It is therefore recommended that global burden of disease type studies are carried out to determine the risk to this large group of extremely vulnerable individuals that is currently providing a critical service to the global material economy, being the main workers delivering a circular economy across the Global South.

Global observatory

To centralise and make available the aforementioned waste-picker-related research, a 'global observatory' is recommended as a repository of data to enable targeted intervention design.

4.4.3 Best practice

Access to waste

The presence of informal waste workers on land disposal sites results in a high risk of exposure to accidents as they interact with vehicles and waste, particularly at the working front where material is unloaded and manipulated by machines. The ISWA working group on landfills[12] has suggested that improving organised access through specific entry points would result in considerable improvements to safety by enabling better demarcation of working space between vehicles and pedestrians. Further management interventions have been suggested by Blaauw et al.[11], who reported that attempts by landfill operators in South Africa to restrict access have been largely unsuccessful, and that requiring

Figure 16: Analytical framework and typology of interventions for integration of the informal sector into waste management systems; after Velis et al.[9]

waste pickers to sign in and out of the site while adhering to site rules improves safety and continues to allow the informal sector to reclaim material to support their livelihoods.

Recognition and integration

While access to waste and improved safety on a site-specific basis may provide some benefits, several authors[23, 158, 159] have proposed providing wider recognition for the informal sector by integrating it into municipal waste management plans. Velis et al.[9] outlined the wider challenges that concern the integration/inclusion/formalisation of waste pickers into modernised waste and resource management systems. The research demonstrated a framework that analysed baseline involvement of waste pickers in municipal systems, providing a standard for systematic interventions to support their integration into commercial, governmental and societal structures **(Figure 16)**. The main thesis here is that their activities, motives and implications touch upon all four spheres and therefore interventions have to be explicitly designed to account for this complexity. Partial, single-sided approaches have historically failed. The complex considerations and wider debate on the role of waste pickers in the circular economy of the Global South have been detailed elsewhere[132].

More recently Samson[10] analysed approaches towards integration of the informal recycling sector in South Africa, reporting the comparative outcomes of different approaches while providing a typology of intervention actors. Samson found that informal reclaimers continue to be largely exploited by municipalities and industry that benefit from reduced waste to manage and feedstock respectively at comparatively little cost.

Market access and development of safe spaces

Development of markets and market access could play an important role in assisting the informal recycling sector. Evidence from North Macedonia[13] indicates significant improvements to the health and livelihoods of informal sector workers gained through the provision of safe working spaces to sort, store and bale recyclate alongside the provision of personal protective equipment, which participants are required to wear on site. These measures reduce the likelihood of material being stolen or confiscated by the authorities and provide facilities for the controlled disposal of residues.

5 Conclusions

Gulls search for food over a European dumpsite; © Roman Mikhailiuk.

A systematic approach was used to review the evidence on the risks posed by the management of end of engineered life (after-use) materials, objects and structures to human health and safety, considering value of human life as a core interest. The review focused on five pre-selected thematic areas, each of which addressed the end-of-life fate of complex engineered: materials (plastics), items/products (e-waste and medical devices), and materials/products used in buildings, along with the solid waste land disposal infrastructure, such as dumpsites.

Discussion of the risks posed to human life by these objects and associated disposal infrastructure was not possible without referring to the concept and legal term of 'solid waste'. It is through the management of solid waste over the last 200 years (the 'sanitation era'), that societies have attempted to control the potential risks posed by engineered products when they no longer serve their intended purpose. The concept of 'solid waste' is today challenged by the aspiration to move the recovery of resources (technical engineered materials; nutrients and bio-based resources like humic substances; and energy and fuels) in a circular use of embodied and embedded resources ('circular economy').

To this end, the analysis presented serves as a critical reminder that just rebranding 'solid waste' as 'after-use' materials, components, items, goods, structures, and infrastructure, does not automatically or to any degree eliminate their potential to cause harm if handled in an unsuitable and substandard way, without the aim of protecting human health and safety also being prioritised and respected.

More than just a list/tabulation of evidence, this review attempted to critically assess each and every source of potential hazard, offering comments on the reliability and suitability for generalisation, while juxtaposing the findings wherever possible. The analysis of H–P–R combinations incorporates consideration of receptors' vulnerability, prevalence and geographical spread, enabling identification of high-level patterns and areas of priority for preventing and mitigating risk to human health and safety.

The present work conveys a need to adjust research agendas and form genuine collaboration between low-income and middle-income countries and high-income countries on these neglected cross-cutting thematic areas

Most interestingly, these priority areas converged across three overlapping and interconnected 'overarching themes' as follows **(Figure 17)**:

A. **Open (uncontrolled) burning:** the most harmful practice of managing end of engineered life materials/items/structures.

B. **Dumpsites:** the most harmful method of disposal, where complex materials/items/products/parts of structures are handled, mixed and often set on fire.

C. **Informal waste sector workers – waste pickers:** a ubiquitous workforce of marginalised urban poor who, under substandard health and safety conditions, deliver resource recovery services across LIMICs at scale; often operating at dumpsites or, for example, using open burning to recover metals from e-waste, and being exposed to pathogen-infected medical waste.

Overall, the evidence collated and critically analysed here indicates that if the safety risks posed to human health associated with open burning of solid waste, disposal in dumpsites and activities related to informal waste management could be addressed, massive risk mitigation can be delivered. Therefore, human life and health can be preserved and valued. However, despite the volume of research efforts reviewed, the analysis also vividly demonstrates the lack of understanding of the fundamental aspects of the specificities of risk and damage involved, and effective mitigation strategies. Open burning, dumpsites and the informal waste sector are beyond any doubt three areas that lack a strong, high-quality research base.

Part of the fundamental research challenge here, is that the phenomena involved are complex (materials–human/societal–environmental interactions) and therefore necessitate genuine interdisciplinary and/or multidisciplinary efforts. In addition, in the current absence of substantial research funding in these areas, one could speculate that the interest from leading research institutions and individual researchers could be limited.

Given that the greatest risks occur mostly in LIMICs, the ability to conduct and publish world-leading research to inform evidence-based estimations of risk and solutions is negatively impacted by the currently established capacity and resources disparity between HICs and LIMICs[160]. Partnerships between HIC and LIMIC researchers, while ensuring findings are shared via open access publications, are suggested alongside clearly defined pathways to impact for any future research investment.

The present work conveys a strong need for suitably adjusting research agendas and associated resources, including increased genuine LIMIC and HIC collaborations on these neglected cross-cutting thematic areas. Specifically, this study juxtaposes the risks posed by end of engineered life objects ('solid waste'), with the positive wider sustainability benefits of the rapidly emergent agenda of circular economy ('after-use'); concepts that must evolve mutually and concurrently. This research and report is a stepping stone toward the development of a circular economy across low- and middle-income countries (the 'Global South') that explicitly and fundamentally values human health and safety; in the same way that is inconceivable not to respect it in high-income countries.

Young waste picker carries a bag of recyclate at a dumpsite in Delhi, India; © clicksabhi (2018).

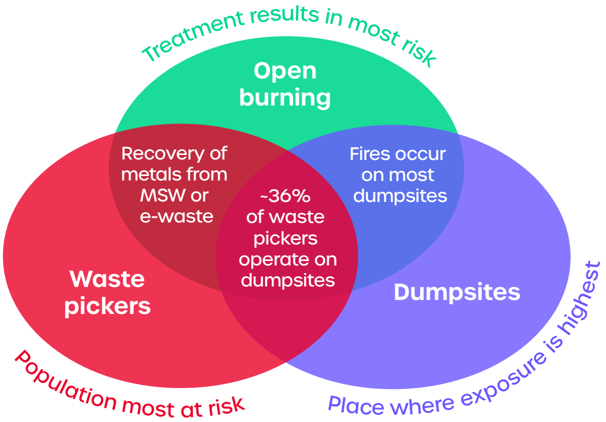


Figure 17: The hazard-pathway-receptor combinations converged across three cross-cutting and interconnected themes (inner Venn diagram).

6 Summary of recommendations

Recommendations for further work were divided into two groups throughout this report:

- **Urgent responses** included actions that could be taken to reduce the hazard exposure to affected individuals and populations where the risk is deemed to be high but for which the research to underpin and target resources may be lacking.
- **Recommendations for research and innovation** included actions that could be taken to improve the understanding of hazard exposure to individuals and populations and thus support the case for funding or otherwise intervening to reduce or eliminate that exposure.

In this section, the urgent responses and recommendations for research are grouped together and summarised in **Table 4** and **Table 5** respectively. For each, an indication has been provided of the types of stakeholders who may be able to action the recommendation or response. However, this was not the core aim of the project and therefore these should be treated as an indication to enable further investigation in the research that is enabled by this review.

The risks to human health identified in this review were overwhelmingly centred around LIMICs where the capacity and capability to mitigate them is limited because of competing priorities with other societal needs such as healthcare, safe water provision and nutrition. This same lack of resources also impacts on research funding in LIMICs, resulting in a large number of poor-quality studies that are insufficient to convince funders to intervene. The lack of funding to intervene and the lack of research funding compound the issue and reduce the efficiency of interventions.

Table 4: Summary of 11 urgent responses to mitigate harm.

Overarching thematic area	Recommendation	Detail	Indicative stakeholder type
Open burning	Manage waste so that populations do not have to manage their own and open burn	Remove the need for individuals to have to take emergency action to manage their own waste. This can be achieved by: • reducing the mass of waste in the system • increasing collection of waste from households and businesses • improving the economics of recycling and preparation for reuse • supporting the informal recycling sector as potentially the largest collector of municipal solid waste recycling on the planet.	Municipal and central governments NGOs Official Development Assistance (ODA)-related organisations
	Managed continuation of open burning by providing guidance on carrying out safer combustion	Provide guidance on safer burning such as: • increasing airflow in fires either by careful burning or through the use of rudimentary incinerators • avoiding combustion of certain materials such as chlorinated plastics, persistent organic pollutants and e-waste containing solder (for instance) • burning away from other human receptors and using respiratory protective equipment.	Municipal and central governments NGOs ODA-related organisations
	Remove or substitute selected substances used in the product system in areas where open burning is prevalent	Remove specific materials and substances from the product system in areas where large amounts of waste are at risk of being open burned, such as: • POPs • Catalytic metals such as iron, copper, aluminium, and chromium.	Product manufacturers, brand owners Central governments ODA-related organisations
	Remove or substitute selected materials used in the product system in areas where open burning is prevalent	Replace some materials with materials that are less harmful when burned subject to risk assessment. For instance: • Chlorinated plastic packaging (e.g. PVC) • Polystyrene packaging • Paper (chlorinated).	Product manufacturers, brand owners Central governments ODA-related organisations

Overarching thematic area	Recommendation	Detail	Indicative stakeholder type
Dumpsites	Reduce the amount of material deposited in dumpsites	Divert material away from dumpsites by implementing alternative treatment and disposal: • Diverting food and garden waste from dumpsites could reduce their mass by more than 50%. Separate collection of large streams and diversion to composting could be implemented at low cost but would require cooperation from civil society • Integration and recognition of informal waste reclamation workers could enhance diversion pf packaging that also makes up a considerable proportion of the waste generated in LIMICS. Waste could be made accessible to informal workers prior to deposition in the dumpsites to reduce the risk of exposure to hazards on the operational front • Divert the remaining material to engineered landfills where materials can be safely deposited without the risk of waste-slope failure and other myriad hazard to which workers and populations may be exposed.	Central and municipal governments with assistance from international funding agencies ODA-related organisations
	Transform existing dumpsites through a series of cost-effective transitionary steps	Given the high cost of engineered landfills in comparison to dumpsites, a series of transitionary steps between dumpsite and engineered landfill could be implemented to reduce the harm from future waste deposits. Management methods could be introduced sequentially according to cost benefit of risk mitigation. For instance: • basic organisation of waste • management of waste inflow • separate cells • intermediate and daily cover • liners and leachate collection • caps • gas capture and flaring or utilisation.	Municipal and central governments with assistance from NGOs and international funding bodies
	Carry out assessment of the risk of slope failure Develop guidance to mitigate the risk of slope failure	Identify the dumpsites at greatest risk of waste-slope failure by engaging with international networks such as ISWA as well as national governments to report dumpsites that can be visually determined to be at risk (for example steep/high sided and large near population centres). Follow up by deploying international team of experts to carry out onsite assessment to determine sheer stability, thus risk to populations, and enable prioritisation. Where necessary evacuate populations.	ODA-related organisations
Waste pickers	Restrict access to hazardous environments in close collaboration with the informal waste workers	Where it is possible to provide continued access to material through safer medium (for example shed with sorting conveyors or tables), access to landfills and dumpsites can be restricted by prohibiting pedestrian access and the application of daily and intermediate cover to the waste surface. It is imperative that this is done in collaboration with the waste pickers themselves to ensure that they are included in the design and implementation of the alternative measures.	International waste sector organisations
	Facilitate managed access to land disposal sites	Where exclusion is not possible, managed access can be provided whereby waste pickers are provided with access to specific and less hazardous areas of land disposal sites in exchange for adherence to basic health and safety procedures. Some operators may be reluctant to suffer ongoing liability for the presence of waste pickers, but in the context of the alternatives whereby they have no control, managed access may be a safer all round option.	National and municipal governments
	Restrict supply chain for certain items and materials (e-waste and medical waste)	Take steps to reduce demand from medical institutions for medical equipment that has been recovered from waste for reuse. Restrict the upstream supply chain of used electrical equipment that is exported from HICs to LIMICs.	NGOs ODA-related organisations
	Integrate waste pickers into municipal solid waste management plans	Evidence indicates that inclusion and integration of informal waste workers into municipal solid waste management planning may improve the health and safety and wellbeing of its participants. It is therefore recommended that municipal governments action this integration as a matter of urgency to begin the process of mitigating further harm to this vulnerable population.	Landfill and dumpsite operators, municipal governments, NGOs and waste picker organisations

Table 5: Summary of 18 recommendations for further research and innovation.

Overarching thematic area	Recommendation	Detail	Potential stakeholder type
All	Research and innovation on the local to global scale and nature of the phenomena and their implications, and system wide challenges and opportunities, including benchmarking and global observatories supported by standardised quantified evidence	Commission high quality, comparable and actionable research targeted at developing a detailed understanding of the magnitude of harm across each thematic area of concern at systems level, including: • Number of people occupationally involved in activities and the number of those affected by negative interactions with emissions • Flows of materials and substances throughout society and across the resource recovery value chain from the use phase through to fate • Development of standardised methods of data gathering and reporting • Establishment of global observatory(s) to host data and knowledge	ODA-related organisations International funding bodies International waste sector organisations Academics and consultancies
Open burning	Collect primary data on prevalence	Research on the quantities of waste open burned is largely based on expert interviews and elicitation with a few articles that source data from surveys and observations leading to significant uncertainty on the mass of material being open burned. Several primary data gathering activities could be carried out: • Transect analysis to determine the prevalence of open burning observing the size and mass burned in different contexts. • Assessment of open burning activities in informal e-waste reclamation centres. • Verbal and written surveys combined with physical analysis of material to determine the mass open burned. • Novel methods to assess the mass that is combusted in long-term smouldering dumpsite fires. • Algorithm based analysis of aerial imaging data collected via satellite, aeroplane or drone.	Academics and consultancies – specialists in waste management and primary data gathering ODA-related organisations
	Link prevalence (above) with management practices	Investigate the link between open burning prevalence and variations in management to provide evidence for predictive modelling in other contexts.	Academics and consultancies – specialists in waste management ODA-related organisations
	Develop reliable emission factors	Develop reliable emission factors – appropriate to the type of material and conditions under which material is combusted. These are likely to be field-based studies of fires across many different contexts and with varying material composition, including: • household backyard burning • burning in the streets • dumpsite fires • fires to recover electrical components • basic brick-built incineration (such as medical waste) • simulated fires.	Academics and consultancies – specialists in atmospheric chemistry ODA related organisations
	Link observed atmospheric concentrations to source	Improve understanding of the contribution of open burning to concentrations of substances detected in the atmosphere in the context of confounding sources. Studies will combine data on other emissions sources such as transport, industry with marker species to model and apportion-measured atmospheric concentrations to sources including open burning.	Academics and consultancies – specialists in atmospheric chemistry ODA-related organisations
	Risk comparison between emissions and pathogen elimination	Quantitatively compare the mitigation of risk of pathogenic infection via open dumping to that associated with the emissions of potentially harmful substances from open burning.	Academics and consultancies – specialists in waste management, risk management and infection control ODA-related organisations

Overarching thematic area	Recommendation	Detail	Potential stakeholder type
	Assess the benefits and motivations for open burning	Understand the reasons why open burning is carried out by different actors to tailor efficiently interventions toward mitigation. Research is likely to include: • large-scale surveys • focus groups • participatory research.	Academics and consultancies ODA-related organisations
	Develop transition practices/guides to work to eliminate hazards	Develop transition practices, guides, processes, protocols for monitoring, rapid elimination or better open burning practice. These types of resource will combine behavioural change theory with risk assessment targeting geographical locations and socioeconomic groups where prevalence of open burning is high.	Academics, consultancies, municipal and central governments ODA-related organisations
Dumpsites	Identification of dumpsites	While the locations of some of the world's largest dumpsites are known by ISWA and the Waste Atlas, there is no centrally recorded data on the location of the majority. This creates a challenge for actors who wish to intervene to prevent harm, for instance assessment of waste-slope failure. The following research activities are therefore suggested: • Engage with ISWA's international network to identify known, high risk-sites. • Develop algorithms to interpret drone, satellite or aeroplane-captured images to identify dumpsites. These could be validated with ground truthing and calibrated against survey, data and waste characterisation studies. • Use the above data to profile sites according to topology, climatic conditions and size, enabling development of a shortlist of sites for on-the-ground assessment.	ISWA, national governments, academics, consultancies ODA-related organisations
	Assessment of the risk of slope failure	Deploy global team of geotechnical engineers; experts in waste-slope failure to assess sites identified as high risk from the desk study.	Geotechnical engineers, academics, consultancies ODA-related organisations
	Guidance to mitigate the risk of waste-slope failure	Develop accessible open access guidance aimed at municipal governments to both assess the likelihood of waste-slope failure and detail steps towards mitigation of risk including evacuation if necessary.	Academics, consultancies ODA-related organisations
	Produce standards for controlled managed disposal alongside guidance and monitoring of transitionary steps to achieve it	Produce minimum standards for low-cost 'controlled land disposal' in LIMICs that recognise the challenges associated with implementation in the context of scarce financial resources. Supplement with guidance and monitoring protocols that support the transitionary steps towards harm reduction and eventual sanitary landfill.	Academics and consultancies – specialists in atmospheric chemistry ODA-related organisations
Waste pickers	Develop standardised reporting criteria to establish causality controlling for confounding factors	Considerable evidence exists that indicates concentrations of hazardous substances in environmental compartment and people. However, many studies do not report sufficient information to infer causality in the context of confounding factors. To improve the quality of these studies it is recommended that standardised and comparable experimental and reporting criteria be developed.	Academics, consultancies ODA-related organisations
	Carry out high-quality, comparable and actionable research that quantifies risk	Many of the studies of waste pickers are non-technical and un-actionable with a strong focus on philanthropic poverty alleviation and anecdotal evidence or reporting of individual experiences. To establish a quantifiable evidence base it is recommended that further studies be carried out that model hazard exposure to calculate reportable hazard quotients and index numbers and thus provide quantifiable risk of morbidity and mortality.	Academics, consultancies ODA-related organisations
	Link epidemiological observations to risk exposure evidence in global burden of disease type studies	Use the above data to extrapolate the global burden of disease type studies that assess risks to the entire global waste picker sector.	Academics, consultancies ODA related organisations

Overarching thematic area	**Recommendation**	**Detail**	**Potential stakeholder type**
	Establish a global observatory to facilitate targeted intervention design	To centralise and make available the aforementioned waste-picker-related research, a 'global observatory' is recommended as a repository of data to enable targeted intervention design.	Academics, consultancies ODA-related organisations
	Empower waste pickers to get organised and work away from high exposure activities	Encourage and work with waste pickers to improve conditions and work in a safer environment, away from the dumpsite front, by depositing feedstock in interim locations that are demarcated to reduce interactions with machinery and vehicles and which do not entail working on top of deep waste piles of unknown composition. As an extension to this concept, undercover environments could be provided with tables or conveyors to improve manual handling, hygiene and welfare. Alternatively waste pickers could be encouraged to engage as sanctioned door-to-door collectors of source separated material as part of municipal waste management planning.	Academics, consultancies ODA-related organisations
	Innovation on PPE and use that can be usable/ acceptable/ affordable by waste pickers	Work with waste pickers to provide and encourage the use of affordable / acceptable / useable personal protective equipment to reduce the risk of hazard exposure	Academics, consultancies ODA-related organisations

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Appendix A Methodology

A systematic review of literature was carried out for each theme according to PRISMA guidelines[28] which are intended to ensure that robust scientific practices are applied to the review process. Comprehensive details of the methodology are briefly summarised here.

Relevant literature was identified by searching established academic output databases with wide disciplinary coverage (Scopus, Web of Science, and Google Scholar) as recommended by Gusenbauer[29] to improve the probability of capturing all relevant information sources. The search strategy involved identifying suitable terms, selected to feature three components, all of which had to be satisfied for a literature document to be included - as follows: (i) material type and waste; (ii) waste processing type or role; and (iii) harm to human health or the environment. Studies in the English language were screened by title, abstract and then a more thorough eligibility screen was carried out, which involved reading or scanning the main publication text in more detail. The systematic search was supplemented with a series of rapid review techniques, such as snowball searching, searching of databases, NGO websites, and citation searching. The screening process is illustrated in **Figure 18**.

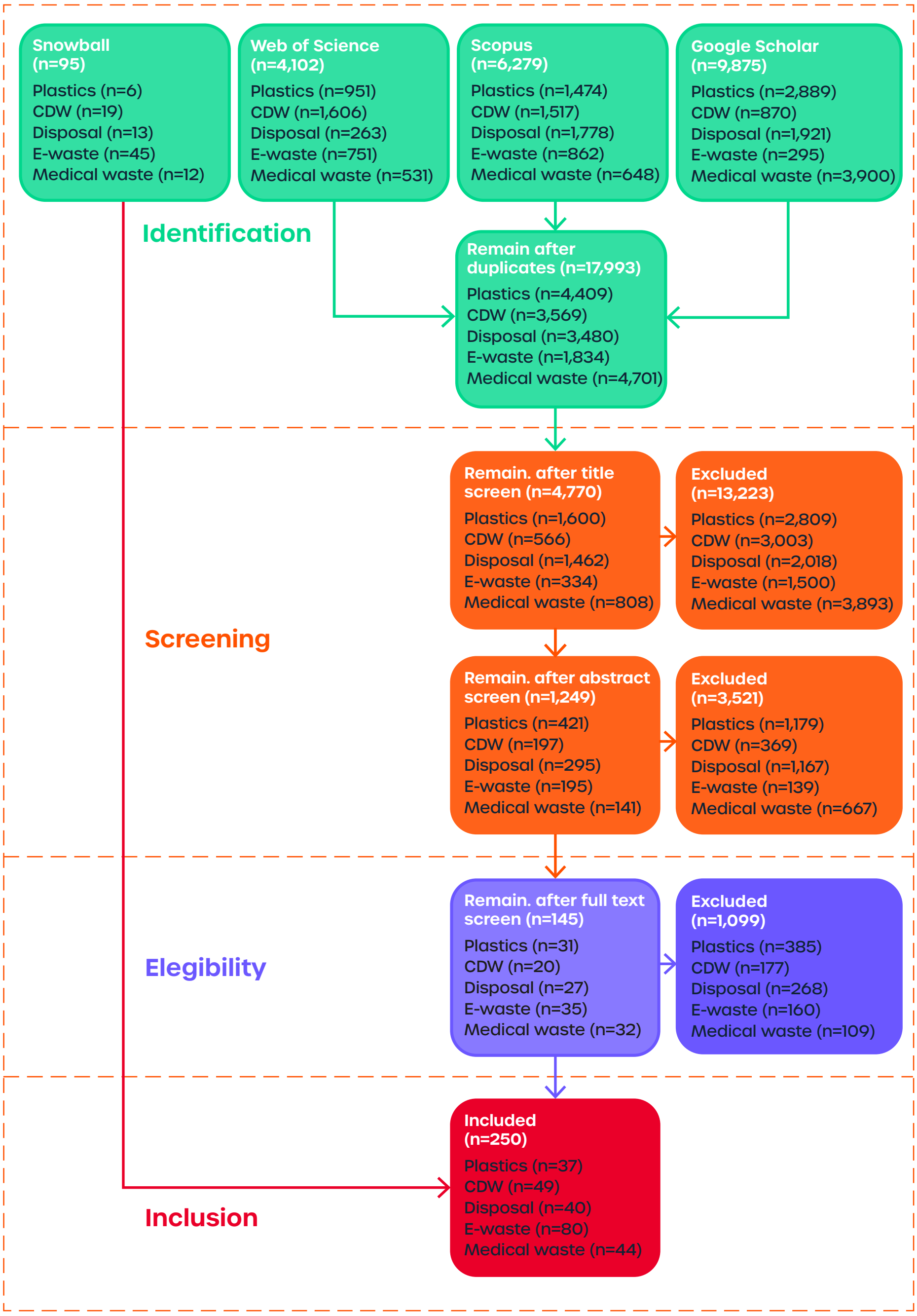
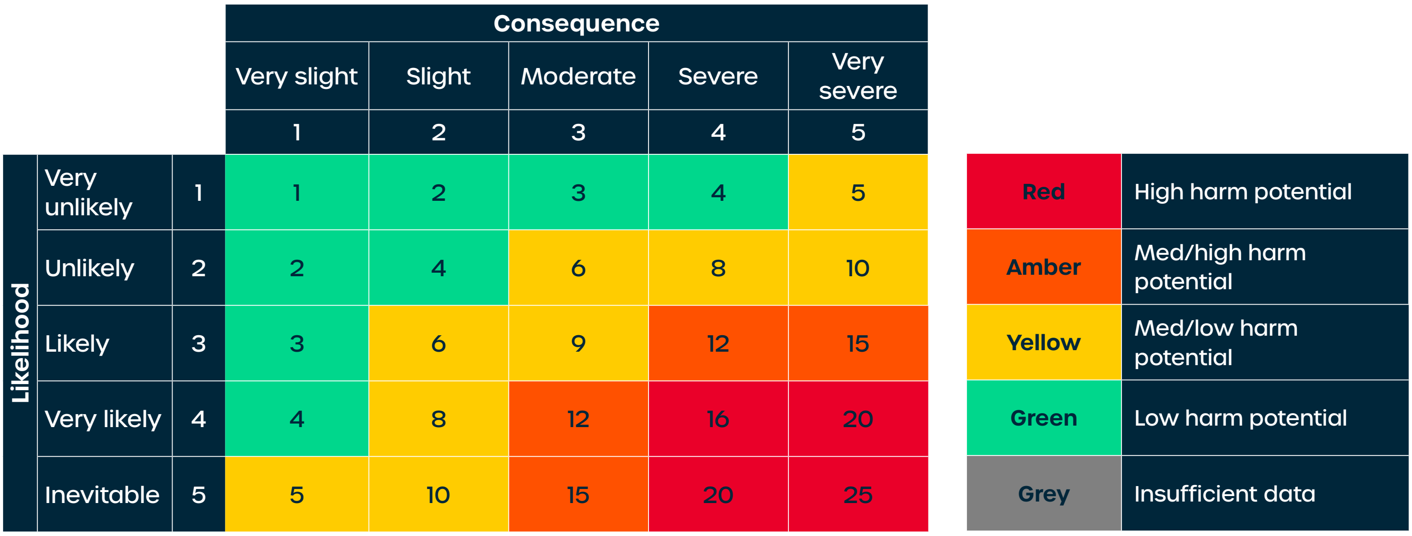


Figure 18: Summary of studies included in this review for each thematic area.

Material flow analysis (MFA) was used to show the generation and management of waste in each thematic area using generic method principles, adapted from Brunner and Rechberger[30].

Hazards and risks identified in the selected studies were summarised and discussed to highlight the key safety challenges. Based on these summaries, a semi-quantitative risk characterisation exercise was carried out to assess selected hazard-pathway-receptor combinations that were identified. This process was not intended to quantify the risk to human health, as to do so across so many scenarios was beyond the resources of this study. Instead, the risk assessment was used as a qualitative indicator to rank and prioritise risk pathways so they could be ranked and compared. A basic risk assessment matrix was used **(Table 6)** for the assessment based on World Health Organization guidance on *Rapid Risk Assessment of Acute Public Health Events*[31]. While this guidance is not directly aimed at a global safety review, similar frameworks have been used by policymakers as a basis for defensible indication of risk that can be used to prioritise action.

In many cases, there was very little information with which to characterise the full hazard-pathway-receptor combination, and as result, harm potential levels were inferred through qualitative adductive reasoning.



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

Red	High harm potential
Amber	Med/high harm potential
Yellow	Med/low harm potential
Green	Low harm potential
Grey	Insufficient data

Table 6: Matrix used to determine the level of risk exposure in each of the specified hazard scenarios.

Acknowledgements

Researched by

Principal Investigator and project lead:
Dr Costas Velis (University of Leeds)
Co-Investigators:
Professor Phil Purnell (University of Leeds) and
Dr Emilio Garcia-Taengua (University of Leeds)
Main researcher:
Ed Cook (University of Leeds)
Graphic design support:
Nick Rigas (D-Waste)
Thematic areas in collaboration with:
International Solid Waste Association (ISWA), D-Waste Ltd. and Independent Safety Services Ltd. (ISSL)

Authors

Ed Cook (University of Leeds)
Dr Costas Velis (University of Leeds)

Contributors

Spyridoula Gerassimidou (University of Leeds)
Sarah Edmondson
Dr Amani Maalouf (D-Waste)
Antonis Mavropoulos (D-Waste)
Maria Plota (D-Waste)
Haris Kamariotakis (D-Waste)
Dr Anne Woolridge (ISSL)
Aditi Ramola (ISWA)
Boris Brkovic (ISWA)
Petra Stapp (ISSL)
Michiel Derks (University of Leeds)
Dr Josh Cottom (University of Leeds)
Dr Godwin Akpeimeh (University of Leeds)
Professor Arne Ragossnig (ISWA)
Carmela Gonzales (University of Leeds)

Technical Advisory Group

Professor William Powrie FREng (Royal Academy of Engineering – Programme Chair)
Professor Linda Godfrey (Council for Scientific and Industrial Research – South Africa)
Stuart Hayward-Higham (Suez UK)
Dr Keith Alverson (UN Environment International Environmental Technology Centre)
Professor Sir Ian Boyd (University of St. Andrews - former Chief Scientific Advisor at Defra)
Mark Ewen (Mott MacDonald)
Tracy Moffatt (Skanska)
Professor Edward Kosior (Nextek)
Crispian Lao (National Solid Waste Management Commission, Philippines)

Programme Board & Academy staff

Professor William Powrie FREng (Royal Academy of Engineering - Programme Chair)
Dr Andrew Clark (Royal Academy of Engineering)
Dr Ruth Boumphrey (Lloyd's Register Foundation)
Steve Gilbert (Lloyd's Register)
Professor Susan Gourvenec (University of Southampton)
Hazel Ingham (Royal Academy of Engineering)
Shaarad Sharma (Royal Academy of Engineering)
Pippa Cox (Royal Academy of Engineering)
Gemma Hummerston (Royal Academy of Engineering)

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Costas Velis' research team at the School of Civil Engineering (2nd in the UK for research power), Faculty of Engineering and Physical Sciences, innovates on recovering resources from solid waste and enabling a global circular economy, whilst preventing risks to public health, such as from plastics pollution and wider waste mismanagement. University of Leeds led and coordinated this international team effort, systematically reviewing and critically assessing the scientific evidence base, to open new pathways for research and solutions.

Woman walks through a burning dumpsite in Dandora, Kenya; © Benedicte Desrus (2013).

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Engineering X
Royal Academy of Engineering
Prince Philip House
3 Carlton House Terrace
London SW1Y 5DG

Tel: 020 7766 0600
www.raeng.org.uk
@RAEngGlobal

Registered charity number 293074

Lloyd’s Register Foundation
71 Fenchurch Street
London
EC3M 4BS
United Kingdom

Tel: +44 20 7709 9166
www.lrfoundation.org.uk/en/
@LR_Foundation

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