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TRANSFORMING WASTE MANAGEMENT SAFETY: AN IMMERSIVE REALITY FRAMEWORK FOR RISK ASSESSMENT AND OCCUPATIONAL HEALTH

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HIGHLIGHTS

1. The MARAT assessment showed that 94% of identified hazards in waste management require structured corrective action.
2. An immersive VR framework was developed to translate semi-quantitative risk data into interactive training experiences.
3. Three Unity VR scenarios were created to address sharps, bioaerosol/VOC, and vehicle-related hazards.
4. The framework aligns with ISO 45001:2018 and provides a scalable, low-cost safety training solution.
5. The system translated risk-assessment results into interactive behaviour-based training.

ABSTRACT

The exponential escalation in global waste generation, driven by rapid urbanisation and industrial consumerism, has precipitated a corresponding surge in occupational hazards within the waste management sector. Workers in this industry function at the nexus of environmental sustainability and public health, yet they are routinely subjected to a debilitating array of mechanical, biological, chemical, and ergonomic risks. Traditional pedagogical paradigms for Occupational Safety and Health (OSH) have been predominantly reliant on static manuals, passive lectures, and theoretical compliance checklists, and have proven insufficient in fostering the deep hazard perception and behavioural modification necessary to mitigate these dynamic risks. This dissertation presents the development of an immersive reality-based framework that integrates Virtual Reality (VR) with the Method of Evaluation of Risks and Work Accidents (MARAT) to support occupational safety training. A systematic literature review, conducted in accordance with the PRISMA Statement, analysed forty-nine indexed studies to identify critical hazard vectors, including bioaerosol exposure, sharps-related injuries, and vehicle–worker interactions. These findings informed the design of a Unity-based VR prototype aimed at simulating high-consequence scenarios within a safe and controlled digital environment. The proposed framework operationalises the preventive logic of ISO 45001:2018 by translating structured risk assessment outputs into interactive simulation mechanics. The results demonstrate the technical and conceptual feasibility of embedding risk assessment methodologies into immersive training environments. While empirical validation with end-users was beyond the scope of this study, the framework provides a structured methodological contribution and highlights the potential of immersive technologies to support risk communication and safety awareness in high-risk occupational contexts. Future research should focus on user-based validation, usability assessment, and the evaluation of training effectiveness.

Keywords: Virtual Reality; Augmented Reality; waste management; health and safety; Risk Assessment; Training.

RESUMO

O aumento exponencial na geração global de resíduos, impulsionado pela rápida urbanização e pelo consumismo industrial, precipitou um aumento correspondente nos riscos ocupacionais no setor de gestão de resíduos. Os trabalhadores dessa indústria atuam na interseção entre a sustentabilidade ambiental e a saúde pública, mas são rotineiramente submetidos a uma série debilitante de riscos mecânicos, biológicos, químicos e ergonómicos. Os paradigmas pedagógicos tradicionais para a Segurança e Saúde Ocupacional (SSO) predominantemente baseados em manuais estáticos, palestras passivas e listas de verificação teóricas de conformidade revelaram-se insuficientes para promover a profunda perceção dos riscos e a modificação comportamental necessárias para mitigar esses riscos dinâmicos. Esta dissertação apresenta o desenvolvimento de um quadro baseado em realidade imersiva que integra a Realidade Virtual (VR) com o Método de Avaliação de Riscos e Acidentes de Trabalho (MARAT) para apoiar a formação em segurança ocupacional. Uma revisão sistemática da literatura, realizada de acordo com a Declaração PRISMA, analisou quarenta e nove estudos indexados para identificar vetores críticos de perigo, incluindo exposição a bio aerossóis, lesões relacionadas com objetos cortantes e interações entre veículos e trabalhadores. Estas descobertas informaram o design de um protótipo de realidade virtual baseado em Unity, destinado a simular cenários de alta consequência num ambiente digital seguro e controlado. O quadro proposto operacionaliza a lógica preventiva da ISO 45001:2018 ao traduzir resultados estruturados de avaliações de risco em mecânicas de simulação interativas. Os resultados demonstram a viabilidade técnica e conceptual de incorporar metodologias de avaliação de risco em ambientes de formação imersivo. Embora a validação empírica com os utilizadores finais tenha ultrapassado o âmbito deste estudo, o quadro oferece uma contribuição metodológica estruturada e destaca o potencial das tecnologias imersivas para apoiar a comunicação de riscos e a consciencialização para a segurança em contextos ocupacionais de alto risco. A investigação futura deve focar-se na validação baseada no utilizador, na avaliação da usabilidade e na avaliação da eficácia do treino.

Palavras-chave – Realidade virtual; Realidade aumentada; Gestão de resíduos; Saúde e segurança; Avaliação de riscos; Formação.

GLOSSARY

ACT – Authority for Working Conditions

AHP – Analytic Hierarchy Process

AI – Artificial Intelligence

AR - Augmented Reality

CL – Consequence Level

Dec.Lei – Decree-Law (in Portuguese legal context, e.g., DL No. 50/2005)

DL – Deficiency Level

EL – Exposure Level

EU-OSHA – European Agency for Safety and Health at Work

GDPR – General Data Protection Regulation

HMD – Head-Mounted Display

ILO - International Labour Organisation

IMS – Integrated Management System

ISO – International Organisation for Standardisation

JSA – Job Safety Analysis

MARAT – Method of Evaluation of Risks and Work Accidents

MCDA – Multi-Criteria Decision Analysis

MSW – Municipal Solid Waste

NACE E38 - Waste collection, treatment, disposal activities and materials recovery

NTP – Notas Técnicas de Prevención (*Technical Prevention Notes*)

OHS – Occupational Health and Safety

OHSA – Occupational Health and Safety Administration

OHSMS – Occupational Health and Safety Management System

OSH – Occupational Safety and Health

OWAS – Ovako Working Posture Analysis System (ergonomic risk assessment)

PL – Probability Level

PPE – Personal Protective Equipment

PRISMA – Preferred Reporting Items for Systematic Reviews and Meta-Analyses

REBA – Rapid Entire Body Assessment

VOCs - Volatile Organic Compounds

VR – Virtual Reality

WHO – World Health Organisation

XR - Extended Reality

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1 INTRODUCTION

1.1 Contextualising the global waste crisis

In the past two decades, the volume and complexity of global waste streams have significantly increased due to rapid urbanisation, industrial growth, and intensified consumer habits. This surge in waste—spanning municipal, industrial, electronic, and hazardous categories—has contributed to a wide range of environmental and occupational health challenges, particularly for those employed in the waste management sector (Duan et al., 2021; Awuchi et al., 2020). Waste workers play a critical role in ensuring urban hygiene and environmental sustainability, yet they are routinely exposed to multiple occupational hazards, making waste management one of the most dangerous sectors worldwide (Uhunamure et al., 2021; Tshivhase et al., 2022).

These occupational hazards are diverse and often overlapping, encompassing chemical exposures, airborne pathogens, injuries caused by sharp objects, traffic-related incidents, and cumulative ergonomic strain. Research has documented simultaneous exposure to biological, chemical, and physical hazards during routine waste-handling tasks (Liu et al., 2023; Ren et al., 2024). Studies such as Lanzarini et al. (2022), Viegas et al. (2024) and Madsen et al. (2024) have shown that inhaling bioaerosols and fine particulates during sorting and recycling increases the risk of respiratory and inflammatory illnesses. Findings by Barkhordari et al. (2022) and Gravel et al. (2023) reinforce these concerns and highlight the need for more targeted occupational safety measures.

The economic implications of this occupational crisis are profound. Workplace accidents and chronic occupational illnesses in the waste sector translate directly into significant productivity losses, elevated absenteeism, and increased pressure on public healthcare systems. The World Health Organization (WHO) has noted that the economic burden of occupational injuries in labour-intensive industries such as waste management is often underestimated, encompassing not only direct medical costs but also long-term losses of human capital.

Further risks include musculoskeletal injuries due to repetitive motions and heavy lifting (Ferrão et al., 2021; Soares, 2021), as well as psychosocial stressors associated with precarious employment conditions, inadequate training, and social stigma—particularly affecting informal workers (Dada et al., 2022; Yamane, 2023).

1.2 The Problem of Ineffective Training Paradigms

Despite the severity of these risks, the mechanisms for protecting this workforce have remained stagnant. The central problem addressed by this research is the systemic failure of traditional Occupational Health and Safety (OSH) training methodologies to effectively mitigate risks in the dynamic, high-stakes environment of waste management. Traditional methods often rely on qualitative checklists or static evaluations that fail to account for the dynamic and evolving nature of modern waste systems (Mutlu et al., 2021; Moloudi et al., 2022). As a result, many hazards are either underreported or misclassified, leading to incomplete prevention strategies.

Furthermore, current risk assessment strategies frequently depend on qualitative tools that do not capture the variability and continuous changes within waste management processes. Consequently, hazards may be misclassified, underreported, or overlooked until a serious incident occurs. There is a distinct lack of integrated frameworks that combine rigorous semi-quantitative risk assessment with advanced immersive training technologies capable of fostering genuine behavioural change. While Industry 4.0 technologies such as Virtual Reality (VR) and Augmented Reality (AR) have transformed training in aviation, medicine, and construction, their application within the waste management sector remains minimal, leaving a critical gap in the safety infrastructure of essential municipal services.

Recent research has called for the integration of quantitative approaches, including toxicological measurements, exposure assessments, ergonomic evaluations, and structured decision-making tools such as the Analytic Hierarchy Process (AHP) and Multi-Criteria Decision Analysis (MCDA), to prioritise risks (Moloudi et al., 2022; Rodrigues et al., 2020). Nonetheless, implementation remains weak, particularly in low- and middle-income countries where waste operations are predominantly manual and informal (González et al., 2022).

According to the International Labour Organization (ILO, 2018), waste workers are among the most vulnerable occupational groups, with significantly higher exposure to biological, mechanical, and chemical hazards. Yet hazard identification systems, health surveillance, and worker involvement in safety programmes are often insufficient. Ferrão et al. (2021) further emphasise that solid waste collection is routinely linked to accidents and environmental risks, reinforcing the need for a proactive safety culture.

Despite the adoption of frameworks such as ISO 45001:2018 and EU directives (e.g., Directive 89/391/EEC), enforcement is inconsistent, particularly in municipal and micro-enterprise contexts, and does not adequately cover contract-based or informal workers (Adewale et al., 2020).

For example, in Portugal, the Authority for Working Conditions (ACT) reported 124 fatal work accidents in 2022, many occurring in sectors that share hazards with waste management. Meanwhile, Eurostat (2022) recorded 2.97 million non-fatal and 3,286 fatal work accidents across the EU, with the waste management industry (NACE E38) consistently ranking among the sectors with elevated chemical, biological, and ergonomic exposure.

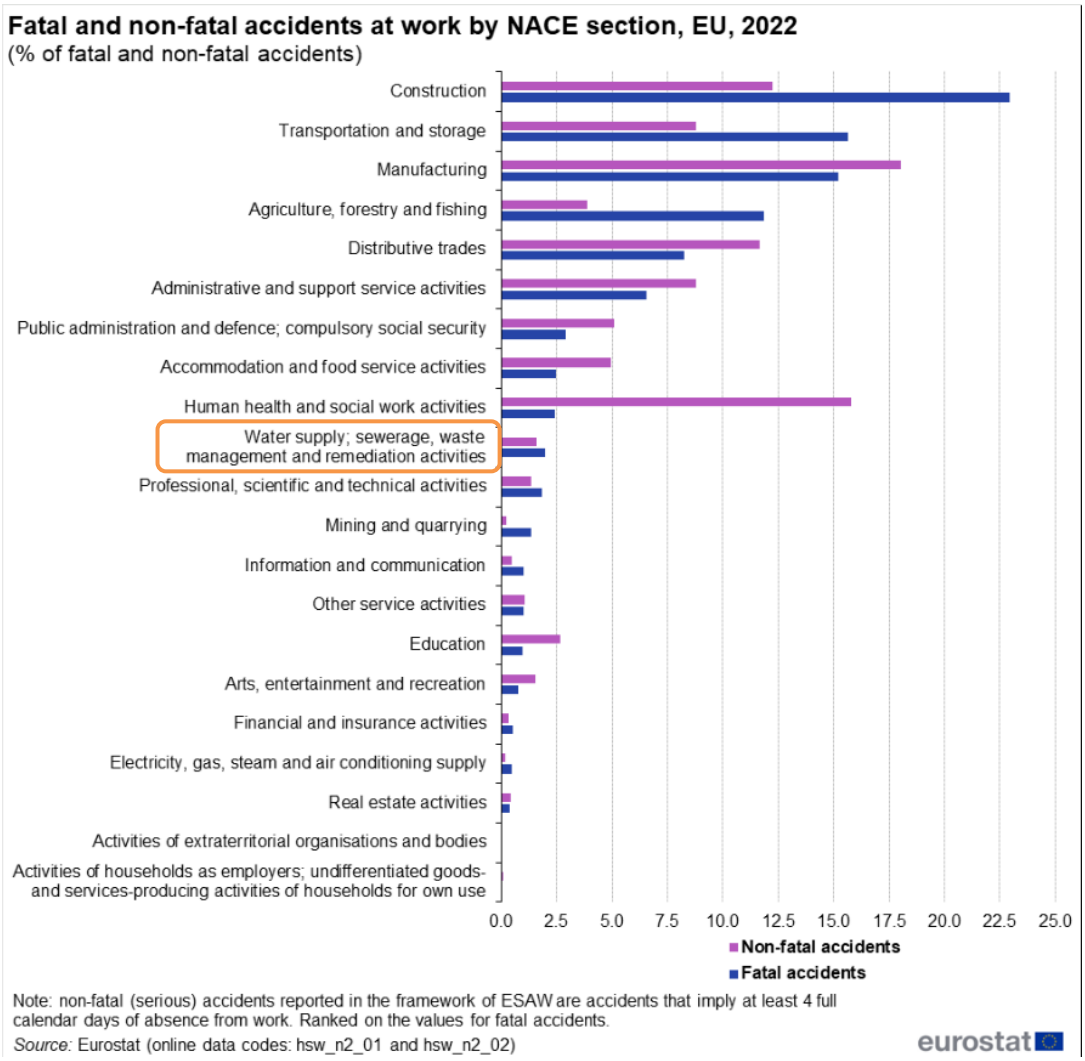


Figure 1: Fatal and Non-Fatal Accidents at Work by NACE Sector (EUROSTAT, 2022).

The "Water Supply; Sewerage, Waste Management and Remediation Activities" sector shows high rates of occupational accidents, confirming the industry's hazardous profile. To address these risks, some progress has been made in personal protective equipment (PPE) development and occupational hygiene practices (Szulc et al., 2022). However, training remains one of the most underutilised pillars of risk prevention. Conventional training via lectures, manuals, or static posters often fails to engage waste

workers, many of whom may have limited literacy or formal education. Consequently, essential information on hazard prevention is poorly retained and inconsistently applied in real-world tasks.

Emerging studies highlight the transformative potential of immersive technologies, especially VR and AR, in training and risk awareness. These tools allow workers to simulate hazardous scenarios, experience the consequences of incorrect actions in real time, and reinforce correct behaviours in a safe and engaging environment (Pereira et al., 2023; Ghobadi et al., 2023).

In sectors such as construction and manufacturing, immersive tools have already demonstrated significant benefits, including improved hazard recognition, enhanced decision-making, and better memory retention (Swallow et al., 2024; Tepe et al., 2023). However, their application in waste management remains limited, despite clear compatibility with the sector's risk profile and training needs.

For instance, Pereira et al. (2023) applied AR in lean production settings to improve hazard identification and task sequencing. García et al. (2023) developed a smart helmet using AR and AI sensors to enhance situational awareness in high-risk environments. Similarly, Méndez et al. (2025) designed adaptive AR frameworks for real-time safety instructions. Studies such as Bes et al. (2024) show that VR and AR outperform traditional training methods in retention and safety behaviour.

Despite the well-documented hazards faced by waste workers and the emerging potential of immersive technologies, there is currently no integrated, scalable framework that merges structured risk assessment with immersive training within the context of waste management—particularly one designed for low-resource, high-risk environments.

This dissertation addresses this critical gap by proposing a practical framework that combines structured risk assessment methodologies with immersive (VR/AR) technologies. It aims to enhance occupational safety, especially for informal and semi-formal waste workers, through accessible, interactive, and context-appropriate digital tools, thereby contributing to sustainable, safe, and resilient waste operations.

1.3 Problem Statement and Motivation

The significance of the problem addressed in this research is multifaceted, encompassing statistical, socioeconomic, legal, and technological dimensions that together emphasise the OSH conditions in the waste management sector. From a statistical perspective, waste workers experience some of the highest rates of occupational injuries and chronic illness globally (ILO, 2018; EUROSTAT, 2022). As noted by Adewale et al. (2020), this informality not only limits the implementation of safety procedures but also reinforces cycles of vulnerability and occupational inequality.

The economic implications are equally substantial. Workplace accidents and chronic occupational illnesses translate directly into productivity losses, absenteeism, and increased healthcare costs. The World Health Organization (WHO, 2017) reports that occupational injuries and diseases impose a heavy economic burden on both enterprises and public health systems, particularly in labour-intensive industries such as waste management.

Technological advancements have created unprecedented opportunities to transform how occupational risks are assessed, communicated, and mitigated. In sectors such as construction, planning, and manufacturing, immersive technologies—particularly VR and AR—have demonstrated strong potential in improving hazard recognition, situational awareness, and behavioural learning. However, as evidenced in recent reviews by Bes et al. (2024) and Pereira et al. (2023), their application in the waste management context remains extremely limited.

1.3.1 Workplace Accidents in the Waste Industry

Globally, research has demonstrated that waste management workers are among the most exposed to occupational risks due to the unstructured and heterogeneous nature of their tasks. Uhunamure et al. (2021) identified recurrent injuries caused by sharp materials and biological waste exposure among South African landfill workers. Similarly, Soares (2021) observed that inadequate ventilation and personal protective equipment (PPE) in Brazilian recycling plants led to frequent chemical inhalation and skin irritation incidents.

In Portugal, while the Authority for Working Conditions (ACT, 2023) does not isolate data specifically for the waste management sector, it reports that fatal and serious accidents are most prevalent in sectors with similar exposure profiles such as construction and manufacturing.

Table 1: Number of investigations concluded by sector of activity - Adapted (ACT, 2023).

CAE	2021	2022	2023	2024	2025	General Total
Water Collection, Treatment and Distribution; Sanitation, Waste Management and Pollution Control	13	20	9	9	7	58

While these statistics encompass all economic sectors, their relevance to waste management is considerable. Waste collection, sorting, and treatment involve tasks that mirror the physical, ergonomic, and environmental hazards found in construction and industrial environments. Rodrigues et al. (2020) identified insufficient OHS monitoring among Portuguese waste firms, while Viegas et al. (2024) documented

biological contamination in e-waste recycling, exposing gaps in microbial risk control. Likewise, Gravel et al. (2023) revealed multi-exposure risks including metal aerosols, organic vapours, and noise in Canadian facilities.

Taken together, these studies confirm that waste management activities entail a combination of mechanical, biological, and chemical hazards, many of which are preventable with adequate risk assessment and training. However, the persistence of similar injury patterns across different countries suggests that existing safety practices often limited to procedural training and manual supervision—are insufficient.

1.4 Structure of the Dissertation

This dissertation is organised into six chapters, each contributing to the overall objective of improving occupational safety by reducing workplace risks, injuries, and fatalities in the waste management sector.

- Chapter 1: Introduction

  This chapter introduces the general theme of the dissertation by presenting the background, research problem, and its broader relevance to occupational health and safety. It provides a general overview of immersive technologies such as VR and AR as emerging tools in workplace risk management.

- Chapter 2: Literature Review

  The second chapter provides a systematic review of relevant literature on occupational health and safety in the waste management industry. It explores the prevailing risk factors, accident patterns, and occupational exposures particularly biological and chemical hazards affecting waste sector workers. In addition to identifying the limitations of existing training and safety systems, the review critically examines regulatory frameworks, assessment methodologies, and technological tools currently in use.

- Chapter 3: Objectives

  This chapter outlines the research design, including the methodological approach, data collection techniques, and analysis procedures used in the development and validation of the proposed framework. It details how the immersive prototype was designed, assessed, and assessed in the context of solid waste management.

- Chapter 4: Materials and Methods

  In this chapter, explain the overall research design (qualitative, descriptive, and analytical). Describe the logic flow: literature review, risk identification, MARAT, immersive framework design.

- Chapter 5: Immersive Framework Development

This chapter describes the development of the immersive training framework that integrates the MARAT with VR-based simulation.

– Chapter 6: Results

This chapter presents the outcomes of the risk assessment conducted in waste management activities, detailing the classification of hazards using the MARAT methodology.

– Chapter 7: Discussion

This chapter critically examines the results by analysing how the integration of the MARAT risk assessment method with VR simulation improves hazard awareness and safety training.

– Chapter 8: Conclusions

This chapter summarises the main findings of the research, highlighting how the integration of the MARAT risk assessment method with immersive VR simulation provides an effective pathway for improving occupational safety in the waste management sector. It emphasises the sector's high-risk profile, the relevance of VR in addressing identified deficiencies, the feasibility of implementing low-cost immersive training, and the framework's alignment with ISO 45001.

2 LITERATURE REVIEW

2.1 The Hazardous Profile of the Waste Sector

A systematic review of the literature yielded forty-nine reviewed articles from an initial search pool of over 19,600 entries. After title and abstract screening, 19,537 articles were excluded for irrelevance to occupational health and safety (OSH) in waste management or for lacking empirical validity. The flowchart in Figure 3, adapted from PRISMA (2020), outlines the screening process.

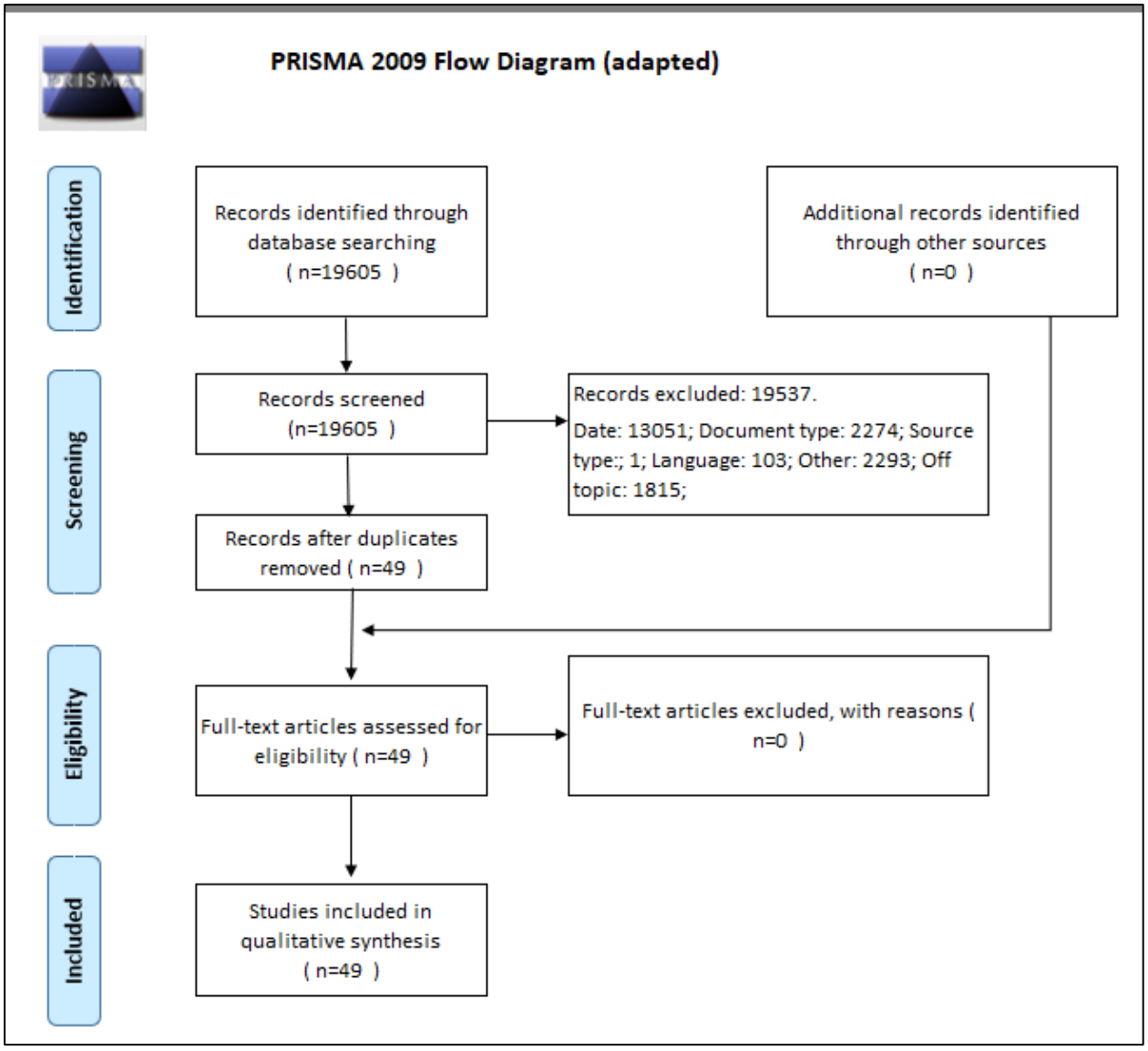


Figure 2: Prisma Flow Diagram (Adapted (PRISMA, 2020)).

Following the PRISMA framework for rigorous literature selection, the review now synthesises findings from the forty-nine (49) selected studies.

The articles studied are summarised in Table 1:

Table 1: Summary of articles selected in the literature review.

Article, Year	Title	Research Objective	Assessment Tools	Risks Identified	Solutions Identified
(Uhunamure et al., 2021)	*Occupational Health Risk of Waste Pickers: A Case Study of Northern Region of South Africa*	To assess the occupational health risks faced by waste pickers at landfill sites in Limpopo, South Africa	Semi-structured questionnaires Observational field visits Risk matrix analysis for evaluation frequency and severity of occupational hazards	Exposure to sharp objects leading to cuts and punctures. Inhalation of toxic fumes and bioaerosols Lack of personal protective equipment (PPE) Exposure to extreme weather conditions High physical demand leading to musculoskeletal strain	Recommendation for provision of appropriate PPE (gloves, boots, masks) Regular occupational health screening and vaccinations Inclusion of waste pickers in formal waste management systems Training programs on safe waste handling practices Improved site infrastructure (e.g., shaded sorting areas, sanitation facilities)
(Ferrão et al., 2021)	*Analysis of Environmental Risks and Accidents at Work in Solid Urban Waste Collection*	To instruct companies in the solid waste sector on using tools to assess environmental impacts, manage occupational risks, and develop action plans using quality management methods.	Environmental risk matrix Occupational accident reports and incident analysis Fishbone diagram (Ishikawa) 5W2H tool (What, why, Where, When, Who, How, and How much) SWOT analysis for safety planning	Contact with contaminated waste leading to biological exposure. Road accidents involving collection vehicles. Manual handling injuries due to improper lifting techniques Poor waste segregation increasing exposure to sharp or toxic materials.	Implementation of risk assessment frameworks integrated into company operations. Use of personal protective equipment (PPE) with routine checks Regular safety training and simulation drills for workers Introduction of a quality management system (QMS) aligned with ISO 14001 and OHSAS 18001

				Lack of standard operating procedures (SOPs) for risk management	Design of strategic action plans to prevent and respond to accidents
(Barkhordari, et al., 2022)	*Characteristics and Health Effect of Particulate Matter in a Waste Facility*	To measure concentrations and health impacts of PM1, PM2.5, and PM10 in a wastepaper centre and evaluate worker exposure risk.	To conduct the assessment, the researchers used environmental air monitoring instruments to detect concentrations of PM1, PM2.5, and PM10 within different zones of the facility. Personal sampling devices were also employed to monitor individual worker exposure levels. The data was analysed using health risk assessment techniques, including dose-response modelling and exposure duration analysis, and compared against WHO air quality standards to determine risk thresholds.	The study found that workers in the facility were at significant risk of developing respiratory problems due to elevated levels of PM2.5 and PM10, particularly during tasks such as shredding and sorting. These particulate levels exceeded recommended safety thresholds and could lead to long-term cardiovascular and pulmonary complications. The facility was also noted for non-compliance with occupational air quality standards in several areas.	The authors recommended the installation of local exhaust ventilation systems specifically in shredding and sorting zones to reduce airborne particulate concentrations. In addition, they advocated for the consistent use of high-grade personal protective equipment (PPE), such as P100 or FFP3 respirator masks. They also proposed rotating workers through high-exposure tasks to minimise prolonged exposure, implementing real-time air quality monitoring systems within the facility, and conducting regular medical evaluations to monitor employees' respiratory health.

(Alarcon, et al., 2022)	*Design of the Occupational Health and Safety Management System*	To design and implement an OHSMS tailored to an association of waste pickers, minimizing occupational hazards and improving safety culture.	The researchers applied a risk matrix methodology to identify, categorize, and prioritize workplace hazards. They also used participatory diagnostic tools such as surveys and interviews with waste pickers to assess safety needs, as well as ISO 45001:2018 standards as a guiding framework for structuring the OHSMS. Document review and compliance audits were used to benchmark current practices against regulatory expectations.	The study identified multiple high-risk factors including sharp object injuries, biohazard exposure from organic waste, lack of personal protective equipment (PPE), and poor ergonomic conditions. Informal waste pickers were found to have minimal safety training and were working in unsafe, unsupervised environments without structured protocols.	To address these risks, the authors designed an OHSMS that included formal training programs on safe handling practices, mandatory PPE usage policies, ergonomic workstation redesign, and improved waste segregation procedures. The system also incorporated regular safety audits, incident reporting protocols, and the creation of a safety committee within the association to monitor and continuously improve workplace safety. Awareness campaigns and onboarding sessions were included to ensure engagement with low-literacy workers.
(Fang et al., 2022)	*Health risks of odorous compounds during the entire process of municipal solid*	To evaluate the concentration levels, olfactory annoyance, and health risks including	The researchers employed field sampling of volatile organic compounds (VOCs),	Significant exposure to volatile odorous compounds—such as hydrogen sulphide, ammonia, benzene, and	The study recommended upgrading ventilation and air purification systems in closed processing units,

	waste collection and treatment in China	carcinogenic risks of odorous compounds across various MSW processing facilities (collection, transfer, composting, landfill) throughout China and to estimate the environmental impact distances.	olfactometry testing for odour intensity, and health risk assessment models (including hazard quotient and carcinogenic risk indices). Geographic Information Systems (GIS) were used to map environmental impact distances of detected emissions.	formaldehyde—was reported across all MSW facilities. Workers and nearby communities were at risk of respiratory distress, eye and skin irritation, and potential long-term carcinogenic effects. The highest concentration peaks occurred near composting and landfill zones. Nuisance odours also contributed to mental and physical stress for waste workers.	implementing buffer zones between facilities and residential areas, and using sealed waste transport mechanisms. They also proposed stricter emission regulations, regular environmental monitoring, and the adoption of biofilters and activated carbon scrubbers in critical zones. Awareness training and respiratory protection for frontline waste workers were also advised.
(Ramos et al., 2020)	*Integrated management systems as a key facilitator of occupational health and safety risk management: A case study in a medium sized waste management firm*	"To analyse how IMSs influence occupational health and safety risk management.	The study utilized qualitative case study methodology, including structured interviews with managers and safety personnel, document analysis, and process audits aligned with ISO 9001, ISO 14001, and ISO 45001 standards. Risk mapping and incident	Common occupational hazards identified included poor procedural compliance, high rates of minor incidents due to human error, lack of standardisation in safety procedures, and fragmented monitoring of safety indicators across departments.	The implementation of an Integrated Management System (IMS) enabled centralized risk monitoring, better communication across departments, and standardized OHS procedures. Key improvements included the introduction of routine safety training, incident reporting systems, and preventive audits. The study highlighted that IMSs fostered a culture of continuous

			trend analysis were also used to assess safety performance pre- and post-IMS implementation.		improvement and initiative-taking hazard mitigation by aligning quality, environmental, and safety goals.
(Cook et al., 2023)	*Medical and healthcare waste generation, storage, treatment, and disposal: a systematic scoping review of risks to occupational and public health*	To assess technicians' perceptions regarding risk management effectiveness.	The study utilized a combination of Virtual Reality simulation platforms and qualitative risk mapping techniques (adapted from standard risk matrices and job hazard analysis frameworks). The VR model simulated waste collection and sorting environments to identify physical hazards. Semi-structured interviews and group observation sessions were also used to assess workers' hazard perception and communication effectiveness during simulated	The study identified a range of physical and operational risks typical in waste handling and site coordination, including: Collisions with vehicles or moving machinery due to inadequate visibility. Poor layout planning leading to unsafe proximity between workers and hazardous zones. Lack of effective emergency evacuation routes. Human error caused by miscommunication or poor situational awareness.	The VR-based collaborative safety planning tool allowed workers and supervisors to interactively visualize site layouts, identify unsafe zones, and propose corrective measures in real time. Key solutions included: 3D hazard visualisation for better spatial awareness and identification of risk hotspots. Interactive route planning to design safer movement paths and evacuation routes. Enhanced team communication through shared immersive environments, improving hazard reporting and decision-making. Integration with traditional safety checklists to ensure findings from VR sessions could be translated into real-

			safety planning exercises.		world corrective actions.
(Szulc et al., 2022)	*Microbiological and toxicological hazard assessment in a waste sorting plant and proper respiratory protection*	To examine accident trends pre- and post-IMS implementation.	The researchers employed a multi-layered AR system integrated with environmental and wearable sensors for real-time hazard detection. The system architecture was built around the principles of Industry 4.0 digitalisation, combining data acquisition from Internet of Things (IoT) devices with predictive analytics and user-interface overlays via AR glasses. Additionally, risk matrices and Failure Mode and Effects Analysis (FMEA) were used to classify and prioritize occupational hazards during the testing phase.	The study identified multiple categories of occupational hazards in waste processing operations: Chemical risks, including exposure to volatile organic compounds (VOCs) and airborne particulates. Mechanical hazards, such as collisions with automated machinery or moving equipment. Ergonomic risks, including repetitive motion and improper lifting postures. Procedural risks, such as incorrect operational sequencing leading to accidents or process inefficiencies.	The proposed adaptive AR architecture addressed these issues through a series of technical and Organisational interventions: Real-time hazard visualisation, displaying danger zones and machine operation alerts directly within the worker's field of view. Adaptive task guidance, providing personalized, context-sensitive safety instructions and procedural checklists. Sensor-based alerts, which automatically notified users of deviations in air quality, temperature, or proximity to restricted areas. Integrated feedback loops, allowing workers to report unsafe conditions or anomalies through gesture- or voice-based inputs, which were then fed into the system's risk database.

(Moloudi et al., 2022)	*Prioritizing health, safety, and environmental hazards by integrating risk assessment and analytic hierarchy process techniques in solid waste management facilities*	To explore the role of leadership and worker participation in safety activities."	The study employed Virtual Reality (VR)-based immersive simulation models combined with qualitative perception analysis tools. Participants—including both waste workers and safety technicians—were exposed to controlled virtual scenarios representing real-life hazards such as handling of hazardous waste, exposure to biological agents, and mechanical operations. Risk perception data were gathered through structured questionnaires, Likert-scale evaluations, and comparative task-based performance scoring.	The study identified several key categories of risks commonly underestimated by workers but consistently recognized by safety experts: Biological risks, including contact with infectious waste and airborne pathogens. Chemical risks, especially during handling of containers with unknown or improperly labelled substances. Ergonomic risks, such as improper lifting techniques and repetitive strain injuries. Psychosocial risks, including fatigue and inattention caused by lack of adequate training or risk awareness.	The VR simulations served as a bridge to improve hazard perception alignment between workers and safety technicians. The following interventions were found to be effective: Immersive hazard visualisation, which helped participants identify risks that were often overlooked in conventional 2D training materials. Interactive training modules, allowing users to experience the consequences of unsafe actions in a controlled environment. Feedback and debriefing sessions, where differences in perception were discussed, fostering a stronger safety culture. Customized scenario design, enabling continuous learning tailored to specific waste management processes.

			Additionally, the researchers used a risk perception alignment index (RPAI) to measure the discrepancy between worker and technician evaluations of workplace hazards.		
(Mutlu et al., 2021)	*Developing an integrated conceptual framework for monitoring and controlling risks related to occupational health and safety*	"RQ1: What evidence exists to indicate risk to public and occupational safety posed by medical waste?	The study integrated IoT-based environmental sensors, wireless sensor networks (WSN), and cloud-based data analytics within a 6G-enabled architecture. Air quality was continuously monitored for concentrations of heavy metals (including lead, cadmium, nickel, and chromium) and particulate matter (PM2.5 and PM10) around recycling plants and adjacent communities. To assess	The research identified significant chemical and respiratory risks to both workers and surrounding residents: Elevated concentrations of heavy metals and fine particulates, surpassing WHO recommended exposure limits. Increased likelihood of respiratory illnesses, including chronic bronchitis, asthma, and potential carcinogenic effects. Occupational risks due to insufficient ventilation and PPE compliance among	Rodriguez et al., proposed a real-time, intelligent monitoring system designed to enhance both occupational and environmental safety through the following interventions: 6G-enabled hazard communication network for instantaneous data transmission between sensors, supervisors, and regulatory authorities. Predictive exposure modelling, allowing early detection of unsafe air quality levels and automated alerts to workers via mobile or wearable devices. Dynamic ventilation control systems, activated through AI-based feedback loops

			occupational exposure, the researchers employed personal air sampling devices, spectrometric analysis (ICP-MS), and spatial risk mapping using Geographic Information Systems (GIS). Data communication was optimized via low latency 6G connectivity to ensure real-time hazard reporting.	recycling plant workers. Environmental spillover, with detectable metal contamination in nearby soil and water sources, indicating potential ecological and community health risks.	that adjust air circulation in high-emission zones. Data dashboards for management decision-making, integrating exposure data with compliance tracking and preventive maintenance alerts.
(Rodrigues et al., 2020)	*Occupational Health & Safety (OHS) management practices in micro- and small-sized enterprises: The case of the Portuguese waste management sector*	RQ2: What are the comparative risks to public and occupational safety that arise from the management of medical waste?"	The study utilized a digital twin simulation platform integrated with AI-driven predictive analytics to model real-time workplace conditions in plastic recycling operations. The researchers applied sensor-based monitoring	The study revealed multiple occupational hazards within recycling and reprocessing environments, particularly in relation to automation and manual task overlap. The most critical risks identified were: Thermal hazards from exposure to	The integration of digital twin technology offered several innovative safety management solutions: Real-time virtual replication of the work environment, enabling proactive risk monitoring and scenario testing without endangering workers. Predictive maintenance algorithms that automatically identified equipment failures and

			systems to capture data on machine vibrations, temperature, emissions, and worker positioning. The analysis framework incorporated: Hazard and Operability Study (HAZOP) to identify deviations in process safety. Job Safety Analysis (JSA) to evaluate worker-machine interaction points. Human reliability assessment (HRA) to assess procedural compliance and potential human error probabilities.	elevated temperatures generated during melting and extrusion. Mechanical and ergonomic risks linked to repetitive motion, improper machine maintenance, and inadequate workstation design. Airborne exposure to microplastics and volatile compounds released during recycling and 3D printing processes. Operational safety gaps, including delays in maintenance alerts and inconsistent hazard communication among staff.	emission spikes before they occurred. Dynamic risk dashboards providing supervisors with immediate visual feedback on OSH compliance levels and potential hotspots. AI-based ergonomic optimisation, which simulated posture and movement to redesign workstations for reduced strain and improved efficiency.
(Liu et al., 2022)	*Occupational health risk assessment of BTEX in municipal solid waste landfill*	"Objective: Conduct a comprehensive assessment of microbiological and toxicological	The study employed a low-cost head-mounted display (HMD) VR training system	The VR scenarios were modelled around occupational risks typically found in solid waste management	The use of immersive VR provided an innovative training mechanism that replicated high-risk conditions without

	based on external and internal exposure	hazards at workstations in a waste sorting plant.	designed to simulate real-world waste handling scenarios. Evaluation was conducted through: Pre- and post-training hazard recognition tests to measure learning retention. Presence and immersion scales (ITC-SOPI) to assess cognitive and emotional engagement levels. Task performance assessments comparing VR-trained participants with those trained via traditional lecture-based methods. Observation checklists to document behavioural changes and safety adherence in simulated waste sorting,	facilities. These included: Mechanical hazards, such as contact with sharp objects or moving machinery parts. Chemical hazards from exposure to cleaning agents and hazardous waste residues. Ergonomic risks, including repetitive bending and improper lifting techniques. Cognitive and attentional risks, where distraction or lack of situational awareness led to simulated errors or near-misses.	physical danger. The main solutions and interventions proposed were: Scenario-based experiential learning, allowing workers to experience hazard situations in a realistic but controlled setting. Immediate feedback mechanisms, providing real-time alerts and corrective guidance for unsafe actions. Cost-effective implementation, demonstrating that even low-cost VR systems can deliver impactful OHS training. Behavioural reinforcement modules, where repetitive safe-practice simulation improved memory retention and hazard anticipation.

			lifting, and chemical handling exercises.		
(Liu et al., 2023)	*Occupational health risks of VOCs emitted from the working face of municipal solid waste landfill: Temporal variation and influencing factors*	Objective: Develop guidelines for selecting filtering respiratory protective devices considering specific workplace conditions.	The researchers implemented an immersive VR-based simulation platform integrated with eye-tracking sensors and real-time gaze data analytics. The system's performance was assessed using: VR attention-mapping algorithms to detect and analyse workers' focus on hazardous zones. Fatigue detection metrics, including blink frequency and gaze dispersion. Privacy-preserving data transmission protocols using secure differential encryption, ensuring personal data anonymity.	The study was conducted in the context of e-waste recycling operations, which presented several categories of occupational hazards: Chemical and toxic exposure from heavy metals (lead, mercury, cadmium) and plastic fumes during dismantling. Visual and cognitive strain from repetitive, high-attention tasks and extended screen exposure. Fatigue-related incidents, where lapses in visual attention led to improper handling of hazardous components. Privacy risks associated with biometric monitoring tools, particularly in workforce	Wilson et al. proposed a dual-objective framework that combines occupational safety enhancement with data privacy protection. Key interventions and solutions included: Real-time attention tracking to identify distraction and potential error onset during simulated work. Automated hazard alert system, providing visual and auditory cues when the user's gaze diverted from safety-critical zones. Encrypted gaze data streaming, which allowed supervisors to assess focus and awareness without collecting identifiable user information. Adaptive workload balancing, adjusting training difficulty and pace according to user fatigue levels. Integration with immersive safety modules, replicating e-

			User experience (UX) surveys and NASA-TLX workload assessments to evaluate system usability, cognitive load, and perceived safety benefits.	surveillance applications.	waste disassembly and sorting operations for realistic exposure assessment.
(Pereira et al., 2023)	*Augmented Reality in a Lean Workplace at Smart Factories: A Case Study*	Objective: Assess and prioritize risk levels of HSE hazards in solid waste management facilities.	The study utilized a VR-based exposure and simulation platform to replicate real-world crowd management and emergency scenarios in confined industrial and public spaces. The methodology included: Behavioural analysis metrics tracking reaction time, gaze focus, and navigation paths during simulated crowd scenarios. Physiological monitoring tools, including heart rate and eye-tracking sensors,	The study targeted occupational and behavioural hazards common to operators and safety managers working in complex crowd or emergency environments, including: Operator inattention, leading to delayed response or misjudgement during emergencies. Cognitive overload, due to simultaneous visual and auditory stimuli. Behavioural panic and miscoordination during crowd dispersal scenarios. Physical collision risks and evacuation errors in high-density work or public environments.	To address these risks, Alshaer (2024) introduced an integrated VR hazard exposure system that simulated emergency crowd movement dynamics with real-time feedback. The main solutions implemented included: Immersive, scenario-based VR training that allowed operators to experience high-pressure crowd control situations safely. Dynamic hazard visualisation, where virtual overlays highlighted unsafe zones and exit bottlenecks in real time. Behavioural response optimisation, achieved through repeated exposure and guided debriefs that improved decision-making under stress.

			to measure stress and attention under simulated pressure. Incident probability modelling using predictive analytics to assess hazard detection and response speed. Post-simulation interviews and Likert-scale assessments to evaluate user perception, comfort, and situational learning outcomes.		Integration of augmented hazard indicators (AR) within the VR environment to reinforce spatial awareness and reaction training. Adaptive learning modules, adjusting difficulty levels based on user performance to prevent fatigue and cognitive overload.
(Ershadi et al., 2020)	*Strategic alignment of project management with health, safety, and environmental management*	Objective: Implement corrective actions based on prioritized hazards using analytic hierarchy process (AHP)."	Analytic Hierarchy Process (AHP), risk registers, and expert judgement scoring for prioritising HSE risks.	Poor safety communication, inconsistent environmental monitoring, and lack of alignment between project goals and safety measures.	Development of a strategic alignment framework integrating project management with HSE control, creation of cross-functional safety committees, real-time reporting mechanisms, and performance-based safety indicators.
(Dada et al., 2022)	*Waste pickers' perception of occupational hazards and well-being in a*	"Objective: Propose an integrated conceptual framework for	Structured questionnaires, field observations, and descriptive	Frequent exposure to sharp objects, toxic waste, infectious materials, and poor hygiene	Proposal of a community-based OSH framework integrating regular safety training, improved protective

	Nigerian megacity	monitoring and controlling risks in occupational health and safety.	statistical analysis to assess workers' perception of hazards and safety practices	conditions; high prevalence of respiratory and musculoskeletal issues.	equipment provision, and formal recognition of informal workers.
(Yamane, 2023)	*Assessment and Perception of Occupational Risks in Waste Picker Organisations: A Portrait of Waste Pickers Situation After Formal Integration*	Objective: Enhance safety performance and achieve continuous improvement by preventing waste of time and resources."	Semi-structured interviews, survey questionnaires, and comparative analysis of pre- and post-integration OSH conditions.	Persistent exposure to biological waste, chemical hazards, and ergonomic strain despite formal sector integration; limited PPE use and irregular training.	Implementation of structured OSH programmes, improved PPE distribution, and periodic safety training to reinforce compliance.
(Han et al., 2020)	*Evaluation of Metal Aerosols in Four Communities Adjacent to Metal Recyclers in Houston, Texas, USA*	To explore OHS management practices in the waste management sector and analyse the relationship between these practices and OHS performance.	Air quality monitoring, aerosol sampling, and quantitative health risk assessment (QHRA) models.	High concentrations of airborne metals such as lead, nickel, and cadmium causing potential respiratory and systemic health effects among workers and nearby residents.	Introduction of enhanced ventilation systems, routine air monitoring protocols, and adoption of engineering and administrative exposure controls.
(Soares, 2021)	*Evaluation of Occupational Safety Conditions in a Waste Plastic Recycling Plant in Brazil*	To assess the health risks of occupational exposures to BTEX from a municipal solid waste landfill via external and internal monitoring.	Air sampling techniques, biomonitoring of urinary metabolites, and occupational exposure limit (OEL) comparisons.	High exposure levels to volatile organic compounds (VOCs), leading to potential neurological, respiratory, and carcinogenic health risks. Poor ventilation and lack	Adoption of engineering controls such as improved ventilation systems, regular air quality assessments, and substitution of hazardous substances where possible. Reinforcement of PPE use and safety training

				of consistent PPE use exacerbated exposure levels.	were also identified as essential preventive measures.
(Tshivhase et al., 2022)	*Occupational Health and Safety Hazards Among Solid Waste Handlers at a Selected Municipality in South Africa*	To characterize VOC emissions from the working face of a landfill.	Structured questionnaires, on-site observational studies, and gas chromatography analysis of VOC concentrations.	Workers were exposed to volatile organic compounds, bioaerosols, and physical hazards including musculoskeletal strain and injuries from manual waste handling. Limited training and PPE use intensified exposure risks.	Implementation of structured safety training programmes, enforcement of PPE compliance, introduction of mechanical handling equipment, and enhancement of workplace hygiene and monitoring systems.
(Viegas et al., 2024)	*Microbial Occupational Exposure in E-waste Recycling: Biological Hazards, Their Sources, and Potential Toxic Effects"*	To assess the temporal variation and health risks associated with these emissions."	Air and surface microbiological sampling, culture-based microbial identification, polymerase chain reaction (PCR) analysis, and risk characterisation using occupational exposure thresholds.	High prevalence of fungal and bacterial contaminants (including *Aspergillus*, *Penicillium*, and *Staphylococcus aureus*) in work areas, particularly during dismantling and sorting. Exposure to bioaerosols was associated with respiratory irritation, allergic reactions, and increased risk of infection. Contributing factors included poor ventilation, inadequate PPE use,	Introduction of improved ventilation and filtration systems, regular environmental monitoring, and periodic disinfection of work surfaces. Reinforcement of PPE protocols—especially the consistent use of respiratory protection and gloves—and targeted worker training on biological hazard control were also identified as critical measures.

				and limited hygiene practices.	
(Akhmetov et al., 2023)	*An Augmented Reality-Based Warning System for Enhanced Safety in Industrial Settings*	To enhance operators' working conditions.	Prototype AR head-mounted display, hazard detection algorithms, real-time proximity sensors, and user experience evaluations in simulated industrial environments.	Frequent near-miss incidents resulting from operator inattention, insufficient visibility of dynamic hazards, and delayed response to machinery movements. Human factors such as fatigue and cognitive overload were also identified as contributors to safety lapses.	Development of an AR-based warning interface projecting visual hazard indicators directly within the operator's field of view. Integration of real-time sensor data allowed for automatic alerts on unsafe proximity to machines or hazardous zones. The study also recommended incorporating auditory feedback to reinforce visual alerts and reduce response time.
(Damilo et al., 2024)	*An Overview of Tools and Challenges for Safety Evaluation and Exposure Assessment in Industry 4.0*	To define the most suitable AR for material handling and motion processes."	Systematic literature review of AR-based safety evaluation systems, digital exposure monitoring platforms, and ergonomic analysis tools integrated into cyber-physical systems.	Complexity in managing multi-source data streams, lack of real-time feedback integration between operators and digital systems, and limited adaptability of AR tools to specific safety contexts. Additional risks included operator overload due to excessive visual input and lack of standardised assessment metrics.	The study proposed a multi-layered safety evaluation framework combining AR visualisation with sensor-driven data analytics for exposure monitoring. It identified the need for harmonised safety data protocols, adaptive AR interfaces for user-specific risk alerts, and improved interoperability between monitoring platforms and existing OSH management systems.
(Ghobadi et al., 2023)	*Augmented Reality Applications in*	To investigate the impact of project	AR-based educational modules, user	Low engagement and retention rates in traditional	Integration of adaptive AR interfaces with real-time feedback loops,

	Education and Examining Key Factors Affecting the Users' Behaviours	management on health monitoring programs, safety prevention monitoring, and environmental monitoring plans.	behaviour analysis models, and post-intervention surveys assessing engagement and comprehension.	training methods, lack of interactive feedback in hazard identification learning, and cognitive fatigue due to non-adaptive visual design.	enabling users to visualise safety risks dynamically. The study recommended AR-supported training programmes that enhance motivation, information retention, and situational awareness by simulating real hazard conditions.
(Paulsen et al., 2024)	*Designing for collaborative learning in immersive virtual reality: a systematic literature review*	To determine the importance of these factors in strategic project management."	Systematic literature review of empirical VR-based learning studies, focusing on collaboration frameworks, usability models, and knowledge transfer outcomes.	Fragmented learning experiences due to limited interactivity, lack of synchronisation in virtual collaborative tasks, and cognitive overload caused by poor interface design.	The study proposed a framework for collaborative learning design that integrates ergonomic user interfaces, synchronous task coordination, and contextual feedback mechanisms within immersive environments.
(Sardar et al., 2024)	*An ergonomic evaluation using a deep learning approach for assessing postural risks in a virtual reality-based smart manufacturing context*	To evaluate waste pickers' well-being and perception of hazards and health risks in their daily work routine.	Deep neural network models for posture detection, VR motion-tracking systems, and ergonomic risk analysis using Rapid Entire Body Assessment (REBA) scores.	Repetitive and awkward movements during waste handling and manufacturing tasks leading to musculoskeletal disorders (MSDs) and fatigue-related injuries.	Implementation of an intelligent VR-based feedback system that provides real-time alerts when unsafe postures are detected, enabling corrective action. Additionally, ergonomic redesign of workstations was proposed based on motion data insights.
(Swallow et al., 2024)	*Enhancing collaboration and engagement using virtual*	To augment existing literature on occupational hazards and	Immersive VR simulation platforms, team-based scenario	Limited hazard perception during traditional planning processes,	Deployment of immersive VR simulations to visualise worksite layouts and

	reality within site safety planning	health risks associated with waste picking."	walkthroughs, and pre/post-test evaluations of situational awareness.	inadequate spatial understanding of risk zones, and weak communication between multidisciplinary safety teams.	hazard zones collaboratively. The study suggested incorporating interactive communication modules and real-time annotation tools to facilitate shared decision-making.
(Méndez et al., 2025)	*Adaptive Augmented Reality Architecture for Optimising Assistance and Safety in Industry 4.0*	To assess occupational risks in WPO.	Adaptive AR interface integrated with IoT environmental sensors, human–machine interaction analysis, and compliance audits of safety procedures.	Frequent procedural errors during machine operation and lack of real-time feedback in hazardous work areas, leading to avoidable safety incidents.	Implementation of an adaptive AR architecture that provides real-time visual and audio instructions during tasks, improving compliance and reducing human error.
(Negahban, 2024)	*Simulation in engineering education: The transition from physical experimentation to digital immersive simulated environments*	To compare waste pickers' risk perception with occupational safety technicians' assessments.	Immersive VR training simulations, performance tracking metrics, and post-training cognitive retention evaluations.	Overreliance on physical experimentation leading to inconsistent training outcomes, lack of exposure to high-risk scenarios in real-world environments.	Replacement of physical experiments with VR-based simulations, enabling safe exposure to hazardous conditions while improving decision-making accuracy.
(Rodriguez et al., 2024)	*A Security Services Management Architecture Toward Resilient 6G Wireless and*	To evaluate the impact of metal emissions from metal recyclers on air quality in nearby communities.	Air sampling and sensor networks combined with a 6G-enabled monitoring architecture for	Elevated levels of airborne metal particulates posing chronic respiratory risks and data vulnerability in monitoring systems.	Adoption of a 6G-integrated environmental monitoring system for continuous exposure tracking and secured safety data exchange.

	Computing Ecosystems		real-time data collection.		
(Rojek et al., 2024)	*Digital Twins in 3D Printing Processes Using Artificial Intelligence*	To evaluate occupational safety and health (OSH) practices and identify opportunities for improvement in a plastic recycling plant.	AI-based digital twin models, virtual simulation environments, and real-time OSH performance indicators.	Inefficient monitoring of operator performance and delayed hazard recognition during 3D printing operations.	Integration of AI-driven digital twins for predictive safety analysis and simulation of emergency responses to pre-empt incidents.
(Tepe et al., 2023)	*Investigating the effects of low-cost head-mounted display based virtual reality environments on learning and presence*	To explore occupational health and safety hazards among waste handlers	Low-cost VR headsets, user presence assessment questionnaires, and learning outcome evaluations.	Limited access to effective safety training for low-income or informal workers, resulting in higher accident rates.	Development of accessible VR-based training modules that increase safety awareness and retention among under-resourced waste workers.
(Wilson et al., 2024)	*Privacy-Preserving Gaze Data Streaming in Immersive Interactive Virtual Reality: Robustness and User Experience*	E-waste recycling facilities	Eye-tracking technology integrated into immersive VR simulations and encryption protocols for data protection.	Potential privacy violations from monitoring gaze patterns and reduced trust in training systems among workers.	Implementation of privacy-preserving algorithms that anonymise gaze data while retaining performance and attention insights.
(Alshaer, 2024)	*Investigating the efficacy of virtual reality exposure for crowd management: a real-world application*	To prevent operator inattention and reduce accidents using an augmented reality (AR) warning system	VR-based emergency evacuation simulations, behavioural response tracking, and stress-response metrics.	Panic behaviour and delayed decision-making during emergency evacuations, particularly in crowded environments.	Deployment of immersive training scenarios that replicate emergencies, improving situational awareness and reducing panic-driven errors.
(Bes et al., 2024)	*Analysis of the Effectiveness of*	"To review tools and technologies	Meta-analysis of case studies and	Low engagement and retention in	Recommendation of hybrid AR/VR safety

	Safety Training Methods	for safety evaluation and exposure assessment in Industry 4.0.	user experience assessments across Industry 4.0 contexts.	traditional training, lack of standardised evaluation frameworks for digital tools.	training methods and standardised evaluation metrics for implementation across industries.
(Chung et al., 2023)	*VRCAT: VR Collision Alarming Technique for User Safety*	To identify challenges and limitations of these technologies."	VR collision detection algorithms, real-time spatial mapping, and user performance testing.	Frequent collision risks in dense machinery zones due to spatial disorientation in VR training environments.	Introduction of real-time visual and auditory collision warnings within VR environments to prevent impact-related accidents.
(Coelho et al., 2024)	*Immersive Creation of Virtual Reality Training Experiences*	"To evaluate users' attitudes towards using AR for learning complex tasks.	Virtual simulation platforms, usability and workload assessment metrics (NASA-TLX), and user performance analysis.	High cognitive workload and difficulty mastering task sequences in manual sorting and handling tasks.	Development of VR training experiences that replicate operational processes to improve spatial awareness and reduce training time.
(Criollo-C et al., 2024)	*Usability and Workload Evaluation of a Cybersecurity Educational Game Application: A Case Study*	To identify key factors affecting users' behaviours in AR adoption."	Usability and workload evaluation frameworks (NASA-TLX), AR-based interactive learning modules, and user feedback surveys.	Cognitive overload, low adaptability of AR systems for different user skill levels, and limited transfer of virtual learning to real environments.	Integration of adaptive AR feedback mechanisms and personalised interface designs to optimise workload balance and learning retention.
(García et al., 2023)	*Smart Helmet: Combining Sensors, AI, Augmented Reality, and Personal*	"To investigate collaborative learning in IVR.	AI-based hazard recognition algorithms, environmental sensors (air quality,	Exposure to fluctuating hazardous conditions in industrial and waste-handling	Implementation of an AR-enabled smart helmet capable of real-time hazard detection and visual/audio alerts, improving response

	Protection to Enhance First Responders' Situational Awareness		temperature, noise), and AR display systems.	zones, delayed recognition of toxic gases and heat stress.	times and reducing exposure-related injuries.
(Viegas et al., 2024)	*Microbial contamination in waste collection: Unveiling this Portuguese occupational exposure scenario*	To identify design recommendations for IVR-mediated collaborative learning."	Air sampling, microbial culture analysis, and quantitative exposure risk assessment.	High airborne microbial load in waste handling areas leading to respiratory infections and allergenic responses among workers.	Recommendation of improved ventilation, respiratory protective equipment, and continuous microbial monitoring as part of routine OSH protocols.
(Duan et al., 2021)	*Trace gas emissions from municipal solid waste landfills: A review*	To identify unsafe postures in VR-based smart manufacturing.	Gas chromatographic analysis, emission factor modelling, and risk quantification frameworks.	Chronic exposure to methane, hydrogen sulphide, and VOCs leading to respiratory and neurological symptoms.	Improved gas extraction systems, continuous air monitoring, and the use of AR-based training to visualise invisible emission zones for worker awareness.
(Lanzarini et al., 2022)	*Human adenovirus in municipal solid waste leachate and quantitative risk assessment of gastrointestinal illness to waste collectors*	To assess viral contamination in waste leachate and evaluate the gastrointestinal infection risks to waste workers	Quantitative microbial risk assessment (QMRA), virological sampling, and dose-response modelling.	High prevalence of human adenoviruses in waste leachate, presenting gastrointestinal infection risks through dermal or mucosal contact.	Enforcement of strict PPE use, worker hygiene training, and improved containment of leachate during waste collection and transport.
(Degli Esposti et al., 2023)	*Door-to-door waste collection: A framework for the socio-economic evaluation and ergonomics optimisation*	To explore the use of VR during practical safety and plant coordination planning workshops.	Ergonomic risk assessments (OWAS, REBA), task duration tracking, and worker fatigue measurements.	Repetitive lifting and awkward postures leading to musculoskeletal strain and fatigue.	Redesign of collection routes, ergonomic equipment adaptations, and integration of VR training modules to teach optimal movement techniques.

(Gravel et al., 2023)	*Occupational health and safety, metal exposures, and multi-exposures health risk in Canadian electronic waste recycling facilities*	To assess the impact of VR on multidisciplinary collaboration and engagement.	Air and blood sample analysis, toxicological modelling, and environmental monitoring systems	Chronic exposure to heavy metals such as lead, cadmium, and nickel, causing respiratory and neurological disorders.	Implementation of exposure control measures, periodic medical surveillance, and awareness training using VR simulation of contamination pathways.
(Jiao et al., 2024)	*Identifying ESG types of Chinese solid waste disposal companies based on machine learning methods*	To propose an adaptive AR architecture designed to enhance real-time operator assistance and occupational safety in industrial environments.	Machine learning classification algorithms, AR visual dashboards, and ESG (Environmental, Social, Governance) datasets.	Lack of real-time monitoring of safety metrics, inconsistent data reporting in ESG practices.	AR-based visualisation of risk indicators and predictive analytics to support data-driven safety management decisions.
(Madsen et al., 2024)	*Fungal and bacterial species on biowaste workers' hands and inhalation zone, and potential airway deposition*	To address challenges in AR adoption, such as dynamic personalisation of instructions and mitigation of technical and cognitive barriers."	Airborne microbiological sampling, next-generation sequencing, and deposition modelling.	Inhalation of fungal spores and bacteria leading to chronic respiratory illness among biowaste workers.	Development of hygienic handling protocols, use of high-efficiency respirators, and workplace ventilation improvements.
(Ren et al., 2024)	*Characterisation of VOC emissions and health risk assessment in the plastic manufacturing industry*	To present an overview of current applications and the ongoing transition from physical experimentation	Gas chromatography-mass spectrometry (GC-MS), exposure assessment models, and risk	Elevated VOC concentrations causing irritation, dizziness, and long-term carcinogenic effects.	Installation of local exhaust ventilation systems, substitution of hazardous solvents, and digital exposure tracking systems.

		to digital simulations in engineering education.	characterisation indices.		
(Smith et al., 2025)	*From present to future: A review of e-waste recycling processes*	To highlight major implementation and research gaps related to simulation-based learning and immersive simulated learning environments."	Comprehensive literature review and comparative analysis of existing e-waste management systems.	Chemical exposure, ergonomic strain, and unsafe dismantling practices in informal recycling contexts.	Recommendation of AR/VR-based safety training systems and stricter global OSH regulation enforcement.
(Xu, et al., 2025)	*Extending from reutilisation to by-product service: A life-cycle environmental, economic, and risk assessment of heavy metal-containing hazardous waste recycling*	To propose a security services management architecture for future 6G networks.	Life-cycle assessment (LCA), quantitative risk assessment (QRA), and cost–benefit analysis.	Cross-contamination of heavy metals during recycling stages and lack of efficient emission control systems.	Implementation of closed-loop recycling technologies, automation of handling processes, and regulatory frameworks for emission management.

2.1.1 Biological and Chemical Exposures

A large body of research (Uhunamure et al., 2021; Ferrão et al., 2021; Dada, Faniran et al., 2022; Tshivhase et al., 2022; Soares, 2021) consistently highlights that waste workers particularly informal pickers and manual handlers are exposed to multiple concurrent hazards, including chemical pollutants, biological agents, ergonomic strain, and accident-prone conditions. These findings align with similar concerns raised by (Yamane, 2023), who analysed the effects of formal integration on risk perception among waste picker cooperatives, and by (Han et al., 2020), who investigated metal aerosol exposure in communities adjacent to recycling facilities.

Quantitative studies (Liu et al., 2023; Barkhordari et al., 2022; Fang et al., 2022; Duan et al., 2021; Lanzarini et al., 2022; Ren, et al., 2024) expand upon this understanding through exposure modelling and toxicological risk quantification, focusing on volatile organic compounds (VOCs), BTEX, particulate matter, and pathogens in landfills and sorting plants. These assessments provide strong empirical evidence of respiratory, inflammatory, and infectious health outcomes among waste sector employees. Complementary microbiological investigations by (Szulc et al., 2022; Madsen et al., 2024; Viegas et al., 2024) further document airborne microbial contamination and bioaerosol exposure, emphasising the need to implement respiratory protection and workplace air monitoring.

2.1.2 Mechanical and Physical Trauma

While chemical risks are chronic, mechanical risks are acute and often catastrophic. Uhunamure et al. (2021) identified injuries from sharp objects (glass, metal, needles) as the most frequent accident category among landfill workers in South Africa. These injuries carry secondary risks of infection from blood-borne pathogens like Hepatitis B and C, particularly when medical waste is improperly segregated.

Traffic-related incidents, or "struck-by" hazards, represent the leading cause of fatalities in the sector. Data from the Portuguese Authority for Working Conditions (ACT) indicates that collisions with moving vehicles account for approximately 22% of serious workplace accidents in comparable heavy industries. The operational tempo of waste collection, often conducted in unpredictable urban traffic, exacerbates this risk. The literature suggests that poor visibility and worker fatigue are primary contributing factors, necessitating training that specifically targets situational awareness in blind spots.

2.1.3 Ergonomic and Psychosocial Strain

The manual nature of waste collection imposes severe ergonomic loads. Soares (2021) applied observational tools such as OWAS and REBA to waste sorting plants, revealing a high prevalence of Musculoskeletal Disorders (MSDs) linked to repetitive lifting, awkward postures, and prolonged standing. These physical strains are compounded by psychosocial stressors. Dada et al. (2022) and Yamane (2023) explored the mental health of waste pickers, identifying precarious employment, social marginalization, and a lack of institutional support as key drivers of stress and burnout, which in turn degrade cognitive attention and increase accident susceptibility.

At the same time, research focused on managing risks suggests organised ways to prioritise and reduce risks, using tools like Analytic Hierarchy Process (AHP), risk matrices, and integrated management systems (IMS) to improve decision-making and safety culture. These methods have proven effective in improving risk identification accuracy, preventive planning, and continuous monitoring key aspects relevant to the

framework developed in this dissertation. Similarly, studies by (Alarcon et al., 2022) emphasize the design of Occupational Health and Safety Management Systems (OHSMS) and emergency response modelling, reinforcing the value of systematic and predictive safety management.

2.2 Technological Innovations in Safety Training

The integration of immersive technologies into OSH represents a paradigm shift from passive to active learning. The literature distinguishes between the utility of Augmented Reality (AR) and Virtual Reality (VR) based on the training objective.

Several studies associate technological innovation with enhanced risk management and workforce training. Recent research demonstrates that AR and VR improve safety training, situational awareness, and ergonomic assessment. Additional studies employing digital simulation and digital twins indicate that data-driven visualisation systems support the prediction, assessment, and optimisation of risks in industrial environments.

Recent advancements include the use of immersive technologies, specifically AR and VR, to improve safety training, hazard identification, ergonomic assessment, and collaborative practices in waste management and industrial settings.

The articles that mention Immersive Technology in Waste Management Safety are summarised below, in table 2:

Table 2: Summary of Immersive Technology in Waste Management Safety

Article	Technology Used	Application	Results	Limitations / Gaps
(Pereira et al., 2023)	AR	Lena waste process optimisation	Improved sequencing, reduced error, enhanced hazard awareness	Limited long-term validation; lacks integration with ergonomic monitoring tools.
(Akhmetov et al., 2023)	AR	AR-based hazard alert system	Reduced near-miss incidents, improve detection	Requires continuous calibration; limited applicability across diverse waste sites.
(Alshaer, 2024)	AR	Crowd and hazard management in emergencies	Improved evacuation time, better behavioural response	Does not account for diverse user experience; lacks real-world testing in waste sector.
(Méndez et al., 2025)	AR	Real-time operator guidance using AR	Improved compliance, fewer procedural errors	Dependent on sensor accuracy; high implementation cost.

(Jiao et al., 2024)	AR + ML	ESG visualisation in waste firms	Enhanced decision-making via safety metric visualisation	Focused on management-level application; lacks worker-level validation.
(García et al., 2023)	AR + AI + Sensors	Smart helmet for hazard monitoring	Improved awareness real-time alerts in waste scenarios	Potential discomfort and sensory overload; cost barriers for large-scale deployment.
(Swallow et al., 2024)	VR	Worksite layout and exit planning	Better risk zone identification	Does not measure post-training retention; limited ergonomic evaluation.
(Tepe et al., 2023)	VR	Low-cost headset safety training	Higher retention and safety protocol adherence	Limited realism; short-term evaluation period.
(Coelho et al., 2024)	VR	Usability testing for training in waste sorting processes	Improved motor-memory training and spatial awareness	Focused on usability, not performance outcomes.
(Bes et al., 2024)	VR & AR	Review of digital training tools in Industry 4.0	Higher engagement and retention, but noted implementation cost issues	Did not evaluate waste-specific environments.
(Wilson et al., 2024)	Immersive VR	Privacy-preserving gaze tracking for safety monitoring	Improved attention monitoring with user privacy	Technological complexity; high hardware dependency.
(Chung et al., 2023)	VR	Virtual collision alert system (VRCAT)	Reduced error rates and improved collision detection	Limited scope of hazard simulation; requires user adaptation time.
(Sardar et al., 2024)	VR + Deep Learning	Postural ergonomic assessment in VR environment	Live feedback reduced musculoskeletal injury risk	Focuses only on posture; not integrated into full OSH workflow.
(Rojek et al., 2024)	Digital Twin + VR	Simulated OSH compliance in waste recycling	Enhanced safety scenario validation	High technical demand; limited worker interaction.
(Smith et al., 2025)	VR	Review of immersive simulation in hazardous training	Simulated risks effectively but faced excessive cost and adoption barriers	Limited accessibility and scalability for small waste facilities.

In summary, the reviewed studies demonstrate a transition toward immersive, interactive, and sensor-integrated technologies in occupational health and safety training. AR is particularly effective for real-time task support and hazard identification. In contrast, VR is better suited for procedural training, emergency response simulations, and ergonomic assessments. The choice between AR and VR should align with defined training objectives, with AR recommended for immediate task guidance and VR for developing procedural knowledge and decision-making skills.

2.2.1 Augmented Reality (AR) for Real-Time Support

AR technologies overlay digital information onto the physical world, making them ideal for "just-in-time" information delivery. Pereira et al. (2023) demonstrated the efficacy of AR in Lean production environments, where digital cues helped workers optimize task sequencing and identify hazards in real-time. Similarly, García et al. (2023) developed "Smart Helmets" equipped with sensors and AR visors that alert workers to environmental hazards like gas leaks or proximity to heavy machinery. While effective for operational support, AR is limited in its ability to simulate catastrophic scenarios safely, as it relies on the physical environment.

2.2.2 Virtual Reality (VR) for Simulation and Behaviour Modification

VR creates a fully synthetic environment, allowing for the safe simulation of high-risk scenarios. Tepe et al. (2023) and Swallow et al. (2024) found that VR training significantly improved hazard recognition and memory retention compared to traditional methods. The immersive nature of VR isolating the user from the real world creates a sense of "presence" that engages the emotional and cognitive center of the brain. Users can experience the consequences of a mistake (e.g., a virtual explosion or injury) without physical harm, creating a powerful learning imprint. This capability makes VR the superior choice for initial OSH training and hazard identification, forming the technological basis for this dissertation's framework.

Environmental and ergonomic optimisation are further addressed in studies by (Degli Esposti et al., 2023; Soares, 2021), which stresses the importance of task redesign and workload balance to reduce injury risk. Broader environmental assessments (Smith et al., 2025; Xu et al., 2025; Gravel et al., 2023) extend the conversation to hazardous waste lifecycle impacts and multi-exposure risk evaluation, linking industrial pollution with worker and community health outcomes. Meanwhile, (Fang et al., 2022; Cook et al., 2023) provide comprehensive reviews of odorous emissions and medical waste handling, revealing persistent deficiencies in regulatory compliance and waste segregation practices.

Overall, the reviewed literature indicates that while risk assessment methodologies in the waste sector are advancing, particularly through structured approaches such as AHP and IMS, significant gaps remain in training engagement and behavioural risk perception. Immersive reality offers a promising bridge, aligning digital innovation with occupational health needs, and providing the conceptual foundation for this dissertation’s proposed framework on immersive risk assessment and training in waste management.

The literature consistently identifies high occupational risk exposure across biological, chemical, and ergonomic domains in waste management. However, gaps remain in the application of immersive

technologies tailored to waste-sector realities, the integration of biological and ergonomic monitoring into risk assessments and long-term evaluation of training effectiveness on accident reduction.

This dissertation addresses these gaps by proposing a scalable, immersive OSH training and risk assessment framework specifically adapted to the waste management sector. It bridges empirical risk data with innovative training delivery methods, an approach supported but not yet implemented in the literature.

The consistent reporting of high exposure levels across these studies underscores a systemic failure in current control measures within the waste management sector. Despite diverse methodologies and regional contexts, the research converges on a troubling reality: workers remain exposed to preventable hazards due to ineffective training, poor enforcement of regulations, and underutilised safety technologies.

While some studies propose structured risk assessment tools or integrated safety systems (Moloudi et. al, 2022; Mutlu et al., 2021), these are often limited in scope or lack field-based validation. Furthermore, immersive technologies like AR/VR have shown promise in other high-risk industries (Pereira et. al, 2023; Jiao et al., 2024), mentioning that it remains vastly underexplored in waste management training. This gap highlights the urgent need for a scalable, engaging, and sector-specific solution, one that this dissertation aims to fulfil. The reviewed literature identifies both systemic risk factors and innovative solutions. The integration of immersive reality within OSH frameworks represents a timely and evidence-based intervention.

This justifies the need for an immersive training and risk assessment framework tailored to the occupational realities of waste workers. The convergence of elevated risk, insufficient control measures, and untapped technological solutions presents a clear and actionable research opportunity one that this dissertation directly addresses.

2.3 Justification and objectives definition

2.3.1 Technological framework

Immersive technologies particularly Augmented Reality (AR) and Virtual Reality (VR) have advanced significantly in the past decade, establishing new standards in education, professional training, and occupational safety. AR integrates digital information into real-world contexts, enabling on-site hazard visualisation, while VR creates fully simulated environments where users can safely experience and respond to realistic scenarios. These technologies have been increasingly applied in high-risk industries such as construction, mining, and aviation, where they support risk communication, procedural training, and situational awareness.

For instance, in the construction sector, VR-based modules have been developed to simulate falls from height, equipment collisions, and confined-space hazards, effectively reinforcing hazard perception and behavioural safety practices (Hamzeh et al., 2024). Likewise, AR tools have been used to provide real-time guidance and overlay safety instructions during live tasks, improving workers' spatial awareness and reducing human error. These approaches have been shown to enhance engagement, cognitive retention, and hazard anticipation, outperforming conventional training models such as lectures or static safety manuals (Pereira et al., 2023; Ghobadi et al., 2023).

Despite these advances, the waste management sector remains underrepresented in immersive safety applications. Most existing interventions focus on traditional safety manuals or classroom instruction, which fail to capture the dynamic, unpredictable, and high-risk nature of waste-handling operations. Waste workers are often exposed to biological, chemical, and mechanical hazards in non-standardised environments conditions that make immersive simulation particularly valuable.

Recent studies have suggested that integrating VR with MARAT could enhance both training and risk perception, enabling workers to visualise hazards such as chemical leaks, sharp object injuries, or vehicular collisions in a controlled yet realistic setting. Platforms like Unity and Unreal Engine have made it technically feasible to develop low-cost, scalable prototypes tailored to specific operational scenarios, facilitating behavioural training, spatial awareness, and emergency response.

However, challenges remain in the validation and standardisation of such immersive systems for occupational use. Few studies measure the long-term impact of AR/VR training on real-world accident reduction or risk mitigation, and most lack integration with existing OHS management frameworks (e.g., ISO 45001:2018). This gap justifies the need for the present research, which proposes a VR-based

immersive risk assessment framework tailored to the waste management sector—combining technical simulation with structured risk evaluation to improve both training outcomes and workplace safety culture.

2.3.2 Concepts and definitions

To ensure conceptual clarity and consistency throughout this dissertation, the following definitions are adopted. These terms serve as the foundation for the development, application, and analysis of the immersive reality framework for occupational safety in the waste management sector.

- Occupational Health and Safety refer to policies, practices, and procedures implemented to protect the health, safety, and welfare of workers within their workplace. According to the International Labour Organisation (ILO), OHS aims to prevent accidents, injuries, and diseases by identifying and managing workplace hazards (ILO, 2018).
- Solid Waste Management involves the collection, transportation, sorting, treatment, and final disposal of waste materials generated by human activity. In this dissertation, SWM specifically refers to municipal solid waste (MSW), which includes household waste, commercial waste, and waste from public spaces.
- Immersive Technologies include systems that simulate or augment real-world environments to engage users in interactive experiences. The main modalities include:
- VR a fully digital simulation of a real or imagined environment, typically experienced through a head-mounted display (HMD) and motion tracking.
- AR the overlaying of digital elements (e.g., visuals, instructions) on the real world through mobile devices, smart glasses, or AR headsets.
- Risk Assessment a systematic process for identifying hazards, evaluating the likelihood and severity of risks, and determining appropriate control measures. Risk assessment is a key component of OHS management systems and is mandated by ISO 45001:2018 and the EU Directive 89/391/EEC.
- Hazard any source with the potential to cause harm (e.g., sharp objects, toxic chemicals, biological agents).
- Risk is defined as the combination of the likelihood of a hazardous event occurring and the severity of its consequences.

2.3.3 Legal and regulatory framework

The development of this framework is grounded in a robust legal architecture. In Portugal, OSH is governed by Law No. 102/2009, which mandates employers to assess risks, provide adequate Personal Protective

Equipment (PPE), and ensure continuous worker training. This national legislation is harmonised with European Directive 89/391/EEC, the "Framework Directive," which establishes the fundamental principles of risk prevention.

Furthermore, the global standard ISO 45001:2018 provides the structural requirements for Occupational Health and Safety Management Systems (OHSMS). It emphasises the "Plan-Do-Check-Act" (PDCA) cycle and requires the active participation of workers in hazard identification. The MARAT risk assessment method used in this study is designed to align with these regulatory requirements, providing the evidentiary basis for the "Plan" phase, while the VR training fulfils the "Do" and "Check" components of the cycle.

The Portuguese legal framework governing occupational health and safety (OHS) in the waste management sector is aligned with European Union directives, ensuring the protection of workers' rights and the promotion of safe work environments. Given the hazardous nature of waste handling, characterised by exposure to chemical, biological, ergonomic, and mechanical risks, compliance with national and international legislation is critical.

Portuguese Law No. 102/2009 defines employer responsibilities in OSH, including risk assessment, provision of PPE, training, and worker health monitoring. This law mandates employers to assess and control occupational risks, provide workers with appropriate personal protective equipment (PPE), ensure continuous training, and offer regular health surveillance. An update through Law No. 3/2014 reinforced the preventive role of employers and emphasised continuous improvement mechanisms.

Regarding equipment, Decree-Law No. 50/2005 regulates the minimum safety requirements for the use of work equipment and PPE. Waste management operations, which often involve machinery for collection, sorting, and treatment, are directly impacted by this legislation, particularly concerning the need for safe handling and operational procedures.

From a broader environmental and safety perspective, Decree-Law No. 73/2011 transposes the European Waste Framework Directive (Directive 2008/98/EC) into Portuguese law. It sets out measures aimed at minimizing the adverse effects of waste generation and management on human health and the environment, thus indirectly reinforcing occupational safety standards for waste sector workers, particularly when dealing with hazardous and special waste streams.

Most of the Portuguese waste management companies have adopted ISO 45001 frameworks to systematically prevent injuries and health issues, enhancing compliance and promoting a culture of safety.

Data privacy regulations, particularly under the General Data Protection Regulation (GDPR - Regulation (EU) 2016/679), further impose obligations regarding the management of workers' health data, especially concerning medical exams and fitness-for-work certificates obtained through occupational health services.

At the European level, the Directive 89/391/EEC, known as the "Framework Directive," lays down general principles concerning the prevention of occupational risks and the protection of safety and health at work. Portuguese laws are in direct alignment with this directive, reinforcing the employer's duty to eliminate risks at the source and adapt work practices to human capabilities.

Overall, the legal and normative framework in Portugal provides a robust structure that aims to minimise occupational risks in waste management. However, effective implementation requires ongoing efforts by waste management companies to integrate legal obligations into their daily operations, invest in preventive technologies, ensure worker training, and maintain strong health surveillance programs. Non-compliance not only results in regulatory penalties but also increases the likelihood of workplace accidents, diseases, and associated social and economic costs.

In light of the hazardous nature of waste operations, continuous alignment with regulatory standards, supported by innovations such as immersive reality tools for risk assessment, becomes essential to enhancing occupational safety and health in the Portuguese waste sector. The articulation of these instruments ensures alignment between strategic global standards, European regulatory coherence, and national enforcement. Together, they provide a structured framework for assessing risks, implementing safety protocols, and promoting a preventive culture within high-risk sectors such as waste management.

This robust legal landscape provides a compelling justification for the development of innovative tools, like the immersive framework proposed here, to help companies comply with these obligations effectively.

a) Regulatory Framework

- EN 45001:2018 - Occupational health and safety management systems – Requirements with guidance for use.
- ISO 31000:2018 - Risk management – Guidelines.

Figure 4 outlines the interrelationship between the various legal and regulatory references.

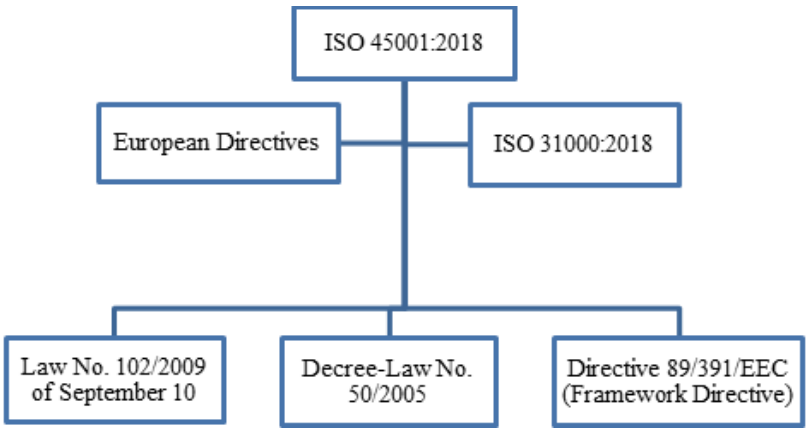


Figure 3: Legal and Regulatory Framework

b) Scientific Knowledge

This dissertation is grounded in the current state of scientific knowledge in the fields of occupational health and safety, waste management, and immersive technologies. Existing research highlights the relevance of risk assessment methodologies and the growing application of virtual and augmented reality tools to improve safety awareness and training in high-risk work environments. A structured analysis of this body of knowledge supports the identification of research gaps and informs the conceptual framework adopted in this study.

2.3.4 Information research methodology

To ensure a rigorous and transparent research process, a systematic literature review was conducted in accordance with the PRISMA Statement (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) (PRISMA, 2020).

The literature search was performed using the databases Scopus, Web of Science, and ScienceDirect. Search strings combined terms related to occupational health and safety, waste management, and immersive technologies, including combinations such as “occupational health,” “waste management,” “risk assessment,” “virtual reality,” “augmented reality,” and “immersive technologies”.

Publications dated between 2020 and 2025 were considered. Inclusion criteria comprised peer-reviewed journal articles, conference proceedings, and official reports published in English, addressing occupational health and safety in waste management and the application of immersive technologies. Studies lacking empirical evidence or not subject to peer review were excluded. The selection process followed the PRISMA framework, documenting the stages of identification, screening, eligibility, and inclusion.

3 OBJECTIVES OF THE DISSERTATION

This dissertation addresses the persistent gap in occupational health and safety (OSH) practices within the solid waste management sector by proposing an innovative, immersive reality-based framework for risk assessment and workforce training. The research further investigates whether, an immersive reality framework improves risk perception and safety outcomes for waste management workers compared to traditional training methods?

3.1 General objective

The aim is to develop and validate a conceptual framework for improving occupational health and safety (OHS) in the waste management sector, grounded in literature-based evidence and a systematic risk assessment using the MARAT methodology.

3.2 Specific objectives

1. To identify and synthesise the main occupational hazards, risks, and control measures in the waste management sector through a systematic literature review.
2. To apply the MARAT to evaluate and prioritise hazards within the operational stages of waste handling, processing, and transport.
3. To analyse the intervention levels and propose corrective measures based on the MARAT results, emphasising biological, chemical, and ergonomic risk factors.
4. To design a conceptual immersive training framework that translates risk assessment findings into potential applications of virtual or augmented reality for hazard awareness and preventive training.
5. To discuss the feasibility and future implementation pathway of integrating immersive tools into OHS systems in the waste sector, aligning with European and ISO 45001 standards.

4 MATERIALS AND METHODS

This chapter outlines the methodological framework developed to achieve the general and specific objectives of the dissertation. Based on the findings of the literature review, the approach integrates established methods from previous occupational health and safety (OHS) studies in the waste management sector with innovative applications of immersive technologies for risk assessment and training. The methodology was designed to be replicable, transparent, and aligned with ethical standards.

The literature review identified several methods that could be applied in the waste industry. The approach integrates structured methods already applied in the literature on occupational safety in waste management and immersive technologies. The pathway, illustrated in Figure 6, is divided into three key phases:

1. **Systematic Literature Review (SLR)** – mapping of hazards and practices.
2. **Risk Identification and Assessment** – the process of risk identification and assessment involves the classification and prioritisation of hazards based on secondary data and international standards.
3. **Immersive Framework Development and Validation** – The process of immersive framework development and validation involves the creation of VR/AR-based scenarios that replicate key risks, which are then validated through benchmarking against established studies and guidelines.

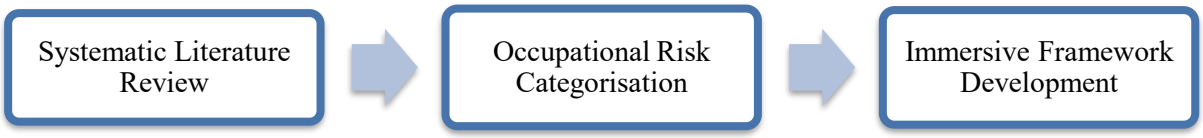


Figure 4: Visual Roadmap of the methodology.

4.1 Systematic Literature Review

The literature review followed the PRISMA Statement to guarantee transparency and replicability.

- **Databases searched**: Scopus, Web of Science, and Science Direct.
- **Keywords used**: *"occupational safety," "waste management," "risk assessment," "VR," "AR,"* and *"immersive technologies."*
- **Inclusion criteria**: Peer-reviewed articles (2019–2025), relevance to occupational hazards in waste management or immersive risk training, published in English or Portuguese.

- **Exclusion criteria**: Articles without empirical data, unrelated industries, or not aligned with OHS.

The final selection comprised forty-nine (49) articles, forming the empirical and conceptual basis for the analysis and subsequent framework development.

4.2 Risk Identification and Assessment

The reviewed literature shows that the waste management sector uses a wide range of risk assessment methodologies, ranging from purely qualitative approaches to more structured semi-quantitative frameworks. These methods vary in complexity and are designed to address the sector's diverse hazards, including biological, chemical, ergonomic, mechanical, and psychosocial risks.

Risk management is essential to improving occupational health and safety and minimising the introduction of new hazards when operational changes occur (ISO 45001:2018). Figure 8 illustrates the general phases of the risk assessment process within the broader context of risk management.

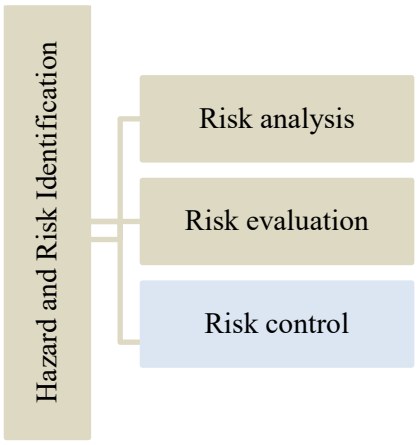


Figure 5: Risk Assessment Process. Adapted from (Moloudi et. al, 2022; Ferrão et al., 2021)

Several studies (e.g., Ferrão et al., 2021; Rodrigues et al., 2020) highlight the value of qualitative and semi-quantitative techniques for mapping accident frequency, determining severity levels, and identifying recurrent unsafe practices. These approaches are particularly useful in settings where quantitative exposure data are limited, enabling practitioners to prioritise hazards based on expert judgement and contextual evidence.

More structured analytical methodologies, such as the hybrid AHP–risk matrix model proposed by Moloudi et al. (2022), enable multi-criteria decision-making and the ranking of risks based on probability, exposure, severity, and organisational factors. However, such approaches require extensive data input and stakeholder

participation, making their implementation challenging in small-scale or informal waste management environments.

The literature also includes hazard-specific frameworks. Biological risks have been quantified through microbial and bioaerosol assessments (Viegas et al., 2024; Madsen et al., 2024); chemical risks such as VOCs, heavy metals, and particulate matter have been characterised by Liu et al. (2023) and Barkhordari (2022); ergonomic risks related to manual handling and posture have been identified in Soares (2021); while psychosocial risks including stress, precarious work conditions, and underreporting have been documented by Dada et al. (2022) and Ferrão et al. (2021).

Taken together, these studies show that waste workers are rarely exposed to a single type of hazard in isolation; instead, they face overlapping biological, chemical, ergonomic and psychosocial risks. This multidimensional exposure pattern reinforces the need for integrated risk assessment approaches, such as MARAT, that can capture combined effects rather than treating hazards separately.

After evaluating these methodologies, the MARAT framework (Santos et al., 2019) was selected for this dissertation. MARAT is a semi-quantitative method widely used in Portuguese occupational risk assessment practice due to its simplicity, transparency, reproducibility, and operational suitability for labour-intensive sectors such as waste management. The method begins with task definition and data collection (including legislation, equipment manuals, safety data sheets, exposure information, and statistical indicators), followed by systematic hazard identification and the construction of a checklist aligned with each activity or workstation.

Risks are then evaluated according to the likelihood of occurrence and potential severity, producing a semi-quantitative risk level that facilitates the prioritisation of preventive and corrective measures. MARAT aligns closely with recognised European risk assessment principles and provides a structured yet accessible approach that supports worker participation and transparent documentation (Ramos et al., 2020). By focusing on essential parameters: Exposure, Deficiency, Probability, and Consequence. MARAT provides the analytical clarity required for operational decision-making in complex environments where workers are exposed to multiple simultaneous hazards.

After evaluating these methodologies, the MARAT framework (Santos et al., 2019) was selected for this dissertation. MARAT is a semi-quantitative method widely used in Portuguese occupational risk assessment practice due to its simplicity, transparency, and suitability for labour-intensive sectors such as waste management.

The method supports systematic hazard identification and prioritisation while remaining applicable in contexts where detailed quantitative exposure data are unavailable. For these reasons, MARAT was adopted as the analytical basis for risk identification and classification in this study.

4.2.1 Method of Evaluation of Risks and Work Accidents (MARAT)

The Method of Evaluation of Risks and Work Accidents (MARAT) evaluate occupational risks using four core parameters:

- Exposure Level (EL): reflects the frequency and duration of worker exposure to a given hazard.
- Deficiency Level (DL): represents the adequacy of existing preventive and protective measures.
- Probability Level (PL): calculated as the product of EL and DL, expressing the likelihood of occurrence.
- Consequence Level (CL): indicates the severity of potential harm resulting from the hazardous event.

The overall Risk Level (RL) is calculated as:

$RL = PL \times CL$

Based on the resulting risk level, hazards are classified into predefined Intervention Levels, which guide the prioritisation of corrective and preventive measures. This semi-quantitative approach allows consistent comparison between hazards and supports transparent decision-making.

In this study, MARAT was applied to the main stages of waste management operations—waste collection, manual sorting, transport, vehicle sanitation, landfill activities, and equipment maintenance. Hazards, triggering events, and consequences were compiled into a Risk Assessment Matrix (Appendix I).

Hazard scoring was performed by a panel of three occupational health and safety specialists with experience in the waste management sector. The evaluation relied on secondary data sources, including accident statistics, safety data sheets, equipment manuals, and regulatory guidelines, combined with expert consensus to assign EL, DL, PL, and CL values.

Exposure Level (EL)

Represents how frequently workers are exposed to the hazardous situation. Table 3 shows the Interpretation of exposure frequency according to the MARAT.

Table 3: Meaning of Exposure Levels (EL).

Exposure Level	EL	Meaning
Continuous	4	Several times per day with prolonged exposure
Frequent	3	Several times per day with intervals without exposure

Occasional	2	Once per day for short periods
Sporadic	1	Irregular exposure

Deficiency Level (DL)

Table 4 indicates the level of inadequacy or failure in preventive measures.

Table 4: Meaning of Deficiency Levels (DL)

Deficiency Level	DL	Meaning
Very Deficient	10	Serious failures; preventive measures ineffective
Deficient	6	Failures requiring correction
Improvable	2	Minor deficiencies; limited impact on prevention
Acceptable	1	No anomalies detected; adequate control

Probability Level (PL)

Table 5 shows that the probability values derived from PL = DL × EL, grouped according to MARAT probability categories. PL is calculated as: **PL = DL × EL**

Table 5: Probability Level (PL) Calculation and Interpretation

Probability Level	PL Range	Meaning
Very High	24–40	Accidents occur frequently
High	10–20	High likelihood of accidents
Medium	6–8	Occasional accidents
Low	2–4	Accidents unlikely but possible

Consequence Level (CL)

The consequence level illustrates in table 6 represents the severity of the potential impact of each hazardous event.

Table 6: Meaning of Consequence Levels (CL)

Consequence Level	CL	Personal Injury	Material Damage
Fatal/Catastrophic	100	Fatality	Total destruction
Very Serious	60	Irreparable injury	Partial destruction
Serious	25	Temporary incapacity	Process stoppage
Minor	10	Non-hospital injury	Repair without stoppage

Risk Level (RL)

Risk levels obtained from **RL = PL × CL**, with associated intervention priorities. Table 7 shows the meaning of the risk level and intervention levels.

Table 7: Risk Level (RL) Classification According to MARAT

IL	Risk Level (RL)	Meaning
1	4000–6000	Critical; immediate correction required
2	150–500	Implement corrective measures
3	40–120	Improve if possible; justify intervention
4	20	No action required unless justified

These thresholds were applied to all identified hazards, forming the basis of the Risk Assessment Matrix presented in **Appendix I**.

5 IMMERSIVE FRAMEWORK DEVELOPMENT

Risk management serves as the foundation for advancing occupational health and safety, enabling systematic identification, evaluation, and mitigation of hazards. It is particularly vital in dynamic environments like waste management, where process changes and material variability can introduce new risks (ISO 45001:2018). To guide this process, the MARAT methodology, widely applied in waste-handling studies (Santos et al., 2019), has been selected for this research. Its accessibility, reproducibility, and alignment with regulatory compliance make it especially suitable for environments with high operational turnover and low digital infrastructure.

To enhance this method, the proposed immersive framework integrates VR as a complementary training and risk perception tool. This decision is grounded in literature findings that demonstrate the effectiveness of VR in simulating hazardous scenarios, reinforcing safety behaviours, and supporting ergonomic assessments (Tepe et al., 2023; Coelho et al., 2024). The integration is designed not only to map and prioritise risks through MARAT, but also to translate these insights into immersive training scenarios intended to support risk awareness and safety training. The framework is conceptual and developmental in nature, and no empirical validation of behavioural change is claimed at this stage. Figure 7 illustrates the proposed workflow for risk management in the waste sector, combining conventional hazard assessment with immersive technology for enhanced awareness and training.

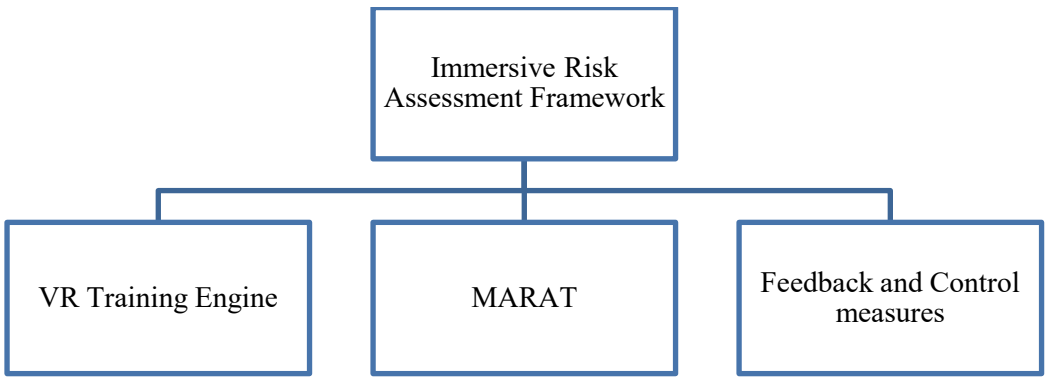


Figure 6: Proposed workflow for risk management with immersive technology.

The next phase concentrates on the technical development of the immersive training tool, building on the findings of the risk assessment and the framework shown in Figure 7. This process involves translating the identified risks and operational tasks into interactive VR scenarios designed for occupational safety training in waste management environments. To ensure methodological consistency and reproducibility, the development followed a structured design protocol based on the Unity VR Development Manual, which provides detailed guidance for constructing and evaluating the prototype.

5.1 Prototype Development in Unity VR

The technical development of the immersive risk assessment prototype was conducted using the Unity 3D Engine (version 2022.3 LTS), selected for its stability, modularity, and compatibility with VR hardware, particularly the Meta Quest headset. The objective was to translate the most significant hazards identified in the literature review and risk assessment process into three interactive, immersive training scenarios that replicate real-world working conditions in waste management.

5.2 Technical Architecture and Development Workflow

The development followed a structured pipeline described in the "Unity VR Development Manual," ensuring reproducibility and adherence to academic standards.

5.3 The Digital Workbench

The Unity Editor served as the Integrated Development Environment (IDE). The architecture relies on the interaction between the Hierarchy (the scene's asset list), the Inspector (property editor), and the Scene View (3D workspace). The fundamental unit of the simulation is the GameObject. Following the Component-based architecture, functionality was composed by attaching discrete scripts and components to empty containers. For example, a virtual "Waste Bag" is constructed by combining a Mesh Filter (shape), Mesh Renderer (visuals), Rigidbody (physics), and Box Collider (interaction boundaries).

5.4 VR Input System Configuration

To interface with the VR hardware, the project utilized the OpenXR standard via the XR Plugin Management module. This ensures the software is hardware-agnostic but optimized for Android-based standalone headsets.

XR Origin (Action-Based): The player rig was established using the XR Origin prefab. This system manages the complex mathematics of mapping the user's physical head and hand movements to the virtual camera and controllers.

Input Action Maps: The "Starter Assets" package was integrated to map the specific button presses of the Meta Quest controllers (Grip, Trigger, Primary Button) to abstract actions (Select, Activate, Teleport) within the simulation logic.

5.5 Scripting and Logic Implementation

The interactivity of the simulation is driven by custom C# scripts that enforce safety protocols.

5.6 The GameManager Singleton

A central GameManager.cs script acts as the logic controller for the entire simulation. It employs the Singleton Pattern to ensure a single, globally accessible instance of the game state exists. This architecture allows any object in the scene (e.g., a hazardous waste bag) to query the GameManager to check if the user has complied with safety requirements (e.g., if (GameManager.instance.hasGloves)). This centralized state management is critical for tracking user performance across different scenarios.

5.7 The "Grabbing Recipe" and Physics Interaction

To simulate manual handling, objects were configured with a specific tri-component architecture:

1. Collider: Defines the physical shape for collision detection.
2. Rigidbody: Enables physics simulation (gravity, mass).
3. XR Grab Interactable: A specialized XRI component that handles the mechanics of picking up, holding, and throwing objects. This setup allows users to physically reach out and grab virtual PPE or waste items, reinforcing motor memory through physical action.

The development followed the step-by-step protocol outlined in the *Unity VR Development Manual* - OSH (Appendix II), which was specifically created to ensure methodological reproducibility for academic applications.

The conceptual foundation of this VR prototype was based on evidence from immersive technology studies demonstrating that virtual simulation improves hazard recognition, procedural compliance, and behavioural safety in high-risk occupations (Pereira et al., 2023; Tepe et al., 2023; Coelho et al., 2024). Unity was selected due to its cross-platform VR capabilities, extensive asset library, and flexibility in importing 3D models, environmental textures, and physics-based interactions key features for replicating realistic waste management environments.

5.8 Scenario Design and Implementation

The selection of scenarios for VR implementation was guided by the results of the MARAT risk assessment (Appendix I) and by the objectives of this study. From the full set of identified hazards, three were selected based on predefined and transparent criteria.

First, priority was given to hazards classified as Intervention Levels 1 and 2 in the MARAT matrix, as these represent situations requiring urgent or structured preventive action. Second, the selected hazards reflect the main categories of occupational risk identified in waste management activities—mechanical (sharps injuries), biological/chemical exposure, and physical hazards related to vehicle interaction—ensuring representativeness of the sector's multidimensional risk profile. Third, preference was given to hazards characterised by high frequency and recurrence across multiple operational stages, as documented in both the literature and the risk assessment results. Finally, technical feasibility and suitability for immersive simulation were considered, favouring hazards that could be realistically and safely represented in a VR environment without the need for complex instrumentation.

Based on these criteria, three hazards were selected for immersive simulation: sharps injuries, bioaerosol and VOC exposure, and traffic/struck-by hazards. These scenarios collectively represent common, recurrent, and potentially severe risks in waste management operations, while remaining appropriate for immersive training design.

The prototype consists of three interactive modules, each designed to address one major risk category commonly found in waste management operations, in the figure 9 it is possible to see the three scenarios:

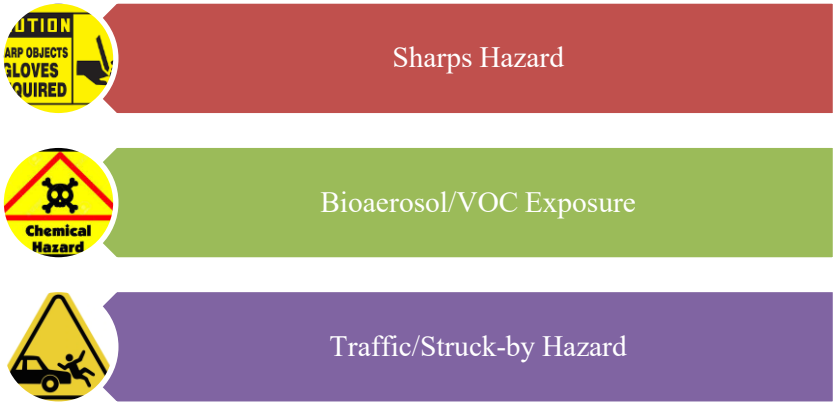


Figure 7: Scenarios for hazard identification including sharps hazards, chemical and biological exposure, and physical hazards.

Scenario 1: Sharps Hazard (Hazard Identification) – This module trains users to identify unsafe handling of sharps, such as broken glass or syringes, based on the most recurrent injury mechanisms identified in the literature (Dada et al., 2022; Ferrão & Moraes, 2021). The environment simulates a manual waste sorting station, where players must correctly identify hazardous items and apply preventive actions using virtual PPE.

Scenario 2: Bioaerosol/VOC Exposure (Corrective Action – PPE) – This scenario demonstrates biological and chemical exposure risks from volatile organic compounds and airborne contaminants, following similar occupational contexts described by (Viegas et al. 2024; Liu et al. 2023). Users interactively select appropriate respiratory protection and environmental controls (e.g., ventilation), learning correct PPE application through feedback mechanisms.

Scenario 3: Traffic/Struck-by Hazard (Hazard Identification) – Based on accident trends in waste collection operations (Ramos et al., 2020; Tshivhase et al., 2022), this scenario recreates an outdoor road collection setting. The player must identify danger zones, maintain safe distances from vehicles, and demonstrate situational awareness under time pressure.

Each scenario follows a didactic structure comprising:

1. Briefing Phase: Introduction to context, task objectives, and safety requirements.
2. Interactive Simulation: Immersive task execution, with dynamic feedback based on user decisions.
3. Debriefing Phase: Performance evaluation and corrective feedback on safe vs. unsafe actions.

This structure is informed by the pedagogical design principles of experiential learning and active error-based feedback (Bes et al., 2024; Swallow et al., 2024), which are proven to enhance retention and behavioural change compared to conventional training methods.

From a technical standpoint, each scenario was developed within Unity using:

- C# scripting for interactive elements (e.g., collision detection, object highlighting, task triggers).
- XR Interaction Toolkit for handling VR interactions such as grabbing, teleportation, and gaze control (Wilson et al., 2024).
- Physically Based Rendering (PBR) materials to ensure realistic lighting and texture mapping of waste environments (Méndez et al., 2025).
- Audio cues and visual feedback for hazard alerts and performance scoring.
- User Interface (UI) overlays for instructional text and score tracking.

Environmental assets were either modelled in Blender or sourced from the Unity Asset Store, ensuring fidelity to real waste management conditions (e.g., sorting lines, vehicles, bins, and PPE). Scenario logic was assessed iteratively following the procedures outlined in the Unity VR Development Manual - OSH, including the build and test pipeline and user navigation optimisation guidelines.

The design also incorporated the MARAT risk assessment results to ensure that the virtual hazards accurately reflected documented workplace risks, thereby maintaining consistency between analytical and immersive components.

5.9 Answer to the Research Objectives

The general objective of this dissertation was to propose and demonstrate the feasibility of a conceptual framework for supporting occupational health and safety in the waste management sector through MARAT-based risk assessment and immersive training tools. Based on the results obtained, the research objectives were addressed as follows:

1. A systematic literature review of forty-nine peer-reviewed studies enabled the identification and synthesis of the main occupational hazards, risk factors, and existing control measures in waste management activities.
2. The MARAT method was applied to representative waste management operations, allowing hazards to be systematically identified, classified, and prioritised across key operational stages, thereby fulfilling.
3. The analysis of the resulting risk levels and intervention thresholds supported the proposal of targeted corrective and preventive measures, particularly for high-priority biological, chemical, and ergonomic risks, addressing.

4. The results of the MARAT assessment were translated into a conceptual immersive training framework, demonstrated through the development of a prototype that represents high-priority hazard scenarios in a virtual environment, fulfilling.
5. The proposed framework was analysed in relation to European occupational safety legislation and ISO 45001 requirements, indicating its conceptual compatibility and feasibility for future integration into occupational health and safety management systems in the waste sector, thereby addressing.

Although no usability testing was conducted in this study, a future validation phase is planned involving waste management workers with diverse educational backgrounds and low digital literacy. This phase will include assisted onboarding, simplified interaction mechanics, and qualitative usability assessment to ensure accessibility and relevance.

6 RESULTS

The results of this study derive exclusively from the systematic identification and classification of occupational hazards in waste management activities, conducted using the MARAT semi-quantitative risk assessment method. No empirical testing, usability evaluation, or user-based validation of the immersive prototype was performed. Therefore, the results presented in this chapter refer solely to the analytical risk assessment outcomes, and not to the effectiveness, usability, or training impact of the VR scenarios.

The application of MARAT enabled the characterisation of hazards by assigning exposure (EL), deficiency (DL), probability (PL), and consequence (CL) levels to each task. These were combined to generate a Risk Level (RL) for each identified hazard, subsequently classified according to the intervention levels defined by the MARAT framework. This process allowed the prioritisation of risks according to their relative severity and the urgency of the recommended control measures.

It is important to note that this study did not include usability testing or empirical validation of the immersive prototype. Therefore, the results presented are limited to the analytical risk assessment component.

A total of 100 hazard scenarios were evaluated using the MARAT Risk Assessment Matrix. The distribution of Intervention Levels (IL) was as follows:

- Intervention Level 1 (IL1 – critical / urgent correction): 9%
- Intervention Level 2 (IL2 – correction and control measures): 38%
- Intervention Level 3 (IL3 – improvement where possible): 47%
- Intervention Level 4 (IL4 – tolerable / no intervention unless justified): 6%

The largest share of scenarios (47%) fell into IL3, indicating situations where the risk is controlled but improvements are advisable. These cases typically involve falls from height, ergonomic overload, and some electric-shock and chemical-exposure scenarios with moderate probability and serious, but not catastrophic, consequences.

Approximately 38% of the scenarios were classified as IL2, requiring the implementation of corrective and control measures within a reasonable timeframe. This group includes many of the biological-exposure situations (e.g. contact with contaminated waste during equipment maintenance, transport and landfill operations), as well as several high-load manual-handling tasks.

Only 9% of the hazards reached IL1, representing critical risks that demand urgent intervention. These are predominantly associated with cuts from sharp objects (e.g. broken glass and syringes) and exposure to

biological agents, where both the probability of occurrence and the potential consequences (serious infection or permanent injury) are high.

Finally, 6% of the situations were rated as IL4, where no immediate intervention is required beyond routine monitoring, provided that existing control measures are maintained and periodically reviewed.

As shown in Figure 10, most identified hazards fall within Intervention Levels 2 and 3, indicating the predominance of medium-priority risks requiring corrective measures and continuous improvement rather than emergency intervention.

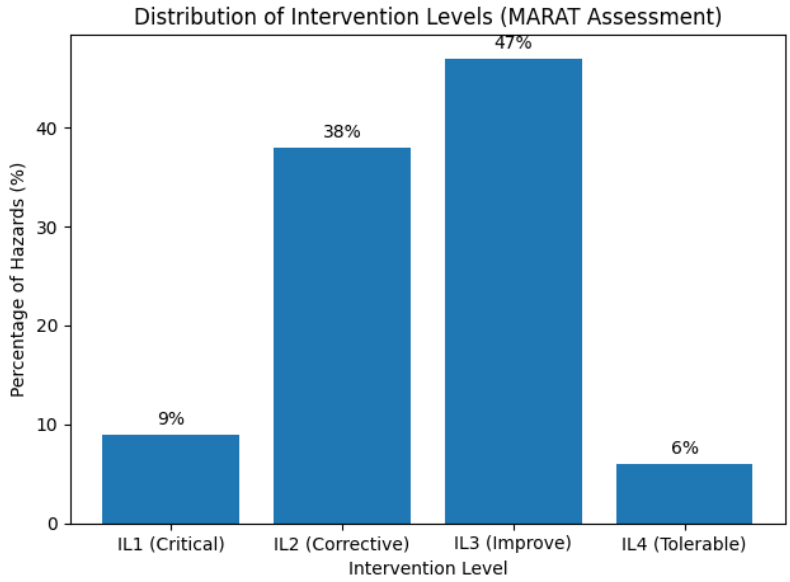


Figure 8: Graphic with intervention levels.

The distribution of intervention levels in the MARAT assessment shows a clear predominance of Level 2 risks, indicating that most hazards require corrective measures but are not immediately critical. This pattern is consistent with findings from previous studies in waste management (Ferrão et al., 2021; Moloudi et al., 2022; Ramos et al., 2020), which similarly report that most occupational risks are of moderate severity but occur with high frequency. This suggests that, although catastrophic events are uncommon, workers experience frequent exposure to unsafe conditions particularly related to manual handling, biological agents, and sharp objects.

The substantial presence of Level 2 and Level 3 risks highlights that existing preventive measures are only partially effective or inconsistently implemented. This aligns with literature noting that many waste management operations apply safety practices in a reactive rather than proactive manner (Ramos et al., 2020; Ferrão et al., 2021), often due to operational pressures, lack of training, or inadequate supervision.

The relatively small proportion of Level 1 (high-priority) risks suggests that extremely severe hazards—though present are limited to specific high-impact events (such as biological exposure or severe cuts). Meanwhile, the occurrence of Level 4 (low priority) risks is minimal, indicating that very few tasks are considered fully controlled or low concern.

Overall, the MARAT methodology effectively captured the prevalence of medium-level, repetitive hazards, providing a structured basis for prioritising interventions such as improved training, engineering controls, and monitoring systems. Its structured and simplified design proved suitable for environments with limited resources and variable safety practices, allowing clear identification of where risk-reduction efforts should be concentrated.

7 DISCUSSION

7.1 Synergising Risk Assessment and Simulation

The main contribution of this research lies in the integration of the MARAT risk assessment methodology with a Unity-based immersive training environment. Traditionally, occupational risk assessments tend to culminate in static documents that may have limited impact on day-to-day safety behaviour. In contrast, the proposed framework translates the analytical outputs of the MARAT matrix—particularly the high prevalence of Level 2 risks into interactive training scenarios explicitly designed to address identified deficiencies.

The MARAT assessment revealed that many of the most frequent hazards in waste management activities, including injuries from sharp objects, exposure to biological agents, and musculoskeletal strain, are strongly associated with deficiencies in preventive measures, such as inconsistent PPE use, inadequate procedural compliance, or poor ergonomic practices. The immersive environment operationalises these deficiencies by embedding them directly into the logic of the VR scenarios.

For example, in the sharps-handling scenario, the simulation incorporates a mandatory “Glove Check” step. Failure to inspect or select appropriate protective gloves leads to task failure or simulated injury. This design establishes a clear pedagogical correspondence between risk assessment outputs and training objectives, whereby deficiencies identified through MARAT are transformed into behavioural checkpoints within the immersive experience.

Rather than demonstrating measured improvements in safety literacy, this approach theoretically supports the enhancement of risk awareness and procedural understanding by aligning learning tasks with real operational vulnerabilities. Previous studies suggest that experiential and error-based learning environments may be particularly suitable for workers with lower formal education levels, as they rely less on textual instruction and more on visual, procedural, and action-based cues. Within this context, the proposed framework provides a plausible and evidence-informed mechanism through which VR-based training could support safety learning, although empirical validation with end users is required to substantiate such effects.

7.2 Feasibility and Scalability

The use of the Unity engine and consumer-grade hardware (Meta Quest) addresses the historical barriers to entry for VR training, cost and complexity. The "Unity VR Development Manual" (Appendix II) demonstrates that these scenarios can be built using standard, reusable assets and logic patterns (e.g., the GameManager singleton, the OnTriggerEnter logic). This suggests that waste management facilities do not need expensive proprietary software; they can develop or adapt modular training content internally or

through low-cost partnerships. This scalability is essential for the waste sector, which is often characterised by tight municipal budgets and reliance on small-to-medium enterprises (SMEs).

7.3 Limitations and Validation

It must be acknowledged that the validation of the framework in this study is limited in scope and restricted to analytical and technical dimensions rather than empirical or longitudinal evaluation. No usability testing or user-based validation was conducted within the timeframe of this dissertation.

Nevertheless, strong alignment validity is demonstrated, as the hazards simulated in the immersive scenarios (Sharps, Bioaerosols, and Traffic-related risks) directly correspond to the high-priority hazards identified in both the literature (Uhunamure, 2021; Liu, 2023) and the MARAT risk assessment.

In addition, functional verification of the prototype confirms the technical feasibility of the approach, demonstrating that the implemented C# logic can detect and penalise predefined unsafe behaviours. This confirms the internal coherence between risk assessment outcomes and immersive scenario design, without constituting evidence of training effectiveness.

Future work will include a structured usability and feasibility evaluation tailored to workers with potentially low digital literacy and limited prior exposure to immersive technologies. The goal of this phase is to assess:

i. usability and learnability.
ii. perceived usefulness and relevance to the job.
iii. feasibility of deployment in a workplace training context.

Future work will involve the recruitment of 12–20 participants from waste collection, sorting, and maintenance roles, ensuring diversity in age group, and previous technology exposure. Basic demographic data will be collected (age range, years of experience, previous VR use, self-reported digital literacy).

A two-stage protocol will be adopted:

1. Orientation and onboarding (5–10 minutes): headset fitting, safety briefing, and a short tutorial scene focused only on basic actions (teleport, grab, select PPE).
2. Scenario execution (15–25 minutes): participants complete the three scenarios under observation, followed by a short debrief.

For each scenario, predefined tasks will be evaluated (e.g., PPE selection, hazard identification, maintaining safe distance from vehicles). Quantitative indicators will include:

- Task completion rate and time to completion
- Number of errors (e.g., incorrect PPE, missed hazard, entering a danger zone)

- Number of prompts/helps requests (proxy for learnability)

Usability and user feedback. After the session, participants will answer a brief questionnaire adapted for low-literacy contexts, using simple wording and 5-point visual Likert scales. Key items will assess:

- perceived ease of use (learnability)
- perceived usefulness for safety
- realism and relevance of scenarios
- discomfort or motion sickness (tolerability)

A short semi-structured interview (5 minutes) will capture qualitative feedback, focusing on what felt confusing, unrealistic, or useful, and suggestions for improvement.

Accessibility adjustments for low digital literacy. The evaluation will include design checks such as:

- minimal text; preference for icons, audio guidance, and highlighted objects
- step-by-step instructions with confirmation feedback (“correct/incorrect”)
- optional “guided mode” with slower pacing and extra cues
- ensuring controller mapping is consistent and requires few buttons

Ethical and safety considerations. Participation will be voluntary with informed consent. Breaks will be allowed at any time, and the session will be stopped if discomfort occurs. No personal identifiers will be reported.

This testing plan provides a practical pathway to validate usability and relevance before any claims about training effectiveness are made.

7.4 Regulatory and Social Implications

The framework supports compliance with national and EU regulations. By providing a documented, interactive training method, companies can demonstrate adherence to the training mandates of Portuguese Law 102/2009 and ISO 45001. Furthermore, the visual, non-text-based nature of VR addresses the social challenge of training a diverse, multilingual workforce. By bypassing text-heavy manuals in favour of "learning by doing," the framework promotes inclusivity and ensures that safety competence is accessible to all workers, regardless of literacy levels.

8 CONCLUSION

This dissertation examined occupational risks in the waste management sector through a structured risk assessment and the development of a complementary immersive training framework. The results of the MARAT-based assessment confirmed that waste management activities are characterised by a high prevalence of moderate but recurrent risks, rather than isolated critical events. Across the assessed tasks, most hazards were classified as Intervention Level 2, indicating the need for corrective and control measures to reduce exposure and improve existing preventive practices.

The predominance of Level 2 risks demonstrates that occupational safety challenges in waste management are largely systemic and cumulative. Hazards such as cuts from sharp objects, exposure to biological agents, manual handling overload, and vehicle-related risks occur frequently and affect multiple operational stages. These findings suggest that risk in this sector is embedded in routine work processes and therefore requires continuous and structured preventive strategies, rather than episodic or emergency-focused interventions.

Based on the outcomes of the risk assessment, an immersive training framework was designed to translate the identified hazards and deficiencies into virtual scenarios. The VR prototype was explicitly informed by the MARAT matrix, ensuring that each scenario corresponded to documented risks and intervention needs. Scenarios addressing sharps handling, exposure to airborne contaminants, and vehicle blind spots were developed to reflect the most prevalent risk categories identified in the results. In this sense, the immersive component functions as an operational extension of the risk assessment, rather than as an independent training tool.

While this study did not include user testing, statistical evaluation, or effectiveness validation of the VR scenarios, it demonstrates the methodological feasibility of integrating a simplified risk assessment approach with immersive technology. The alignment between the MARAT results and the design of the VR scenarios supports the internal coherence of the proposed framework and illustrates how risk assessment outputs can be systematically transformed into targeted training content.

Future research should focus on the empirical validation of the proposed immersive framework through structured usability and feasibility studies conducted in real waste management contexts. A next phase of work will involve controlled user testing with waste collection, sorting, and maintenance workers, including participants with low digital literacy and limited prior exposure to immersive technologies. These studies should assess usability, learnability, perceived usefulness, and feasibility of deployment using a combination of quantitative performance indicators and qualitative user feedback. Such validation is necessary before any claims regarding training effectiveness or behavioural impact can be substantiated

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10 APPENDIX

Appendix 1: Risk Assessment Matrix (MARAT)

10.1 Appendix I – Risk Assessment Matrix (MARAT)

The following table presents a comprehensive risk assessment matrix adapted from the MARAT, as outlined by (Santos et al. 2019; Ferrão et al., 2021). This matrix systematically identifies and evaluates hazards associated with typical waste management activities, using established risk parameters to determine intervention and control measures. Each entry details the activity, task, hazard, triggering event, risk outcome, levels of exposure and deficiency, calculated probability and consequence, risk level, recommended intervention, and proposed control measures.

Table 8: MARAT adapted from (Santos et al. 2019; Ferrão et al., 2021).

ACTIVITY	TASK	HAZARD	TRIGGERING EVENT	RISK	MARAT Risk Assessment Matrix						PROPOSED CONTROL MEASURES
					EXPOSURE LEVEL (EL)	DEFICIENCY LEVEL (DL)	PROBABILITY LEVEL (PL) = (DL * EL)	CONSEQUENCE LEVEL (CL)	RISK LEVEL (RL) = (PL * CL)	INTERVENTION LEVEL	
Mechanical processing	Mechanical processing - Fall from height	Fall from height	Climbing onto vehicles or structures without protection	Fracture or trauma	2	8	16	100	1600	2	Use of safety belts, guardrails
Mechanical processing	Mechanical processing - Cutting with sharp objects	Cuts from sharp objects	Contact with broken glass or syringes	Serious injuries, infection	5	7	35	75	2625	1	Use of cut-resistant gloves, training
Manual waste sorting	Manual waste sorting - Fall from height	Fall from height	Climbing onto vehicles or structures without protection	Fracture or trauma	2	8	16	75	1200	2	Use of safety belts, guardrails
Vehicle sanitation	Vehicle cleaning - Electric shock	Electric shock	Contact with exposed wires	Electrocution	1	7	7	50	350	3	Energy lockout, use

			during maintenance								of insulated tools
Vehicle sanitation	Vehicle cleaning - Heavy metal contamination	Heavy metal contamination	Contact with batteries or electronic devices	Chronic poisoning	2	5	10	75	750	3	PPE, isolated area, proper disposal
Waste transport	Waste transport - Being run over	Being run over	Working on public roads	Death or serious trauma	2	9	18	100	1800	2	Signage, reflective vests, surveillance
Mechanical processing	Mechanical processing - Excessive physical exertion	Excessive physical exertion	Manual handling of loads	Muscle injuries	4	4	16	100	1600	2	Ergonomic training, use of carts
Container unloading	Unloading containers - Electric shock	Electric shock	Contact with exposed wires during maintenance	Electrocution	1	7	7	25	175	4	Energy lockout, use of insulated tools
Mechanical processing	Mechanical processing - Inhalation of toxic dust	Inhalation of toxic dust	Handling dry waste	Respiratory problems	3	5	15	75	1125	2	Filter masks, ventilation
Solid waste collection	Solid waste collection - Chemical explosion	Chemical explosion	Mixing incompatible products	Serious burns	1	6	6	50	300	3	Separate storage, proper labelling
Container unloading	Unloading containers - Fall from height	Fall from height	Climbing onto vehicles or structures without protection	Fracture or trauma	2	8	16	75	1200	2	Use of safety belts, guardrails
Manual waste sorting	Manual waste sorting - Chemical explosion	Chemical explosion	Mixing incompatible products	Serious burns	1	6	6	25	150	4	Separate storage, proper labelling
Solid waste collection	Solid waste collection -	Cuts from sharp objects	Contact with broken glass or syringes	Serious injuries, infection	5	7	35	25	875	3	Use of cut-resistant

	Cutting with sharp objects										gloves, training
Equipment maintenance	Equipment maintenance - Exposure to biological agents (bacteria, viruses)	Exposure to biological agents (bacteria, viruses)	Contact with contaminated waste	Infectious diseases	4	6	24	100	2400	1	Use of appropriate PPE, vaccination, hand hygiene
Separation of recyclables	Separation of recyclables - Chemical explosion	Chemical explosion	Mixing incompatible products	Serious burns	1	6	6	75	450	3	Separate storage, proper labelling
Solid waste collection	Solid waste collection - Chemical explosion	Chemical explosion	Mixing incompatible products	Serious burns	1	6	6	100	600	3	Separate storage, proper labelling
Manual waste sorting	Manual waste sorting - Being run over	Being run over	Working on public roads	Death or serious trauma	2	9	18	75	1350	2	Signage, reflective vests, surveillance
Equipment maintenance	Equipment maintenance - Exposure to biological agents (bacteria, viruses)	Exposure to biological agents (bacteria, viruses)	Contact with contaminated waste	Infectious diseases	4	6	24	75	1800	2	Use of appropriate PPE, vaccination, hand hygiene
Equipment maintenance	Equipment maintenance - Inhalation of toxic dust	Inhalation of toxic dust	Handling dry waste	Respiratory problems	3	5	15	100	1500	2	Filter masks, ventilation
Solid waste collection	Solid waste collection - Chemical explosion	Chemical explosion	Mixing incompatible products	Severe burns	1	6	6	50	300	3	Separate storage, proper labelling
Waste transport	Waste transport - Exposure to biological	Exposure to biological agents	Contact with contaminated waste	Infectious diseases	4	6	24	50	1200	2	Use of appropriate PPE,

	agents (bacteria, viruses)	(bacteria, viruses)									vaccination, hand hygiene
Mechanical processing	Mechanical processing - Excessive physical effort	Excessive physical exertion	Manual handling of loads	Muscle injuries	4	4	16	50	800	3	Ergonomic training, use of trolleys
Waste transport	Waste transport - Chemical explosion	Chemical explosion	Mixing incompatible products	Severe burns	1	6	6	100	600	3	Separate storage, proper labelling
Waste transport	Waste transport - Inhalation of toxic dust	Inhalation of toxic dust	Handling dry waste	Respiratory problems	3	5	15	100	1500	2	Filter masks, ventilation
Solid waste collection	Solid waste collection - Excessive physical exertion	Excessive physical exertion	Manual handling of loads	Muscle injuries	4	4	16	50	800	3	Ergonomic training, use of trolleys
Waste transport	Waste transport - Electric shock	Electric shock	Contact with exposed wires during maintenance	Electrocution	1	7	7	75	525	3	Energy lockout, use of insulated tools
Separation of recyclables	Recyclable separation - Inhalation of toxic dust	Inhalation of toxic dust	Handling dry waste	Respiratory problems	3	5	15	75	1125	2	Filter masks, ventilation
Landfill	Landfill - Fall from height	Fall from height	Climbing onto vehicles or structures without protection	Fracture or trauma	2	8	16	50	800	3	Use of safety belts, guardrails
Landfill	Landfill - Exposure to biological agents (bacteria, viruses)	Exposure to biological agents (bacteria, viruses)	Contact with contaminated waste	Infectious diseases	4	6	24	25	600	3	Use of appropriate PPE, vaccination, hand hygiene

Equipment maintenance	Equipment maintenance - Inhalation of toxic dust	Inhalation of toxic dust	Handling dry waste	Respiratory problems	3	5	15	100	1500	2	Filter masks, ventilation
Solid waste collection	Solid waste collection - Being run over	Being run over	Working on public roads	Death or severe trauma	2	9	18	25	450	3	Signage, reflective vests, surveillance
Equipment maintenance	Equipment maintenance - Inhalation of toxic dust	Inhalation of toxic dust	Handling dry waste	Respiratory problems	3	5	15	25	375	3	Filter masks, ventilation
Solid waste collection	Solid waste collection - Inhalation of toxic dust	Inhalation of toxic dust	Handling dry waste	Respiratory problems	3	5	15	100	1500	2	Filter masks, ventilation
Landfill	Landfill - Exposure to biological agents (bacteria, viruses)	Exposure to biological agents (bacteria, viruses)	Contact with contaminated waste	Infectious diseases	4	6	24	100	2400	1	Use of appropriate PPE, vaccination, hand hygiene
Landfill	Landfill - Chemical explosion	Chemical explosion	Mixing incompatible products	Severe burns	1	6	6	100	600	3	Separate storage, proper labelling
Waste transport	Waste transport - Electric shock	Electric shock	Contact with exposed wires during maintenance	Electrocution	1	7	7	100	700	3	Energy lockout, use of insulated tools
Vehicle sanitation	Vehicle sanitation - Animal bite	Animal bite	Contact with loose dogs during collection	Lacerations, trauma	3	6	18	50	900	3	Animal control campaign, vaccination
Vehicle sanitation	Vehicle sanitation - Electric shock	Electric shock	Contact with exposed wires during maintenance	Electrocution	1	7	7	25	175	4	Energy lockout, use of insulated tools

Container unloading	Container unloading - Animal bite	Animal bite	Contact with loose dogs during collection	Lacerations, trauma	3	6	18	75	1350	2	Animal control campaign, vaccination
Landfill	Landfill - Exposure to biological agents (bacteria, viruses)	Exposure to biological agents (bacteria, viruses)	Contact with contaminated waste	Infectious diseases	4	6	24	50	1200	2	Use of appropriate PPE, vaccination, hand hygiene
Container unloading	Container unloading - Fall from height	Fall from height	Climbing onto vehicles or structures without protection	Fracture or trauma	2	8	16	25	400	3	Use of safety harness, guardrails
Equipment maintenance	Equipment maintenance - Cut by sharp objects	Cuts from sharp objects	Contact with broken glass or syringes	Serious injuries, infection	5	7	35	100	3500	1	Use of cut-resistant gloves, training
Mechanical processing	Mechanical processing - Electric shock	Electric shock	Contact with exposed wires during maintenance	Electrocution	1	7	7	25	175	4	Energy lockout, use of insulated tools
Mechanical processing	Mechanical processing - Animal bite	Animal bite	Contact with loose dogs during collection	Lacerations, trauma	3	6	18	25	450	3	Animal control campaign, vaccination
Equipment maintenance	Equipment maintenance - Inhalation of toxic dust	Inhalation of toxic dust	Handling dry waste	Respiratory problems	3	5	15	100	1500	2	Filter masks, ventilation
Landfill	Landfill - Inhalation of toxic dust	Inhalation of toxic dust	Handling dry waste	Respiratory problems	3	5	15	100	1500	2	Filter masks, ventilation
Manual waste sorting	Manual waste sorting - Inhalation of toxic dust	Inhalation of toxic dust	Handling dry waste	Respiratory problems	3	5	15	25	375	3	Filter masks, ventilation

Mechanical processing	Mechanical processing - Heavy metal contamination	Heavy metal contamination	Contact with batteries or electronics	Chronic poisoning	2	5	10	50	500	3	PPE, isolated area, proper disposal
Manual waste sorting	Manual waste sorting - Inhalation of toxic dust	Inhalation of toxic dust	Handling dry waste	Respiratory problems	3	5	15	50	750	3	Filter masks, ventilation
Internal transport	Internal movement - Cuts from sharp objects	Cuts from sharp objects	Contact with broken glass or syringes	Serious injuries, infection	5	7	35	100	3500	1	Use of cut-resistant gloves, training
Landfill	Landfill - Fall from height	Fall from height	Climbing onto vehicles or structures without protection	Fracture or trauma	2	8	16	75	1200	2	Use of safety belts, guardrails
Manual waste sorting	Manual waste sorting - Fall from height	Fall from height	Climbing onto vehicles or structures without protection	Fracture or trauma	2	8	16	50	800	3	Use of safety belts, guardrails
Container unloading	Container unloading - Animal bite	Animal bite	Contact with loose dogs during collection	Lacerations, trauma	3	6	18	100	1800	2	Animal control campaign, vaccination
Solid waste collection	Solid waste collection - Heavy metal contamination	Heavy metal contamination	Contact with batteries or electronics	Chronic poisoning	2	5	10	50	500	3	PPE, isolated area, proper disposal
Manual waste sorting	Manual waste sorting - Electric shock	Electric shock	Contact with exposed wires during maintenance	Electrocution	1	7	7	50	350	3	Energy lockout, use of insulated tools
Waste transport	Waste transport - Cuts from sharp objects	Cuts from sharp objects	Contact with broken glass or syringes	Serious injuries, infection	5	7	35	75	2625	1	Use of cut-resistant gloves, training

Manual waste sorting	Manual waste sorting - Inhalation of toxic dust	Inhalation of toxic dust	Handling dry waste	Respiratory problems	3	5	15	25	375	3	Filter masks, ventilation
Equipment maintenance	Equipment maintenance - Fall from height	Fall from height	Climbing onto vehicles or structures without protection	Fracture or trauma	2	8	16	75	1200	2	Use of safety belts, guardrails
Waste transport	Waste transport - Heavy metal contamination	Heavy metal contamination	Contact with batteries or electronic devices	Chronic poisoning	2	5	10	50	500	3	PPE, isolated area, proper disposal
Container unloading	Container unloading - Exposure to biological agents (bacteria, viruses)	Exposure to biological agents (bacteria, viruses)	Contact with contaminated waste	Infectious diseases	4	6	24	100	2400	1	Use of appropriate PPE, vaccination, hand hygiene
Equipment maintenance	Equipment maintenance - Being run over	Being run over	Working on public roads	Death or serious trauma	2	9	18	50	900	3	Signage, reflective vests, surveillance
Manual waste sorting	Manual waste sorting - Inhalation of toxic dust	Inhalation of toxic dust	Handling dry waste	Respiratory problems	3	5	15	25	375	3	Filter masks, ventilation
Landfill	Landfill - Exposure to biological agents (bacteria, viruses)	Exposure to biological agents (bacteria, viruses)	Contact with contaminated waste	Infectious diseases	4	6	24	25	600	3	Use of appropriate PPE, vaccination, hand hygiene
Internal transport	Internal movement - Animal bite	Animal bite	Contact with stray dogs during collection	Lacerations, trauma	3	6	18	25	450	3	Animal control campaign, vaccination

Manual waste sorting	Manual waste sorting - Cuts from sharp objects	Cuts from sharp objects	Contact with broken glass or syringes	Serious injuries, infection	5	7	35	75	2625	1	Use of cut-resistant gloves, training
Landfill	Landfill - Fall from height	Fall from height	Climbing onto vehicles or structures without protection	Fracture or trauma	2	8	16	100	1600	2	Use of safety belts, guardrails
Internal transport	Internal movement - Exposure to biological agents (bacteria, viruses)	Exposure to biological agents (bacteria, viruses)	Contact with contaminated waste	Infectious diseases	4	6	24	75	1800	2	Use of appropriate PPE, vaccination, hand hygiene
Mechanical processing	Mechanical processing - Exposure to biological agents (bacteria, viruses)	Exposure to biological agents (bacteria, viruses)	Contact with contaminated waste	Infectious diseases	4	6	24	50	1200	2	Use of appropriate PPE, vaccination, hand hygiene
Solid waste collection	Solid waste collection - Heavy metal contamination	Heavy metal contamination	Contact with batteries or electronics	Chronic poisoning	2	5	10	100	1000	2	PPE, isolated area, proper disposal
Container unloading	Container unloading - Animal bite	Animal bite	Contact with loose dogs during collection	Lacerations, trauma	3	6	18	75	1350	2	Animal control campaign, vaccination
Equipment maintenance	Equipment maintenance - Inhalation of toxic dust	Inhalation of toxic dust	Handling dry waste	Respiratory problems	3	5	15	25	375	3	Filter masks, ventilation
Waste transport	Waste transport - Chemical explosion	Chemical explosion	Mixing incompatible products	Severe burns	1	6	6	75	450	3	Separate storage, proper labelling

Equipment maintenance	Equipment maintenance - Heavy metal contamination	Heavy metal contamination	Contact with batteries or electronics	Chronic poisoning	2	5	10	25	250	4	PPE, isolated area, proper disposal
Waste transport	Waste transport - Animal bite	Animal bite	Contact with loose dogs during collection	Lacerations, trauma	3	6	18	25	450	3	Animal control campaign, vaccination
Solid waste collection	Solid waste collection - Chemical explosion	Chemical explosion	Mixing incompatible products	Severe burns	1	6	6	100	600	3	Separate storage, proper labelling
Equipment maintenance	Equipment maintenance - Chemical explosion	Chemical explosion	Mixing incompatible products	Severe burns	1	6	6	25	150	4	Separate storage, proper labelling
Manual waste sorting	Manual waste sorting - Exposure to biological agents (bacteria, viruses)	Exposure to biological agents (bacteria, viruses)	Contact with contaminated waste	Infectious diseases	4	6	24	25	600	3	Use of appropriate PPE, vaccination, hand hygiene
Manual waste sorting	Manual waste sorting - Excessive physical exertion	Excessive physical exertion	Manual handling of loads	Muscle injuries	4	4	16	100	1600	2	Ergonomic training, use of trolleys
Internal transport	Internal movement - Excessive physical effort	Excessive physical exertion	Manual handling of loads	Muscle injuries	4	4	16	50	800	3	Ergonomic training, use of trolleys
Waste transport	Waste transport - Cuts from sharp objects	Cuts from sharp objects	Contact with broken glass or syringes	Serious injuries, infection	5	7	35	75	2625	1	Use of cut-resistant gloves, training
Separation of recyclables	Separation of recyclables -	Chemical explosion	Mixing incompatible products	Severe burns	1	6	6	50	300	3	Separate storage,

	Chemical explosion										proper labelling
Waste transport	Waste transport - Exposure to biological agents (bacteria, viruses)	Exposure to biological agents (bacteria, viruses)	Contact with contaminated waste	Infectious diseases	4	6	24	75	1800	2	Use of appropriate PPE, vaccination, hand hygiene
Separation of recyclables	Separation of recyclables - Exposure to biological agents (bacteria, viruses)	Exposure to biological agents (bacteria, viruses)	Contact with contaminated waste	Infectious diseases	4	6	24	25	600	3	Use of appropriate PPE, vaccination, hand hygiene
Waste transport	Waste transport - Exposure to biological agents (bacteria, viruses)	Exposure to biological agents (bacteria, viruses)	Contact with contaminated waste	Infectious diseases	4	6	24	75	1800	2	Use of appropriate PPE, vaccination, hand hygiene
Waste transport	Waste transport - Excessive physical exertion	Excessive physical exertion	Manual handling of loads	Muscle injuries	4	4	16	75	1200	2	Ergonomic training, use of trolleys
Mechanical processing	Mechanical processing - Excessive physical exertion	Excessive physical exertion	Manual handling of loads	Muscle injuries	4	4	16	75	1200	2	Ergonomic training, use of trolleys
Equipment maintenance	Equipment maintenance - Inhalation of toxic dust	Inhalation of toxic dust	Handling dry waste	Respiratory problems	3	5	15	100	1500	2	Filter masks, ventilation
Vehicle sanitation	Vehicle cleaning - Contamination by heavy metals	Heavy metal contamination	Contact with batteries or electronics	Chronic poisoning	2	5	10	75	750	3	PPE, isolated area, proper disposal

Separation of recyclables	Separation of recyclables - Excessive physical exertion	Excessive physical exertion	Manual handling of loads	Muscle injuries	4	4	16	100	1600	2	Ergonomic training, use of trolleys
Vehicle sanitation	Vehicle cleaning - Inhalation of toxic dust	Inhalation of toxic dust	Handling dry waste	Respiratory problems	3	5	15	100	1500	2	Filter masks, ventilation
Landfill	Landfill - Electric shock	Electric shock	Contact with exposed wiring during maintenance	Electrocution	1	7	7	50	350	3	Energy lockout, use of insulated tools
Mechanical processing	Mechanical processing - Electric shock	Electric shock	Contact with exposed wiring during maintenance	Electrocution	1	7	7	50	350	3	Energy lockout, use of insulated tools
Container unloading	Container unloading - Animal bite	Animal bite	Contact with loose dogs during collection	Lacerations, trauma	3	6	18	100	1800	2	Animal control campaign, vaccination
Internal transport	Internal movement - Fall from height	Fall from height	Climbing onto vehicles or structures without protection	Fracture or trauma	2	8	16	100	1600	2	Use of safety belts, guardrails
Container unloading	Container unloading - Excessive physical exertion	Excessive physical exertion	Manual handling of loads	Muscle injuries	4	4	16	25	400	3	Ergonomic training, use of trolleys
Solid waste collection	Solid waste collection - Fall from height	Fall from height	Climbing onto vehicles or structures without protection	Fracture or trauma	2	8	16	100	1600	2	Use of safety belts, guardrails
Solid waste collection	Solid waste collection - Exposure to	Exposure to biological agents	Contact with contaminated waste	Infectious diseases	4	6	24	25	600	3	Use of appropriate PPE,

	biological agents (bacteria, viruses)	(bacteria, viruses)									vaccination, hand hygiene
Landfill	Landfill - Animal bite	Animal bite	Contact with loose dogs during collection	Lacerations, trauma	3	6	18	75	1350	2	Animal control campaign, vaccination
Internal transport	Internal movement - Chemical explosion	Chemical explosion	Mixing incompatible products	Severe burns	1	6	6	100	600	3	Separate storage, proper labelling
Separation of recyclables	Separation of recyclables - Being run over	Being run over	Working on public roads	Death or severe trauma	2	9	18	50	900	3	Signage, reflective vests, surveillance