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Preventing Needle Stick Injuries (NSI) Among Medical Waste Handlers: A Systematic Review Based on the Hierarchy of Hazard Controls

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Abstract
Introduction: *Needle Stick Injuries (NSI) is representing a significant safety hazard in hospitals, affecting frontline healthcare workers and medical waste handlers. Improper disposal of used medical needles into infectious waste bins instead of designated safety boxes became the primary cause of these incidents.* ***Objective:*** *This study is aiming to evaluate medical waste management interventions to prevent NSI using the Hierarchy of Hazard Controls.* ***Method:*** *A systematic literature review conducted following PRISMA 2020 guidelines. Articles published between 2019 and 2026 were searched in PubMed, ScienceDirect, and Google Scholar, utilizing PICO to select relevant studies.* ***Result and Discussion:*** *Healthcare facilities primarily rely on administrative controls, such as Standard Operating Procedures (SOPs), and Personal Protective Equipment (PPE). However, these approaches frequently fail due to human errors and non-compliance worker. Current engineering interventions, including Internet of Thing (IoT) smart bins and RFID sorting, tend to be too complex and lack direct physical barriers to prevent Improper needle disposal.* ***Conclusion:*** *Current reliance on PPE and administrative protocols is not enough to protect waste handlers from NSI risk. Hospitals need to prioritizing practical engineering controls, such as direct physical barriers integrated with waste bins, to prevent NSI at the source.*

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Introduction

Effective Occupational Safety and Health (OSH) management in healthcare facilities is really essential for protecting the entire hospital workforce. Furthermore, effective medical waste management is intricately linked to overall hospital accreditation standards and patient safety goals. Poor waste segregation not only endangers waste handlers but also creates potential vectors for cross-contamination that can compromise patient safety and the overall quality of healthcare delivery (Windfeld & Brooks, 2015). One of the most persistent occupational hazards in this sector is Needle Stick Injuries (NSI). NSI refers to accidental skin punctures caused by medical sharps, which carry a significant risk of transmitting blood-borne pathogens, including the Human Immunodeficiency Virus (HIV), Hepatitis B Virus (HBV), and Hepatitis C Virus (HCV) (Alhumaid et al., 2021). From a broader public health perspective, the impact of these infections extends far beyond the individual worker. The transmission of such pathogens contributes significantly to the global burden of disease, leading to long-term morbidity, chronic liver diseases, and heavily straining public health systems and national healthcare budgets (Mengistu et al., 2021). In addition to the risk of infection, NSI also imposes a psychological burden on injured workers, causing distress while waiting the serological test results (Cooke & Stephens, 2020). The financial implications for healthcare systems stemming from post-exposure prophylaxis and medical treatments are also substantial (Grimmond & Good, 2021).

Most existing research and preventive programs regarding NSI tend to focused primarily on clinical staff, such as doctors and nurses, who directly handle medical sharps. Consequently, non-medical support staff, particularly medical waste handlers and cleaners, are frequently underrepresented in healthcare occupational safety discussions (Zungu et al., 2021). Unlike clinical staff, waste handlers are mostly exposed to used medical needles due to procedural failures at the point of disposal. A retrospective study conducted at the King Hussein Medical Center revealed that 36.6% of all recorded NSI cases occurred among cleaning and waste management staff, highlighting their significant vulnerability (Saadeh et al., 2019). Systematic reviews of global data consistently position waste handlers as a high-risk occupational group due to their high frequency interaction with hazardous medical waste (Bouya et al., 2020).

The incidence of NSI among medical waste handlers is primarily caused by improper needles or sharps disposal. According to safety standards, used needles and sharps must be discarded into rigid, puncture-resistant safety boxes. However, non-compliance remains high, with used needles and metal sharps frequently disposed of improperly into standard infectious waste bags (Hosseinipalangi et al., 2022). When waste handlers collect or transport these soft plastic bags, hidden needles can easily pierce through the material. Research indicates that upstream segregation failures account for up to 37.17% of all NSI incidents globally (Hosseinipalangi et al., 2022).

To address these NSI hazards systematically, the implementation of the Hierarchy of Hazard Controls is recommended. This framework prioritizes risk mitigation strategies from the most effective to the least effective: elimination, substitution, engineering controls, administrative controls, and Personal Protective Equipment (PPE) (Lestari et al., 2023). Current hospital safety programs often relying on the lowest and least effective tiers namely, administrative controls (such as standard operating procedures (SOPs) and training) and PPE (such as standard latex gloves) (Kaya et al., 2023). These lower-tier controls can easily fail because they depend on human compliance, which can be compromised by workload and fatigue (Alhumaid et al., 2021).

Achieving a sustainable risk reduction in NSI particularly for medical waste handlers and cleaners requires prioritizing engineering controls over administrative measures. Engineering controls are designed to isolate the worker from the danger, operating independently of human behavior. While recent technological advancements have introduced modern concepts to medical waste management, a critical gap remains. Current innovations, such as Internet of Things (IoT)-based smart bins, primarily focus on monitoring trash volume for logistical efficiency (Ishaq et al., 2025). Other developments explore Radio Frequency Identification (RFID) for sorting (Renhoran et al., 2024) or employ Artificial Intelligence (AI) for general image recognition of waste (Muthukumar et al., 2024). Although these technologies show progress, there is a distinct lack of literature focusing on targeted engineering controls—such as physical detection barriers at the lip of infectious waste bins—that proactively prevent the insertion of metallic needles. Most existing systematic reviews evaluate NSI prevalence or post-exposure treatments, leaving a gap in preventive technologies designed specifically for waste segregation safety.

To address this gap, this systematic review aims to evaluate the effectiveness of current medical waste management interventions through the theoretical lens of the Hierarchy of Hazard Controls. By critically assessing existing strategies, this study seeks to highlight the limitations of administrative interventions and emphasize the need for developing targeted engineering controls to prevent NSI among medical waste handlers.

Method

Study Design

This study used a Systematic Literature Review (SLR) design to identify, evaluate, and synthesize existing evidence regarding the interventions used to prevent Needle Stick Injuries (NSI) among medical waste handlers. This review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines to ensure transparency, completeness, and methodological accuracy.

Research Targets (Eligibility Criteria)

In this systematic review, the research population comprised available scientific literature discussing occupational hazards in medical waste management, while the sample consisted of the final selected articles that met specific eligibility criteria. The eligibility criteria were defined using the PICOS framework to ensure the relevance of the included studies.

Table 1
PICOS Eligibility Criteria

Component	Criteria
Population (P)	Medical waste handlers, cleaning staff, and healthcare workers involved in the disposal and management of medical sharps and infectious waste.
Intervention/Exposure (I)	Implementation of occupational safety interventions based on the Hierarchy of Hazard Controls (e.g., engineering controls, administrative protocols, smart bins, physical barriers).
Comparison (C)	Standard hospital waste management practices without specific technological or procedural interventions, or comparisons between different tiers of hazard controls.
Outcome (O)	Reduction of NSI incidence, effectiveness of the hazard control mechanism, and prevention of improper needle disposal.
Study Design (S)	Observational studies (cross-sectional, cohort, case-control), experimental studies, technological design reports, and relevant systematic reviews published between 2019 and 2026.

Articles excluded if they were not published in English or Indonesian, fully focused on post-exposure medical treatments (e.g., prophylaxis) without discussing preventive management, or lacked full-text accessibility.

Data Collection Techniques

The data collection process involved a comprehensive literature search all across major electronic databases, including PubMed, ScienceDirect, and Google Scholar. The search strategy utilized specific keywords combined with Boolean operators (AND/OR) to maximize sensitivity. Search terms included: ("Needlestick Injury" OR "NSI") AND ("Medical Waste Management" OR "Waste Handlers") AND ("Hierarchy of Controls" OR "Engineering Control" OR "Occupational Safety"). The study selection process was conducted in multiple stages. Initially, duplicate records from the databases were removed. Subsequently, titles and abstracts of the remaining articles were screened for relevance. Articles that passed the initial screening underwent a full-text assessment to determine their final eligibility based on the established PICOS criteria.

Data Analysis Techniques

Data extraction and analysis were conducted using a structured narrative synthesis approach. Quantitative meta-analysis was not performed due to the expected heterogeneity in the study designs, especially between epidemiological studies and technological engineering reports. Extracted data included the author, year of publication, study design, key interventions assessed, and primary results. The analysis systematically categorized the extracted findings into different tiers of the Hierarchy of Hazard Controls to evaluate the overall effectiveness of physical barrier interventions compared to procedural compliance.

Result and Discussion

1. Result

Study Selection

The literature research across the selected databases yielded a total of 154 initial records. After removing duplicates, 120 articles were screened based on their titles and abstracts. This screening excluded 85 articles that were irrelevant to the occupational safety of medical waste handlers or fully focused on clinical treatments. The remaining 35 full-text articles were assessed for eligibility using the PICOS criteria. A total of 9 studies met the inclusion criteria and were included in the final qualitative synthesis. The complete study selection process is illustrated in the PRISMA flow diagram below.

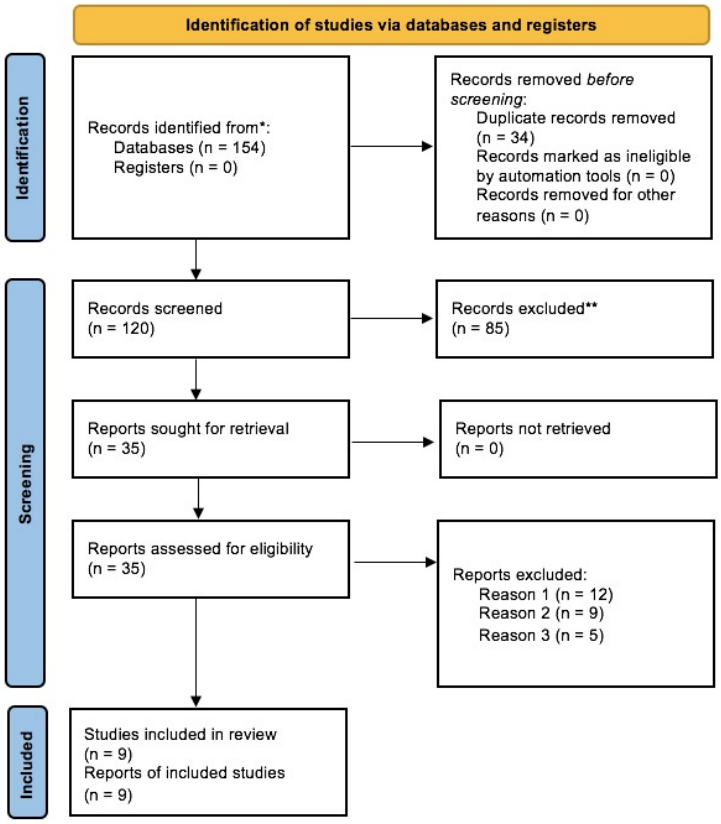

Figure 1. PRISMA Flow Diagram

Characteristics of Included Studies

The included studies are included observational studies evaluating safety compliance, retrospective incident analyses, and technological design reports focusing on medical waste management innovations. The characteristics, key interventions, and dominant findings of these studies are summarized in Table 2.

Table 2
Characteristics of Included Studies

Author (Year)	Study Design	Key Interventions / Focus	Main Findings
Saadeh et al. (2019)	Retrospective Observational Study	Prevalence of Needlestick Injuries (NSI) among healthcare workers.	Cleaners and waste management staff are highly vulnerable, accounting for **36.6%** of all NSI incidents, almost equaling clinical staff.
Hosseinipalangi et al. (2022)	Systematic Review and Meta-analysis	Global incidence and primary causes of NSI in healthcare settings.	Improper disposal of used medical needles at the source (upstream failure) is a major cause, contributing to **37.17%** of all NSI cases globally.
Toybah et al. (2025)	Cross-sectional Study	Determinants of NSI incidents among hospital staff.	High incidence of NSI is strongly associated with fatigue, high workload, and non-compliance with safe disposal SOPs.
Zungu et al. (2021)	Cross-sectional / Qualitative Study	Occupational health and safety challenges reported by medical waste handlers.	Hospitals heavily rely on administrative controls and PPE, which often fail to protect waste handlers from hidden sharps in waste bags.
Alhumaid et al. (2021)	Systematic Review	Knowledge and compliance regarding infection prevention among healthcare workers.	Despite high knowledge of safety protocols (administrative controls), actual behavioral compliance remains inconsistent due to rushing and fatigue.
Ishaq et al. (2025)	Experimental / Technological Design	Smart waste bin monitoring using Internet of Things (IoT).	The IoT system effectively monitors waste volume for logistics but lacks a specific physical barrier mechanism to prevent incorrect needle disposal.
Renhoran et al. (2024)	Experimental / Technological Design	Solid medical waste sorting system using RFID and Inductive Proximity Sensor.	The system successfully identifies metallic objects but is designed for general sorting rather than acting as an immediate, proactive barrier at the bin's opening.
Laksmiati & Fariansyah (2025)	Experimental / Technological Design	Metal and non-metal waste detector based on ESP32 Microcontroller.	The sensor accurately detects metal, but the design does not specifically engineer a lip-barrier mechanism tailored for hospital infectious waste bins.
Muthukumar et al. (2024)	Experimental / Technological Design	AI-based smart bin for waste segregation and monitoring.	Utilizes complex Artificial Intelligence and image recognition for general waste, which is pretty costly and overly complex for simple needle rejection.

Findings on Administrative Controls and Personal Protective Equipment (PPE)

The synthesis of the literature reveals that many healthcare facilities manage NSI risks mainly through the lower-tier hazard controls. Studies report that hospitals are relying heavily on providing safety training, standard operating procedures (SOPs), and warning signs installed, which are classified as administrative controls (Zungu et al., 2021). In addition, the provision of PPE, such as latex or nitrile gloves, remains the primary physical defense provided to the medical waste handlers (Kaya et al., 2023).

However, observational data indicate that despite adequate knowledge regarding these SOPs, actual compliance among hospital staff remains inconsistent due to high workloads and fatigue (Alhumaid et al., 2021). Consequently, procedural failures frequently occur, leading to the incorrect disposal of medical sharps into soft plastic infectious waste bags, which directly endangers waste handlers in the hospitals (Hosseinipalangi et al., 2022; Toybah et al., 2025).

Findings on Engineering Controls and Technological Innovations

A smaller portion of the reviewed literature focuses on engineering controls, which aim to physically isolate the hazard from it source. Recent studies have introduced advanced technological interventions in medical waste management. For instance, Ishaq et al. (2025) developed a smart waste bin utilizing the Internet of Things (IoT) to remotely monitor the fill level of biomedical waste bins. Another approach by Renhoran et al. (2024) explored the use of Radio Frequency Identification (RFID) combined with inductive proximity sensors to sort solid medical waste automatically. Laksmiati and Fariansyah (2025) also tested ESP32 microcontroller-based metal detectors. Furthermore, Muthukumar et al. (2024) designed a smart bin using Artificial Intelligence (AI) and image recognition to segregate different types of waste. While these innovations represent progress in waste management automation, the literature shows that they are primarily focused on sorting efficiency and volume monitoring rather than proactively preventing the initial incorrect disposal of medical needles.

2. Discussion

The Overreliance on Lower-Tier Hazard Controls

The findings of this systematic review indicate a significant gap in current hospital safety management: an overdependence on administrative controls and PPE to protect medical waste handlers. According to the Hierarchy of Hazard Controls, these two methods are the least effective because they do not remove the hazard; instead, they require constant human behavioral compliance (Lestari et al., 2023). As demonstrated by Saadeh et al. (2019), despite the implementation of disposal SOPs, waste management staff still account for 36.6% of NSI incidents. This high incidence rate suggests that educating clinical staff on proper disposal and providing standard gloves to waste handlers are ineffective. Medical gloves basically designed to prevent fluid contamination, not to withstand the puncture force of a hypodermic needle hidden inside a compressed waste bag (Kaya et al., 2023). When a needle is improperly disposed of, the administrative barrier has already failed, leaving the downstream waste handler unprotected.

When comparing the effectiveness between interventions, engineering controls provide a more reliable physical safeguard against hazards than administrative measures. However, it is crucial to recognize that engineering controls cannot operate by itself. Human aspects, particularly organizational safety culture and individual needle disposal behavior, still have the major role in the success of any safety intervention. Administrative controls and safety training are not obsolete; rather, they are necessary elements that shape a strong safety culture. A poor safety culture or negative disposal behavior can render even the most advanced engineering controls ineffective, especially if workers intentionally bypass safety mechanisms. Therefore, while engineering controls offer superior physical protection, they must be seamlessly integrated with robust safety culture initiatives to ensure comprehensive protection for medical waste handlers.

The Efficacy and Gaps in Current Engineering Controls

To effectively reduce the risk of NSI particularly to waste handlers, hospitals must implement targeted engineering controls. Engineering controls are more reliable because they operate independently of human error, physically preventing the hazardous event from occurring (Lestari et al., 2023). The recent surge in "smart bin" technologies shows a promising shift towards automated safety. However, a critical gap remains in the practical application of these technologies.

Innovations utilizing complex AI and IoT systems require substantial maintenance and do not offer a direct physical barrier against needles (Muthukumar et al., 2024). Similarly, while RFID and inductive sensor systems successfully identify metallic objects, the mechanisms are often too slow or cumbersome for the fast-paced environment of a hospital ward (Renhoran et al., 2024). These existing engineering controls fail to provide a simple, immediate physical barrier at the opening of the infectious waste bin.

Future Implications and Recommendations

To address this safety gap, future innovations must focus on developing targeted, barrier-based engineering controls. There is a need for the development of early-warning systems and automated locking mechanisms such as proximity metal sensors integrated with automated mechanical gates at the opening of infectious waste bins. If a metallic medical needle is detected entering the wrong bin, the system should instantly close the lid or trigger an alarm, physically rejecting the improper disposal. By implementing specific engineering controls, hospitals can shift the safety burden away from vulnerable human compliance and place it onto reliable technological barriers, effectively addressing the root cause of NSI for medical waste handlers.

Conclusion

Needle Stick Injuries (NSI) remain a critical occupational hazard for medical waste handlers, primarily driven by upstream segregation failures and the improper disposal of medical sharps into soft waste bags. This systematic review demonstrates that current safety strategies in many healthcare facilities are insufficient due to an overreliance on lower-tier hazard controls. Administrative protocols and Personal Protective Equipment (PPE) are inadequate for preventing NSI because they depend entirely on human compliance, which is easily compromised by fatigue and high workloads in fast-paced clinical environments.

Furthermore, while recent technological advancements in medical waste management have introduced automation, they largely focus on logistical volume monitoring or complex general waste sorting. There remains a significant lack of proactive hazard isolation mechanisms. To effectively protect medical waste handlers, healthcare management must prioritize higher-level hazard controls. There is an urgent need for the development and implementation of practical, barrier-based technologies such as metal-detecting sensors integrated with automated mechanical gates at the opening of infectious waste bins that can automatically reject the incorrect disposal of medical needles. Nevertheless, the success of these technological barriers ultimately relies on their integration with a strong organizational safety culture and disciplined disposal behavior. By shifting the primary safety mechanism from human compliance to physical engineering barriers, hospitals can systematically reduce NSI risks and ensure a safer occupational environment for waste management personnel.

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