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ENVIRONMENTAL HEALTH RISK CONTROL IN THE MANAGEMENT OF INFECTIOUS MEDICAL WASTE IN HOSPITALS USING THE FMEA METHOD

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ABSTRACT

Medical waste refers to the waste generated from medical activities within healthcare facilities, including hospitals. Other studies indicate that 15-25% of medical waste is toxic, infectious, or radioactive, while 75-85% is non-hazardous. Despite the smaller volume of medical waste compared to other waste types, its improper management can pose significant health and environmental risks. This research aims to investigate the control of environmental health risks in the handling of infectious medical waste at hospitals using the FMEA method. This study employed an observational research design using a cross-sectional approach. A mixed-methods approach was applied, combining both quantitative and qualitative analyses to assess environmental health risk management related to medical waste processing based on priority or critical risks at RSUP Persahabatan. The target population included individuals involved in both the handling and treatment stages of medical waste using an incinerator at the facility. The sample selection for the FMEA analysis employed purposive sampling with a quota sampling technique.The study utilized an environmental risk analysis framework based on the Failure Mode and Effect Analysis (FMEA) method. The critical Risk Priority Number (RPN) analysis revealed the following three primary environmental health risks: (1) The risk of contracting environmental health-based infectious diseases through the transmission of pathogenic microorganisms or hazardous materials, associated with 12 failure modes in the medical waste handling process. (2) The risk of ambient air (work environment) contamination, associated with 5 failure modes in the medical waste handling process. (3) The risk of contamination of facilities and rooms where medical waste is generated, associated with 4 failure modes related to the operation of the incinerator during the medical waste treatment process. Environmental health risks with a high potential to arise from failure modes during the medical waste management stage at RSUP Persahabatan, as indicated by critical Risk Priority Number (RPN) scores.

Keywords: environmental; health risks; infectious; medical waste; medical waste management

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INTRODUCTION

Medical waste refers to the waste generated from medical activities within healthcare facilities, including hospitals (Ministry of Health, 2020), and is classified as hazardous and toxic waste (Government Regulation, 2021). According to the WHO (2018a), medical waste accounts for approximately 15% of the total waste produced by healthcare facilities and is considered hazardous. Other studies indicate that 15-25% of medical waste is toxic, infectious, or radioactive, while 75-85% is non-hazardous (Padmanabhan & Bariks, 2019). Despite the smaller volume of medical waste compared to other waste types, its improper management can pose significant health and environmental risks.

The risks to human health and environmental quality due to medical waste continue to increase over time as the amount of medical waste generated rises (WHO, 2018a). The ICRS (2011) reports that medical waste also poses risks to public health and the environment if it is not properly processed and disposed of. Interviews with 11 residents near an incinerator revealed that 9 (82.2%) experienced respiratory problems such as coughing, shortness of breath, odor, and skin irritation during the incinerator's operation. Further preliminary interviews with 13 respondents, including 2 incinerator operators and 11 medical waste handlers at RSUP Persahabatan, indicated that both incinerator operators (100%) experienced respiratory issues such as coughing and irritation with moderate to frequent occurrences, while 6 (54.5%) waste handlers reported occasional coughing. Visual observations also found contamination of leachate water around the incinerator area and residue scattered inside the incinerator building.

The incineration of medical waste using high-temperature incinerators is still widely used in hospitals across Indonesia. According to data from the Ministry of Health of the Republic of Indonesia in 2019, there were 2,877 hospitals nationwide. However, by November 2020, only 117 hospitals had permits for hazardous waste processing, with 111 using incinerators and 6 using autoclaves (KLHK, 2023). The use of medical waste incinerators in Indonesian hospitals cannot be avoided, primarily due to the lack of centralized hazardous waste treatment infrastructure (offsite treatment system) accessible to all hospitals. In certain areas with available systems and infrastructure, the waste treatment capacity is still limited and inadequate to match the medical waste generated. The Ministry of Health (2020) reports that healthcare facilities, particularly hospitals and community health centers, generate 296.86 tons of waste per day, but the processing capacity of third-party service providers is only 151.6 tons per day. RSUP Persahabatan, a class A teaching hospital under the Ministry of Health, generates 500-700 kg of infectious medical waste per day and should implement an infectious medical waste treatment system that meets safety standards to mitigate environmental and health risks. Therefore, the application of local medical waste treatment systems using incinerators remains a key solution to address health and environmental risks.

While the benefits of medical waste treatment via incinerators in hospitals are recognized, as it can significantly reduce both the volume and weight of medical waste (Abdulla et al., 2008), operating incinerators also presents new challenges. These include the potential release of hazardous substances, such as NOx, SO2, CO, HC, O3, TSP, PM2.5, PM10, and toxic residues containing heavy metals, wet scrubber sludge, and medical waste leachate, all of which need to be controlled. These emissions are particularly hazardous to the health of operators and nearby residents and can cause environmental contamination in air, soil, groundwater, and surface water.

Previous studies have shown that the incineration of medical waste releases heavy metals and potentially toxic elements (PTEs) such as cobalt (Co), copper (Cu), chromium (Cr), manganese (Mn), and zinc (Zn), as well as non-essential elements like arsenic (As), cadmium (Cd), lead (Pb), and mercury (Hg), along with secondary pollutants such as particulates, SO2, NOx, HCl, dioxins, and polycyclic aromatic hydrocarbons (PAHs) into the environment (Liu et al., 2018). These pollutants are released into the atmosphere during incineration and may either volatilize as metal vapors or settle as ash/residue (Li et al., 2017; Liu et al., 2018; Wu et al., 2014). Additionally, the burning of medical waste can generate emissions of contaminants such as dioxins and furans, leaving toxic residues in the environment (Rani & Sampal, 2019).

Particulates emitted by incinerators, such as Total Suspended Particulate (TSP) and particulate matter (PM) of both 10 microns (PM10) and 2.5 microns (PM2.5), are particularly concerning. These fine particles, especially at high concentrations, can lead to respiratory issues such as coughing. Due to these risks, particulate matter is a key parameter for emissions standards of stationary sources (KLHK, 2021). PM2.5 and PM10 are critical indicators of ambient air pollution, strongly predicting health impacts such as cardiovascular diseases, respiratory diseases, and lung cancer (WHO, 2022). In a study of 63 epidemiological studies focusing on health effects of incinerators, exposure to particulate emissions during incineration was linked to respiratory health risks (Negri E, 2020). Populations living near hospitals are at high risk of exposure to particulate pollution and are most affected by it (Haryoto, 2011).

To control environmental health risks associated with medical waste incinerators in hospitals, an environmental risk analysis approach is needed. According to Exit and Fereshte (2009), risk management and analysis aim to identify and analyze hazards to determine strategies for preventing adverse events, serving as a vital task for assessing impacts and formulating mitigation strategies (Fam et al., 2010). Environmental risk control can be achieved using tools like Failure Mode and Effect Analysis (FMEA) (Vazdani et al., 2017; Barendsa et al., 2012; Dailey, 2014). Conducting an environmental health risk analysis of medical waste treatment using FMEA is crucial for hospitals, particularly those like RSUP Persahabatan, where incinerator operations may not meet technical requirements set out in Ministry of Environment and Forestry Regulation No. 56 of 2015 regarding hazardous waste management in healthcare facilities. This research aims to investigate the control of environmental health risks in the handling of infectious medical waste at hospitals using the FMEA method.

METHOD

Study Design

This study employed an observational research design using a cross-sectional approach, in which each research subject was observed at a single point in time and measurements were taken concurrently. A mixed-methods approach was applied, combining both quantitative and qualitative analyses to assess environmental health risk management related to medical waste processing based on priority or critical risks at RSUP Persahabatan. The study utilized an environmental risk analysis framework based on the Failure Mode and Effect Analysis (FMEA) method.

Population and Sample

The population of this study comprised data related to medical waste processing activities at RSUP Persahabatan. The target population included individuals involved in both the handling and treatment stages of medical waste using an incinerator at the facility. The sample selection for the FMEA analysis employed purposive sampling with a quota sampling technique. Inclusion criteria for respondents were as follows: a minimum educational background of a three-year diploma (D3) in Environmental Health; at least five years of professional experience in environmental or waste management at their workplace; and current active employment in a hospital environmental health or medical waste management role. Exclusion criteria included: an educational background limited to senior high school (SLTA) or equivalent; no professional experience in environmental or waste management; and not currently active as a staff member or official in environmental or waste management roles.

Instruments

FMEA evaluations were conducted by expert personnel, consisting of eight environmental health specialists from the Environmental Health Installation at RSUP Persahabatan. The research instrument used was a structured questionnaire containing respondent opinion fields, employing a Likert scale to rate perceptions regarding environmental health risk control during medical waste handling and treatment stages using incinerators, based on the Risk Priority Number (RPN) derived through the FMEA method. The questionnaire collected scores for three key criteria—Severity (S), Occurrence (O), and Detection (D)—along with the calculation of the RPN for each identified environmental health risk at both the handling and treatment stages. These results informed the analysis of environmental health risk management strategies based on critical risk values following the FMEA framework.

Data Analysis
The analysis of infectious medical waste generation rates (kg/Bed/Day) was conducted using mathematical formulas. The relationships and significance tests between occupied beds (X1) and the Bed Occupancy Rate (X2) with the volume of medical waste generation (Y) were analyzed using multivariate analysis with descriptive statistics. Univariate analysis was performed to describe each variable independently without drawing conclusions about the relationships between variables.

Ethical Approval
This research has been approved by the Persahabatan Hospital Ethics Committee with approval number 0046/KEPK-RSUPP/03/2025

RESULT

MEA Data Analysis and Risk Priority Number (RPN) Calculation
After identifying potential environmental health risks through the flowchart of the medical waste handling and treatment process, scores for occurrence, severity, and detection were determined. These scores were collected through questionnaires completed by respondents. Each score ranged from 1 to 5, following the criteria established in the methodology. Based on the completed research instruments and subsequent brainstorming sessions, the Risk Priority Number (RPN) was calculated for each environmental health risk element, both during the waste handling and treatment stages (using the incinerator).

Each environmental health risk element was then assessed to determine its critical RPN score. An element was classified as critical if its RPN exceeded the average RPN across all stages of waste handling and treatment. These critical RPN scores form the basis for developing effective strategies for environmental health risk control during medical waste handling and treatment at RSUP Persahabatan. The following presents the average RPN scores and critical RPN scores identified in this study.

RPN Calculation Results for the Medical Waste Handling Stage
The RPN calculation results for the medical waste handling stage are presented in the Appendix tables. According to the FMEA methodology, the RPN value is obtained by multiplying the severity, occurrence, and detection scores for each stage of medical waste handling at RSUP Persahabatan. Based on the RPN calculation results detailed in the Appendix, a summary is provided in the following table:

Table 1.
Summary of RPN Questionnaire Scores for the Medical Waste Handling Stage

No.	Handling Stage	Potential Failure Modes	Environmental Health Risk Elements
1	Reduction Stage	2 potential failure modes	4 environmental health risk elements
2	Segregation Stage	1 potential failure mode	4 environmental health risk elements
3	Containment Stage	4 potential failure modes	16 environmental health risk elements
4	Transportation Stage	3 potential failure modes	6 environmental health risk elements
5	Temporary Storage Stage	5 potential failure modes	20 environmental health risk elements

Critical Risk Priority Number (RPN) Calculation for the Waste Handling Stage
The critical RPN value for an environmental health risk in the medical waste handling stage was determined based on whether the calculated RPN exceeded the critical threshold value. The critical threshold value was calculated using the following formula:

$$\text{Critical RPN Threshold} = \frac{\text{Total RPN of High-Priority Risks}}{\text{Number of Risks Evaluated}}$$

From the table of average RPN calculations for the medical waste handling stage at RSUP Persahabatan, the following critical threshold was obtained:

- Total RPN value = 1,782.23
- Number of environmental health risk effects evaluated = 50

Thus, the critical threshold for the waste handling stage is:

$$\text{Critical RPN Threshold} = \frac{1,782.23}{50} = 35.64$$

Based on the critical RPN threshold value of 35.64, the potential critical environmental health risks during the medical waste handling stage were identified. These risks are illustrated in the following graph.

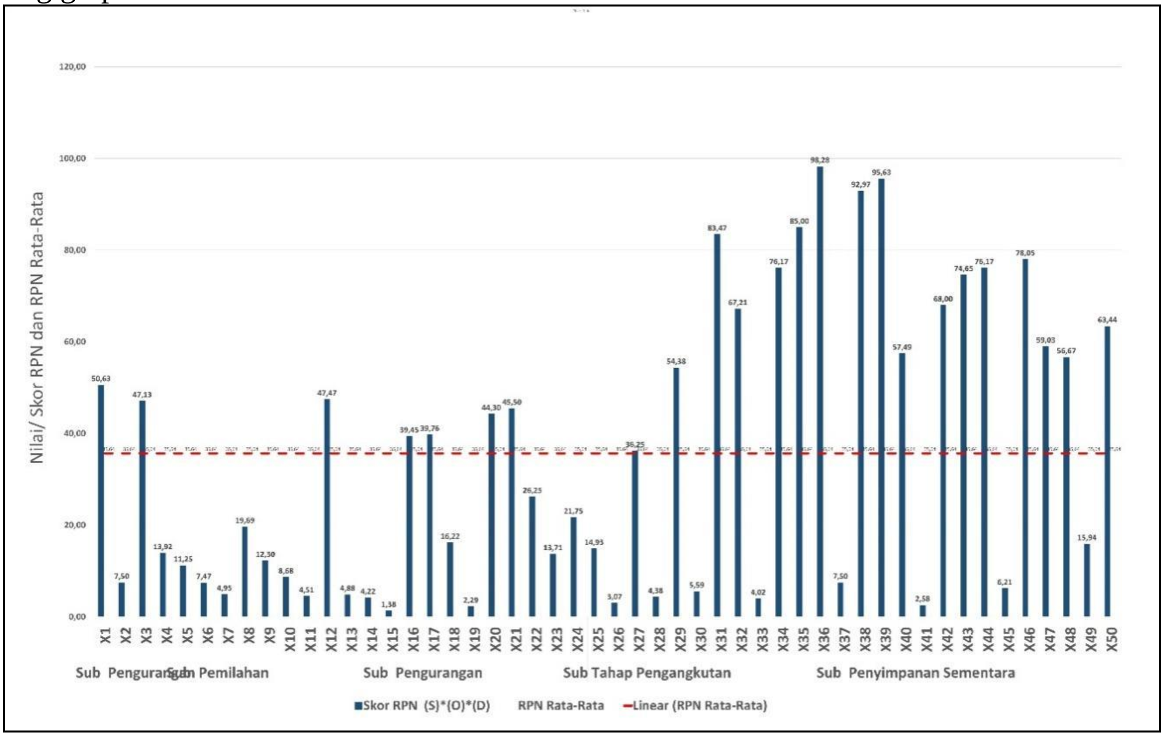

Figure 1. Graph of Critical RPN Values for the Medical Waste Handling Stage

From the graph above, it can be observed that there are 24 RPN values exceeding the critical threshold of 35.64. This indicates the presence of 24 potential critical environmental health risks during the medical waste handling stage that require priority control measures at RSUP Persahabatan. The list of these 24 potential critical environmental health risks during the medical waste handling stage is presented in the table 2 below. Based on the calculation table presented above, the failure modes and failure effects associated with the medical waste handling stage that contribute to critical environmental health risks were identified. Among the eight types of potential environmental health risks arising from the five sub-stages of medical waste handling examined in this study, only three critical environmental health risks were identified. These risks are considered to require the highest priority attention by RSUP Persahabatan in the management and control of environmental health risks during the medical waste handling process across the five sub-stages.

The critical Risk Priority Number (RPN) analysis revealed the following three primary environmental health risks: (1) The risk of contracting environmental health-based infectious diseases through the transmission of pathogenic microorganisms or hazardous materials, associated with 12 failure modes in the medical waste handling process. (2) The risk of ambient air (work environment) contamination, associated with 5 failure modes in the medical waste handling process. (3) The risk of contamination of facilities and rooms where medical waste is generated, associated with 4 failure modes related to the operation of the incinerator during the medical waste treatment process.

DISCUSSION

The findings of this study revealed that, of the eight potential environmental health risks identified across five sub-stages of medical waste handling, only three were classified as critical environmental health risks. These critical risks should receive priority attention from RSUP Persahabatan in efforts to control environmental health risks at the medical waste handling stage. Based on the analysis of critical Risk Priority Number (RPN) scores, the three critical environmental health risks identified are: (1) the risk of infection by environmentally-based diseases through the transmission of pathogenic microorganisms or hazardous materials, identified across 12 failure modes of medical waste handling; (2) the risk of ambient air (work environment) contamination associated with 5 failure modes; and (3) the risk of contamination of facilities and rooms associated with 4 failure modes related to incinerator operation in medical waste treatment.

To ensure the sustainable implementation of environmentally friendly medical waste handling—comprising reduction, segregation, containment, transportation, and temporary storage—at RSUP Persahabatan, effective strategies for environmental health risk control are required. According to Akbarzadeh and Abbas (2008), environmental risk assessments can serve as an integral part of environmental impact assessments. Jensen (2001) further noted that among various risk assessment techniques, Failure Mode and Effect Analysis (FMEA) is the only analytical method capable of assessing potential risks more comprehensively by identifying associated causes and effects, ranking priorities, and enabling quantitative risk assessment and reliable prediction of issues, along with the identification of effective preventive solutions. Accordingly, RSUP Persahabatan must establish a priority sequence for risk control interventions, specifically targeting failure modes that may lead to the three critical environmental health risks identified through FMEA. The failure modes within the medical waste handling sub-stages that form the basis for risk control are detailed as follows:

Primary Environmental Health Risk:

The most dominant potential risk across sub-stages of medical waste handling is the transmission of environmentally-based diseases to staff via pathogenic microorganisms or hazardous materials. Although this risk has the highest individual RPN (92.97) among personal exposure risks, the contamination of facilities and rooms holds the highest priority score overall (98.28). Previous studies have similarly indicated that medical waste handling poses significant risks to human health due to the presence of pathogenic microorganisms in medical waste.

Critical Failure Mode at Temporary Storage (TPS) Stage:

The storage of infectious medical waste at the hazardous waste temporary storage area (TPS limbah B3)—specifically the activities of placing and arranging waste bags—was identified as the most critical operational failure mode for facility and room contamination. Failures such as spills and pooling of waste liquids and leachate, bacterial transmission due to open or damaged medical waste packaging, and bacterial dispersion caused by air movement in the TPS were highlighted. Additionally, at the containment sub-stage, pathogen transmission was linked to waste accumulation exceeding bin capacity. Given the ease of microorganism transmission through air and surfaces at the TPS, technical interventions are urgently needed. These include repairing drainage systems for leachate and liquid waste, ensuring spills are immediately cleaned, and reinforcing packaging standards by mandating resealing or repackaging any open or damaged medical waste bags. These measures aim to reduce transmission risks to the surrounding environment.

Containment Sub-stage Policy Recommendations

For source rooms with large service capacities that generate higher volumes of medical waste, adequate numbers and sizes of waste bins must be provided to prevent overloading and its associated risks. The stages of reduction, containment, and temporary storage, which involve critical failure modes leading to pathogen transmission risks, must be given particular attention. Management at RSUP Persahabatan must recognize that this risk affects approximately 135 cleaning staff, nurses, and other healthcare workers in source rooms. Pathogenic microorganisms remain the primary hazard for environmental health risks in this context. Contaminated ambient air and surfaces pose direct risks to waste handlers and healthcare workers through skin, eye, and respiratory exposure, with potential cumulative clinical or subclinical impacts. Critical failure modes include pathogen transmission during segregation and containment of recyclable medical waste, cleaning of contaminated waste bins, handling of leaking waste bags, and transportation through patient-dense areas. Other issues include improper waste packaging, delayed incineration, and poor environmental hygiene at the TPS.

Control Measures for Critical Environmental Health Risks

Technical, managerial, and human resource capacity-strengthening approaches are required. Specific actions include tightening procedures, strict supervision, enforcing disinfection protocols, mandatory use of personal protective equipment (PPE), and conducting regular evaluations and audits of medical waste management practices, from source segregation to temporary storage, in accordance with the Ministry of Health Regulation No. 7 of 2019 on Hospital Environmental Health and Ministry of Health Regulation No. 2 of 2023 on Environmental Health.

Third Critical Environmental Health Risk

The third critical risk, based on the number of failure modes reaching critical RPN scores (95.63), is ambient air (work environment) contamination. Given the presence of microorganisms on the surface of medical waste, this risk can be seen as an extension of the contamination of facilities and rooms. Failure modes contributing to this include activities during containment, such as inserting waste into dirty bins, waste accumulation exceeding bin capacity, leakage from waste packaging, spills at the TPS, delays in incineration, and poor hygiene maintenance at the TPS.

Recommended Actions

To address these risks, RSUP Persahabatan must enhance technical procedures, management systems, and human resource capacities, applying strict supervision, disinfection protocols, PPE use, and continuous evaluation and auditing, in compliance with applicable health regulations (Ministry of Health Regulation No. 7 of 2019 and No. 2 of 2023).

CONCLUSION

Environmental health risks with a high potential to arise from failure modes during the medical waste management stage at RSUP Persahabatan, as indicated by critical Risk Priority Number (RPN) scores, include: (1) the risk of infection with environmentally-based diseases through the transmission of pathogenic microorganisms or hazardous materials across 12 failure modes of medical waste handling, (2) the risk of ambient air (work environment) contamination associated with 5 failure modes of medical waste handling, and (3) the risk of contamination of facilities and rooms serving as sources of medical waste through 4 failure modes related to the operation of incinerators during medical waste treatment. Meanwhile, environmental health risks with a high potential to arise from failure modes during the medical waste treatment stage using incinerators, as indicated by critical RPN scores, include: (1) the risk of environmental health pollution through air media across 11 failure modes of incinerator operation in medical waste treatment, (2) the risk of infection with environmentally-based diseases through the transmission of hazardous materials, pathogenic bacteria, particulates, or dust across 3 failure modes of incinerator operation, and (3) the risk of environmental health pollution through soil media across 4 failure modes of incinerator operation in medical waste treatment.

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