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RISK ANALYSIS IN THE OPERATION OF MEDICAL WASTE INCINERATORS: A LITERATURE REVIEW

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ABSTRACT

Medical waste incinerators play a critical role in reducing the volume of hazardous medical waste and eliminating infectious agents through high-temperature combustion. However, various studies show that waste incinerators also pose complex risks to workers, the environment, and surrounding communities. This literature review aims to synthesize research findings related to technical hazards, occupational health risks, environmental pollution, and operational challenges in medical waste incineration. This review analyses from ten national and international studies identified through Google Scholar using the keyword "Medical Waste Incinerator Risk Analysis." The results show that emissions generated during incineration contribute to health impacts such as respiratory problems, increased cancer risk, and exposure to toxic pollutants, including fine particles, heavy metals, dioxins, and furans. Incineration ash also contains concentrations of hazardous metals that can contaminate soil and water if not properly managed. Several studies revealed inadequate operating temperatures, poor combustion efficiency, malfunctioning gas cleaning systems, and inadequate monitoring practices, which increase pollutant formation. In addition, occupational risks are increased by limited worker training, incomplete use of personal protective equipment, unsafe work practices, and non-compliance with standard operating procedures. These findings emphasize the multidimensional nature of the risks associated with incinerators, which require comprehensive control measures, improved worker competence, and enhanced environmental monitoring. This review contributes to a clearer understanding of how risks arise at various stages of incinerator operation and highlights the importance of safer and more sustainable waste management strategies in healthcare facilities.

Keywords: Medical Waste; Incinerator; Occupational health; Risk analysis

1. INTRODUCTION

Occupational safety and health is an important issue that has gained global attention due to the increasing number of workers affected by work-related accidents and illnesses. The 2023 International Labor Organization (ILO) report notes that there are nearly three million work-related deaths each year, an increase of more than five percent compared to 2015. Most of these deaths are caused by work-related illnesses, including circulatory disorders, cancer, and

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respiratory diseases. In addition, there are approximately 395 million cases of non-fatal injuries each year, indicating that efforts to create a safe working environment remain a major challenge in various industrial and public service sectors (ILO, 2023). This data shows that occupational risks not only affect workers' health, but also productivity and the sustainability of the work system as a whole.

The national situation in Indonesia shows a similar upward trend. Based on the 2024 Single Employment Data, the number of work accidents rose from 370,747 cases in 2023 to 462,241 cases in 2024. The majority of incidents were experienced by wage workers, accounting for more than 91 percent of the total victims. This condition shows that occupational safety risks are still high, including in the health care sector, which is actually expected to be the safest place for its workers. This trend indicates that risk management in health facilities needs to be strengthened in order to protect health workers and other support workers involved in various operational processes.

One important source of risk in hospitals is medical waste management. Medical waste is classified as hazardous waste because it can cause serious dangers, such as cross-infection, exposure to toxic chemicals, and environmental pollution if not handled properly (Ernawati et al., 2025). The government has regulated medical waste management through strict regulations, including Government Regulation No. 22 of 2021 and Minister of Environment and Forestry Regulation No. 6 of 2021, which emphasize the need for safe and environmentally conscious management (KLHK, 2021). However, challenges in the field are not only related to the availability of adequate treatment technology, but also to workers' understanding of the risks, compliance with operational standards, and the readiness of supporting infrastructure.

One of the technologies widely used in the treatment of solid medical waste is incinerators. The use of incinerators is considered effective in deactivating pathogens at high temperatures and significantly reducing waste volume (Darmawan, 2024). However, this technology is not without risks that can affect workers and the environment. The process of burning medical waste can produce hazardous pollutants such as dioxins, heavy metals, fine particles, and volatile organic compounds. Repeated exposure to these pollutants has been linked to respiratory disorders, increased cancer risk, and hormonal disorders (Tait et al., 2020). On the other hand, incinerator operators may also experience physical risks such as exposure to heat, noise, and mechanical hazards.

The types of hazards faced by incinerator workers are quite extensive. In 2018, the National Safety Council (NSC) recorded various common injuries experienced by health workers, such as needle sticks, lacerations, sprains, and infections (Pinontoan et al., 2020). The Centers for Disease Control and Prevention (CDC) in 2019 also recorded approximately 385,000 cases of healthcare worker accidents per year, including injuries from contaminated sharp objects. During incinerator operation, these risks increase due to working conditions involving infectious waste, high temperatures, the need for a stable combustion system, and the possibility of emission leaks if the equipment is not properly maintained (Hardiyono et al., 2021). These circumstances indicate that incinerators are a source of risk that requires special attention through technical supervision, operator training, and the implementation of strict work procedures.

In addition to risks to humans, incinerators also have the potential to cause significant environmental impacts. Combustion ash can contain heavy metals and be corrosive, posing a danger to soil and water if not managed properly. Uncontrolled exhaust gas emissions can cause air pollution around health facilities and impact the surrounding community. Therefore,

incinerator management requires a strict monitoring system, routine maintenance, and consistent emission control policies to minimize its impact.

Given the complexity of the hazards posed, risk analysis for incinerators becomes a crucial step to ensure all potential hazards can be properly identified and controlled. Risk analysis enables healthcare facilities to understand the main sources of hazards, assess the level of risk that may arise, and determine effective control strategies. This literature review is compiled to provide a comprehensive overview of various forms of risk arising from the operation of medical waste incinerators, as well as to summarize key findings from previous studies regarding the factors causing risks and the control strategies that have been implemented. This study is expected to provide a scientific foundation for developing more effective and sustainable mitigation measures in healthcare facilities.

2. METHODS

This research employs a literature review method to map, evaluate, and synthesize scientific evidence related to risk analysis in medical waste incinerators. This approach was chosen because it is capable of providing a comprehensive understanding of various previous studies discussing hazard aspects, risks, and control measures in incineration facilities. Referring to the literature review concept according to Kitchenham & Charters (2007), this research was conducted through systematic steps of searching, selecting, evaluating, and synthesizing information to produce a valid and replicable scientific summary. The research design used is a narrative-based literature review, allowing the researcher to combine various types of studies, ranging from empirical research, risk reports, to technical guidelines relevant to medical waste incinerators.

The literature search was conducted through the online database of Google Scholar to obtain a broad scope of sources. Source selection was performed using the keyword "Risk Analysis Medical Waste Incinerator". From the initial search results, articles were selected based on title and abstract, then re-examined through full-text access to ensure their relevance to the research topic.

To make the literature selection process more focused, this research established inclusion and exclusion criteria. Inclusion criteria include journal articles or scientific reports discussing risk analysis, occupational hazards, exposure to incinerator workers, risk control systems, or occupational health and safety aspects related to medical waste processing, published between 2012 and 2024, available in full text, and written in Indonesian or English. Conversely, articles were excluded if they did not contain discussions on incinerator risks, were not available in full-text format, were opinion-based or non-scientific, or discussed waste technologies outside the context of incineration. Based on this screening process, ten scientific articles qualified as primary sources.

The literature selection process consists of three stages: identification, screening, and eligibility determination. The identification stage began with the collection of all initial search results. The screening stage was conducted by evaluating titles and abstracts to determine initial relevance. Articles that passed the screening were then read thoroughly to ensure their quality and compliance with the inclusion criteria. In the final stage, articles that met all criteria were declared eligible as analysis sources and included in the data extraction process. Each article was then analyzed using an extraction sheet containing elements such as research identity, objectives, the risk analysis method used (e.g., FMEA, HIRARC, HAZOP), types of hazards identified, dominant risk factors, and control recommendations suggested by previous researchers.

Data analysis was conducted descriptively-narratively by grouping findings based on risk analysis methods, hazard categories such as physical, chemical, biological, and ergonomic hazards, and the reported risk levels. Furthermore, a comparison between studies was made to identify common patterns, differences in findings, and research gaps that are still rarely discussed. Thematic synthesis was then used to compile a comprehensive picture of the common risks in incinerators, their causative factors, and the effectiveness of risk controls implemented in medical waste processing facilities across various studies. This approach allows for a more structured presentation of results and provides a scientific contribution to improving occupational safety standards.

This research does not involve human or animal subjects, nor primary data, thus it does not require formal ethical approval. Nevertheless, the entire writing process still adheres to scientific ethics through proper citation, selection of credible sources, and objective presentation of information. With this structured research method systematics, the study's results are expected to provide a comprehensive overview of risks in medical waste incinerators and directions for strengthening risk management in healthcare service facilities.

3. RESULTS AND DISCUSSION

The findings were obtained through a literature review process using the keyword "Risk Analysis Medical Waste Incinerator" across various scientific databases, particularly Google Scholar. The literature review encompasses national and international research on the risks of medical waste incinerators, covering technical, environmental, public health, and occupational health and safety (OHS) dimensions for operators. The review results indicate that incinerator risk issues are not only related to technology performance or emissions but are also closely linked to human factors, work behaviors, waste composition, combustion processes, and the environmental context in which the incinerator operates. The analyzed literature includes various research designs ranging from Life Cycle Assessment (LCA), cross-sectional studies, hazard identification, risk assessment, to multi-criteria analysis (MCDA). This methodological diversity allows for a comprehensive mapping of how risks arise, are classified, and are evaluated across various operational contexts of incinerators.

In addition to presenting the main results of each study, the discussion section integrates these findings to identify consistent risk patterns, methodological differences, research gaps, and implications for strengthening the OHS system in medical waste incinerators. This is important because incinerator operation is one of the highest-risk activities in healthcare facilities, given the direct exposure to high heat, hazardous gases, metal-rich ash, infectious waste, and potential exposure to hazardous chemicals. Therefore, this synthesis of findings provides a scientific basis for formulating a more comprehensive risk analysis system and addressing the shortcomings of previous research approaches.

No	Year/ Journal	Authors	Tittle	Research Method	Result
1.	2021/ *Science of The Total Environment*	Francesco Di Maria, Marina Mastrantonio, Raffaella Uccelli	The Life Cycle Approach for Assessing The Impact of Municipal solid Waste Incineration on	Life Cycle Assessment (LCA) using ILCD 2011+ for midpoint and IMPACT 2000+ for endpoint,	The incinerator generates negative impacts of approximately -0.11 kgPM2.5eq/ton for particulate matter and -2.5×10^{-3} kgSbeq/ton for resource depletion. Positive impacts were found for global warming (900 kgCO2eq/ton) and freshwater

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			The Environment and on Human Health	with secondary data from official reports and literature.	ecotoxicity (15,000 CTUe/ton). The impact on human health shows negative values, with -1×10^{-6} CTUh/ton for cancer toxicity and -2×10^{-4} DALY/ton for the human health indicator. Epidemiological studies show a correlation between incinerators and several cancer and non-cancer health outcomes; however, there are methodological limitations that prevent definitive identification of a causal relationship. Biomonitoring studies show correspondence with LCA results regarding heavy metal concentrations in blood and urine samples of exposed individuals.
2.	2023/ *Frontiers in Public Health*	Lahiru Udayanga, Loganatahan Sahana, Ayesha Perera, Koshila Ranasinghe, Tharaka Ranathunge	Knowledge, Perceptions and Practices on Healthcare Waste Management and Associated Occupational Health Hazards among Healthcare Professionals in the Colombo District, Sri Lanka: a Cross-Sectional Study	A cross-sectional survey of 407 healthcare workers using a structured questionnaire and binary logistic regression analysis.	The majority of respondents had a high level of knowledge (76.9%) and a positive attitude (53.8%) towards medical waste management. Incineration (82.6%) is the most widely used waste treatment method. The use of Personal Protective Equipment is at a satisfactory level (85.5%), but liquid waste treatment remains limited (57.5%). Significant risk factors associated with occupational health hazards include job position, training level, professional experience, tetanus vaccination status, and level of knowledge and attitude towards medical waste management. Attendants showed the highest vulnerability to waste-related hazards (OR=3.82), followed by nurses (OR=3.22) and cleaning staff (OR=2.44). Respondents without training had a very high prevalence of health impacts (OR=13.31), while those not vaccinated for tetanus showed higher vulnerability (OR=9.49).
3.	2021/ *BMC Public Health*	Salma Khalid, Najibul Haq, Zia-ul-Ain Sabiha, Abdul Latif, Muhammad Amjad Khan, Javaid Iqbal, Nowsher Yousaf	Current Practices of Waste Management in Teaching Hospitals and Presence of Incinerators in Densely Populated Areas	A descriptive cross-sectional study of 16 hospitals using questionnaires, site visits, observation; descriptive analysis plus Kruskal-Wallis	There is no significant difference in waste management practices among hospitals ($p>0.05$), but there is a statistical difference in the amount of waste per day ($p<0.017$). Government tertiary hospitals generate the most waste (900 kg/day), followed by non-tertiary hospitals (166.7 kg/day) and private hospitals (78.6 kg/day). There is no proper waste segregation from the point of generation to final disposal. Private hospitals (50%)

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				and Fisher's exact test.	performed better in terms of personnel and waste management practices. Only 9 hospitals (56.3%) have incinerator facilities; the remaining (43.7%) practice open disposal. Incinerator operational parameters are unsatisfactory and are located in densely populated areas with an average distance of 3.3 km, emitting hazardous gases. Waste handling workers do not use all required PPE except for gloves, and there are no vaccination records for protection against hepatitis A, B, and tetanus.
4.	2022 / *Journal of Environmental Management*	Jiahe Miao, Jining Li, Fenghe Wang, Xinyi Xia, Shaopo Deng, Shengtian Zhang	Characterization and Evaluation of The Leachability of Bottom Ash from A Mobile Emergency Incinerator of COVID-19 Medical Waste: A Case Study in Huoshenshan Hospital, Wuhan, China	A physicochemical analysis of bottom ash (BA) using XRF, ICP-MS/OES, IC, SEM, BET, XRD, and three standard leaching tests.	No COVID-19 virus was detected in the BA samples, indicating the incinerator is capable of completely eliminating the virus. The BA has a highly alkaline pH (>12) with a bulk density of 1.3678-1.4308 g/cm^3. High chloride content is due to increased use of chlorine-based disinfectants and physiological saline solutions. The chemical composition is dominated by Ca (53.62-62.18%), followed by SiO2 (10.45-15.35%), MgO (7.54-9.47%), and Cl (4.31-5.66%). Increased use of polypropylene products altered the chemical properties of the BA, with Ca as the main element. More than 90% of BA particles are smaller than 225.0 μm. The main metals in the leachate are Ca, Na, and K, while toxic heavy metals like Zn, Pb, Cu, and Cr are difficult to extract due to the high pH of the BA. Heavy metal content in the leachate is below the regulatory limits of GB 18598-2019; however, the BA must be disposed of in a rigid landfill because its pH exceeds the limit (7.0-12.0) for flexible landfills.
5.	2022/ *Environment, Development and Sustainability*	Adis Puška, Željko Stević, Dragan Pamučar	Evaluation and Selection of Healthcare Waste Incinerators Using Extended Sustainability Criteria and Multi-criteria Analysis Methods	Multi-Criteria Decision Analysis using FUCOM for weighting and CRADIS for ranking, plus validation with other MCDA methods.	Technical criteria are the most important (weight 0.2843), followed by economic (0.2735), environmental (0.2337), and social (0.2085). The best incinerator is A2/I8-M50, followed by A1/I8-M40, while A5/I8-M100 ranks last. The results were confirmed by six other MCDA methods (MARCOS, MABAC, SAW, WASPAS, ARAS, TOPSIS) and sensitivity analysis. The CRADIS method showed consistency with the MARCOS method in the dynamic decision matrix but differed

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					from TOPSIS and ARAS. Sensitivity analysis across 17 scenarios showed that A2 remained the best in 15 scenarios; only in 2 scenarios did A1 become the best alternative. Incinerators with smaller capacities showed lower environmental impacts due to lower fuel consumption and smaller space requirements.
6.	2012/*Journal of Community Health*	Nkonge A. Njagi, Mayabi A. Oloo, J. Kithinji, Magambo J. Kithinji	Health-Care Waste Incineration and Related Dangers to Public Health: Case Study of the Two Teaching and Referral Hospitals in Kenya	In-situ flue gas emission measurements using a flue gas analyzer and calculation of Combustion Efficiency from several burn batches.	The KNH incinerator operates at a mean stack temperature of 746°C and achieves a CE of 48.1%. The MTRH incinerator operates at a mean stack temperature of 811°C and achieves a CE of 60.8%. Both incinerators achieve a CE below Kenya's national minimum limit (99%) and the Environmental Management and Co-ordination Act standard. SO2 emissions at KNH (45.7 mg/m^3) are below the EU limit (50 mg/m^3) due to the use of ultra-low sulphur diesel, while at MTRH (159.4 mg/m^3) they exceed the limit due to the use of low sulphur diesel. NOx emissions at KNH (104.5 mg/m^3) are below the EU standard (400 mg/m^3); however, NOx at MTRH (604.8 mg/m^3) exceeds the limit. Both incinerators have the potential to release dioxins and furans because their operational temperatures are below 800°C, and they are not safe for burning cytotoxic drugs, which require a minimum of 1200°C. There is no outlet sampling in the flue for routine monitoring, no regular quality monitoring for flue gases, and CE assessment was conducted for the first time during the research even though NEMA requires it to be done periodically. The incinerators are not well-maintained, with the scrubber at KNH not functioning.
7.	2023/ *Sustainability*	Ying Li, Ruyan Zhao, Haonan Li, Wenting Song, Haoxiang Chen	Feasibility Analysis of Municipal Solid Waste Incineration for Harmless Treatment of Potentially Virulent Waste	A comparative analysis of operational parameters and CEMS data from three municipal solid waste incineration facilities during 2020–2023.	The research shows that municipal solid waste incinerators can be used for treating potentially viral municipal solid waste, with the priority order of furnace types being that grate furnace incinerators are better than fluidized bed incinerators and cement kilns. The combustion chamber temperatures for the three types of incinerators range between 860.27°C and 1170.41°C, all exceeding 850°C and far higher than the virus inactivation temperature, thus

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					effectively eliminating pathogens. Flue gas emissions from the three incineration facilities in Beijing during the pandemic showed all parameters met the established emission standards. Dioxin concentrations fluctuated between 0.00052 and 0.031 ng TEQ/m³, HCl between 1.6 and 23.742 mg/m³, CO between 0.18 and 59.15 mg/m³, heavy metals between 0.000008 and 0.855 mg/m³, and particulate matter between 0.64 and 12.13 mg/m³. Fluctuations in HCl, CO, and particulate matter emissions occurred due to changes in waste composition during the pandemic, with higher plastic and disinfectant solution content. Grate furnace incinerators showed lower flue gas pollutant concentrations compared to fluidized bed incinerators due to higher average temperatures resulting in more complete combustion. Cement kilns can achieve material temperatures of 1400-1500°C and gas temperatures of 1700-1800°C. This research verifies the feasibility of using municipal solid waste incinerators to treat potentially viral municipal solid waste during a major pandemic while still meeting safe flue gas emission standards.
8.	2024/ *Journal of Physics: Conference Series*	Nabaa Qassim Kadhem, Itab F. Hussein, Basim A. Hussain	Health and Environmental Risk Assessment of Heavy Metals Contamination from Medical Wastes Ash of Baghdad Hospitals	Measurement of metal elements in ash using XRF and quantitative health risk assessment through Contamination Factor, Metal Pollution Index, Hazard Index, and Cancer Risk Index across three exposure pathways.	The research found over 20 heavy metal elements in medical waste ash, with 8 metals having high concentrations: Zn, Pb, As, Co, Cu, Ni, Cr, and Hg. Contamination Factor values indicate very high pollution levels for As, Cd, Hg, Zn, Pb, and Cu, while Co and Ni show moderate values. The Hazard Index for adults at Imam Ali Central Hospital is 1.040, exceeding the safe limit and indicating a high health risk, while the other two hospitals, Sheikh Zayed and Dhari Al Fayyad, recorded values below 1, indicating no health risk. The highest exposure pathway is through ingestion with a value of 0.857, followed by dermal contact at 0.182, and inhalation at 0.0007. For cancer risk, all values fall within the acceptable range between 10^{-4} and 10^{-6} and are generally less than 10^{-6}. The incinerator temperature reaches over 850°C with a residence time of 1

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					to 1.5 hours, which is effective in deactivating viruses and pathogens. The Metal Pollution Index shows high values, indicating that medical waste ash contains a high percentage of heavy metals and thus has the potential to cause health damage and soil pollution if not managed properly.
9.	,2024/ *PREPOTIF: Jurnal Kesehatan Masyarakat*	Roosdiana Irawati, Tri Joko, Mursid Raharjo	Analisis Risiko Pengelolaan Limbah Medis di RSUPN Dr. Cipto Mangunkusumo dengan Metode LCA (Life Cycle Assessment)	LCA based on ISO 14040 using SimaPro 9.3 with IMPACT 2002+, field data, and institutional documents.	The research shows that onsite waste treatment using a hospital incinerator has the most significant impact across all studied environmental impact categories. For the human health category, the incinerator contributes an impact of 2.66E-8 DALY, representing the number of years lost due to health disorders, disabilities, and premature death. For the ecosystem quality category, the impact is 0.0019 $PDFm^2yr$, indicating the extent of species or ecosystem damage on the surface over one year. The climate change category yields an impact of 0.0618 $kgCO_2eq$, while the resources category is 1.784E4 MJ Primary, which is the amount of primary energy for resource extraction, primarily natural gas as fuel. Waste recycling management contributes an impact of 6.7E-17 DALY for human health and 5.33E-9 $PDFm^2yr$ for ecosystem quality, which is far lower compared to the incinerator. Normalization analysis results show the highest impact occurs in the resources aspect with a value of 0.117, followed by climate change at 6.24E-6, human health at 3.75E-6, and ecosystem quality at 2.14E-8. Single score analysis confirms that the resources category has the highest risk due to the use of non-renewable natural gas energy, with a value of 117 mPt. The average medical waste generation is 37.013 kg per month, requiring 1.530 kg of plastic bags and 324 kg of safety boxes per month. From the total waste, 11.377 kg per month is treated in the incinerator, producing 2.756 kg of residue and 216 m^3 of liquid waste per month. Incinerator emissions include particulate matter at 1 mg/Nm^3, SO_2 at 5 mg/Nm^3, NO_2 at 290 mg/Nm^3, CO at 97 mg/Nm^3, HCl

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					at 0.12 mg/Nm³, CO_2 at 61.654 mg/Nm³, and heavy metals such as As, Cd, Cr, Pb, Hg, Ti in small amounts. Recyclable waste of 469 kg per month requires 60 liters of chemicals and 16 m³ of fresh water, producing 12.8 m³ of liquid waste. Incinerator operation is not continuous due to a lack of operators, resulting in high fuel consumption to raise the combustion chamber temperature. Proper waste segregation and optimization of recycling can reduce the impact of onsite waste treatment using incinerators.
10.	2023/*Jambura Health and Sport Journal*	Sylva Flora Ninta Tarigan, Ramly Abudi, Jelita Agustina Malahika	Identifikasi Risiko Keselamatan dan Kesehatan Kerja pada Pengoperasian Incinerator	A descriptive mixed method with observation, interviews, and PHA for hazard identification; fishbone for root cause analysis; risk assessment with a probability and impact matrix.	Five hazard categories were identified: mechanical (5 sources of sharps waste hazards, 6 conditions of slippery floors, 4 instances of PPE usage, 2 cases of overloaded storage, 6 worker postures), electrical (5 sources of hazards from electrically-powered machines, 7 locations of panel boxes), biological (3 sources of microorganism hazards), chemical (3 sources of hazardous ash/smoke, 1 source of toxic chemical waste, 2 sources of explosive waste), and ergonomic (2 sources of repetitive motion, 4 non-ergonomic work postures). The risk assessment resulted in 1 moderate-high risk category, namely minor/severe injury due to not using complete PPE, and 60 low-moderately low risk categories. Fishbone analysis identified 31 root causes of problems from 4 perspectives (manpower, material, method, environment), with the main causes being workers not following SOPs and having insufficient knowledge. Control recommendations include 10 administrative actions such as daily CMC (Counseling, Monitoring, Coaching), PPE checklist sheets, hourly patrol checks, discussion forums/seminars, periodic health examinations, and the installation of OHS signs.
11.	2021/ *Identifikasi: Jurnal Keselamatan, Kesehatan Kerja dan*	Hardiyono, Andri Indra Kelana, Syamsul Arifin	Analisis Risiko pada Incinerator Pengolahan Limbah Medis PT. Pengelola	HAZOP on 8 main equipment nodes based on PFD and P&ID; risk assessment using	Node 1 (Chamber 1) identified 6 critical deviations (No Flow, High Flow, Reverse Flow, High/Low Temperature, Wrong Concentration) with 10 causes and 11 consequences. Node 2 (Chamber 2) identified 5

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	Lindungan Lingkungan		Limbah Kutai Kartanegara, Samboja – Kalimantan Timur	probability and consequence scales from interview data and documents.	deviations with 9 causes and 16 consequences. Node 3 (Heat Exchanger) identified 5 deviations with 4 causes and 5 consequences. Node 4 (Water Scrubber) identified 3 deviations with 3 causes and 4 consequences. Node 5 (Cyclone) identified 3 deviations with 3 causes and 4 consequences. Node 6 (Induce Draft Fan) identified 3 deviations with 3 causes and 5 consequences. Node 7 (Sampling Point) identified 3 deviations with 3 causes and 5 consequences. Node 8 (Exhaust Stack) identified 2 deviations with 2 causes and 2 consequences. All process hazards (No Flow, High Flow, Reverse Flow, High/Low Temperature, Wrong Concentration) fall into the high-risk category, requiring management follow-up. Recommendations include SOP socialization, PLC calibration, a routine inspection schedule for the Induce Draft Fan, provision of MSDS for waste, intensive supervisor monitoring, and Pre-Inspection activity.

The results of the literature review show that risk analysis for medical waste incinerators is a multidimensional issue involving technical, environmental, and occupational safety aspects. From the various international and national studies reviewed, it is evident that incinerators do not only function as waste treatment tools but also become a potential source of hazards for operators, surrounding communities, and the environment. The research by Di Maria et al. (2021) clearly illustrates that the incineration process impacts human health by contributing to cancer and non-cancer toxicity, where epidemiological studies found a correlation between incinerator exposure and specific health disorders, although a definitive causal relationship cannot be established. This finding is reinforced by biomonitoring results showing increased heavy metal content in the blood and urine of individuals exposed to incinerators, indicating that health risks are not limited to air pollution but also include internal exposure to hazardous materials.

Apart from emission risks, combustion residues such as bottom ash and fly ash also represent a significant source of hazard. The research by Miao et al. (2022) shows that incinerator ash has a highly alkaline pH, high chloride content, and a metal-rich chemical composition, making it prone to soil and water contamination if not handled properly. Meanwhile, the research by Kadhem et al. (2024) indicates that medical waste ash contains over 20 types of heavy metals with very high pollution levels for elements such as As, Cd, Zn, Pb, and Hg, where the Hazard Index for one hospital exceeds the safe limit (HI = 1.040), thus indicating a real health risk to humans through ingestion, inhalation, and dermal contact routes. This finding confirms that incinerator risks do not cease at the combustion process but extend to the residue handling stage, which is often overlooked in medical waste management practices.

Technical risks also form a crucial aspect in incinerator operation. The research by Njagi et al. (2012) in Kenya found that two major hospital incinerators did not meet combustion efficiency standards as they operated below optimal temperatures, resulting in NOx and SO_2 emissions exceeding international standards, and even having the potential to produce dioxins and furans due to combustion temperatures below 800°C. This operational instability increases the likelihood of acute and chronic exposure to hazardous pollutants. In line with this, the research by Hardiyono et al. (2021) using the HAZOP method found various critical process deviations in nodes such as the rotary kiln, cyclone, water scrubber, and exhaust stack. All these deviations fall into the high-risk category and have the potential to cause operational failures, toxic gas leaks, and even explosion risks if routine maintenance and calibration are not performed continuously. This indicates that incinerators require strict technical supervision and optimally functioning automatic control systems to maintain combustion process stability.

On the other hand, findings regarding occupational safety aspects show that incinerator operators are in the highest-risk group. The research by Udayanga et al. (2023) shows that workers without training have up to 13 times higher risk of hazard exposure, while cleaning staff and nurses are the most vulnerable groups to medical waste-related hazards in healthcare facilities. In Indonesia, the research by Tarigan et al. (2023) dentified five main hazard categories in incinerator operation: mechanical, electrical, biological, chemical, and ergonomic. The dominant causative factors stem from non-compliance with SOPs, incomplete use of PPE, and a lack of operator knowledge regarding incinerator hazards. Even one moderate-high risk was found related to injury due to incomplete PPE, indicating weaknesses in administrative controls in the field. Thus, operator safety risk is not merely a technical issue of the equipment but also involves work behavior and OHS management at healthcare facilities.

Systemic weaknesses in medical waste management were also found in various studies. For example, the study by Khalid et al. (2021) shows that over 40% of hospitals do not have incinerators and still practice open dumping, while the available incinerators are located close to densely populated residential areas and have inadequate operational parameters. Waste handling workers also do not use complete PPE and lack routine vaccination records, further increasing the risk of exposure to infections and toxic materials. Meanwhile, the research by Irawati et al. (2024) using LCA at RSUPN Cipto Mangunkusumo shows that the incineration stage contributes the largest environmental impact compared to all other waste management stages, especially in the human health and resources categories, due to the use of natural gas and emissions of heavy metals, particulate matter, and other hazardous gases.

When reflected upon comprehensively, the findings from these various studies show a consistent risk pattern: that incinerators have three main layers of risk: combustion risk (hazardous gas emissions and toxic pollutant formation), residue risk (ash containing heavy metals and corrosive properties), and risk to operators (direct exposure during operational processes). These three layers of risk are closely interconnected, where failure in one aspect can increase the risk level in the others. However, most previous studies have only focused their analysis on one of these aspects separately. No research has integrated an analysis of technical processes, residues, and operator safety comprehensively. Furthermore, most studies on OHS only highlight PPE usage and work behavior without linking operator risk to incinerator technical deviations and the quality of emissions or residues.

4. CONCLUSION

This literature review shows that medical waste incinerators, while playing a crucial role in reducing waste volume and deactivating pathogens, present various interconnected risks affecting operators, surrounding communities, and the environment. The review results indicate that the combustion process generates hazardous emissions such as fine particles, heavy metals, dioxins, and toxic gases, which have the potential to cause both short-term and long-term health impacts. Several studies also confirm that combustion residues in the form of bottom ash and fly ash contain high concentrations of heavy metals and are corrosive, potentially contaminating soil and water if not managed properly. Furthermore, various studies find that many incinerators operate below optimal temperature standards, have low combustion efficiency, and suffer from technical weaknesses in emission control systems, ventilation, and routine maintenance, which ultimately increase pollution risks. From the occupational safety perspective, incinerator operators are the group most vulnerable to hazard exposure. Non-compliance with procedures, incomplete use of Personal Protective Equipment (PPE), minimal training, and low awareness of risks are the dominant factors that exacerbate the level of hazard. Research also indicates the existence of systemic risks due to a lack of facilities, the absence of routine emission monitoring, and the location of incinerators in close proximity to densely populated settlements. Therefore, the risks arising from incinerators are not merely technical machine issues but represent an interaction between technological, human, and environmental factors. Based on the overall analysis, it can be concluded that incinerator operation requires a comprehensive risk management approach. Efforts that need to be strengthened include meeting combustion operational standards, enhancing flue gas purification systems, conducting periodic environmental monitoring, consistent facility maintenance, and providing adequate operator training to improve compliance with safety procedures. This strategy is essential to minimize potential hazards and ensure that incinerators can be used safely and sustainably. These findings provide a scientific basis for developing safer medical waste management policies and practices and serve as a reference for healthcare facilities in strengthening their Occupational Health and Safety (OHS) systems and environmental protection in the incineration process.

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