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QUANTITATIVE HEALTH RISK ASSESSMENT OF ICU MICROBIAL AEROSOL POLLUTION

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Abstract: Indoor air quality in hospital intensive care units (ICUs) is crucial to the health and safety of patients and medical staff. Aerosolized bacteria are a significant contributor to nosocomial infections, highlighting the need for continuous environmental monitoring. This study conducted a Quantitative Microbial Risk Assessment to evaluate the health risks associated with inhalation exposure to airborne bacteria in the ICU of RSUP Dr. Wahidin Sudirohusodo. Using a cross-sectional observational design, aerosol air samples were collected three times daily across three weekly intervals at three designated ICU locations. Forty-eight ICU nurses participated as respondents. Revealed that bacterial concentrations at several sampling points exceeded established safety standards. Pearson correlation analysis showed that humidity significantly influenced bacterial aerosol concentrations ($p = 0.000$), with higher humidity correlating with increased bacterial presence. QMRA findings indicated that at point 1, 95.8% of respondents had a Hazard Quotient (HQ) > 1, suggesting potential health risk, while 100% at points 2, 3, and 4 were similarly at risk. These results underscore the need for improved infection control and environmental management practices within ICU settings to reduce microbial aerosol exposure and protect healthcare workers and patients.
Keywords: Quantitative Microbial Risk Assessment (QMRA); Intensive Care Unit (ICU); Indoor Air Quality; Health Risk Assessment; Aerosolised Bacteria

INTRODUCTION

The Intensive Care Unit (ICU) is a hospital area with a very high level of patient vulnerability to nosocomial infections. Patients in the ICU generally experience a decrease in the immune system so that they are very susceptible to opportunistic pathogens. One significant source of exposure in the ICU is the presence of microorganisms in the form of bioaerosols (Rochfika et al., 2024). These bioaerosols can be spread through various sources, such as ventilation systems, patient care activities, and interactions with medical staff. Although infection control has been strictly implemented, the presence of bioaerosols remains a difficult challenge to overcome (Huang et al., 2025).

Bioaerosols consist of biological particles such as bacteria, viruses, fungi, and other microbial fragments that can be dispersed in the air. In the ICU environment, bioaerosols can survive for quite a long time and reach dangerous concentrations. Some pathogens that are often found in the ICU include Staphylococcus aureus, Pseudomonas aeruginosa, and Acinetobacter baumannii (Tangestani et al., 2025). These pathogens not only cause local infections but can also trigger sepsis, leading to multiorgan failure. Quantitative evaluation is needed to identify the extent of the health risk posed by exposure to these bioaerosols (Liu et al., 2025).

Quantitative Health Risk Assessment (QHRA) is a systematic approach that combines exposure data with toxicity data to estimate the level of health risk. The application of QHRA to ICU bioaerosols allows the identification of

specific risks based on the concentration of microbes detected (Paddy et al., 2025). The QHRA process includes four main stages: hazard identification, dose-response assessment, exposure assessment, and risk characterization. This methodology provides a comprehensive picture of the potential health impacts that may arise. In addition, QHRA is also able to accommodate data uncertainty through a probabilistic approach (Wei et al., 2024).
The main sources of bioaerosols in the ICU include patients, medical equipment, HVAC (Heating, Ventilation, and Air Conditioning) systems, and daily activities of medical staff. Every activity such as dressing changes, intubation procedures, and room cleaning has the potential to produce microbial aerosols (Rahayu et al., 2019). The closed ICU environment and often limited ventilation increase the accumulation of bioaerosols. Humidity, temperature, and airflow factors also affect the persistence of microorganisms in the air. Therefore, bioaerosol management requires a thorough understanding of the sources and dynamics of its spread (Praptiwi et al., 2021).
Several previous studies have identified a correlation between bioaerosol concentrations and the incidence of nosocomial infections in the ICU. These studies emphasize the importance of routine monitoring of air quality in order to minimize health risks (Astawa et al., 2024). However, many of them are only qualitative and have not integrated a holistic quantitative approach. In addition, differences in sampling methodology, microbial detection, and data analysis often make it difficult to generalize the results. Therefore, a standardized QHRA approach based on local data is needed to produce accurate risk estimates (Parobe, 2019).
Bioaerosol detection and quantification are generally carried out through culture techniques, PCR, and other molecular methods. Each method has advantages and limitations, both in terms of sensitivity and specificity. Conventional culture often cannot detect microbes that are in VBNC (Viable But Non-Culturable) conditions. Meanwhile, PCR techniques can identify microbial DNA but do not always describe its viability. In addition to microbial factors, individual patient factors also play a role in determining the level of health risk (Zulfa et al., 2022). Patients with comorbidities, elderly age, or immunocompromised have a much higher vulnerability. Therefore, in QHRA, risk stratification needs to be carried out based on patient characteristics. This stratification allows the development of more specific and effective interventions. For example, strengthening protection in high-risk patient groups can significantly reduce the incidence of infection (Pala'langan et al., 2023).
Bioaerosol control in the ICU has so far relied on standard protocols such as the use of HEPA filters, negative pressure ventilation, and strict hygiene protocols. Although effective, implementation in the field often faces technical and financial obstacles. In addition, the absence of quantitative risk data makes the effectiveness of interventions difficult to measure objectively. With the results of the QHRA, hospital managers can evaluate intervention priorities more rationally (Apriyani et al., 2020).
In addition to the impact on patients, exposure to bioaerosols also poses a risk to health workers working in the ICU. Medical staff exposed to antibiotic-resistant microbes have the potential to become carriers which then expands the spread of infection (Djasfar & Pradika, 2023). The development of antimicrobial resistance adds to the complexity of managing bioaerosol-related infections in the ICU. Resistant microorganisms such as MRSA, VRE, and CRE are often difficult to overcome even though optimal treatment protocols have been implemented. The spread of resistant strains through the air increases the risk of outbreaks in the ICU environment (Sivagnanasundaram et al., 2019).
Implementation of QHRA requires the availability of accurate and representative local data. Geographical variations, hospital characteristics, and medical staff behavior can affect the bioaerosol profile in each ICU. Therefore, research results in one location cannot necessarily be generalized universally. Based on the description above, the research on Quantitative Health Risk Assessment of ICU Microbial Aerosol Pollution is very relevant and urgent. This research aims to fill the gap in quantitative data related to health risks due to bioaerosols in the ICU (Berliana & Tanamaah, 2021). With a comprehensive approach including bioaerosol sampling, microbial identification, dose-response models, and probabilistic simulations, it is expected to obtain an accurate picture of the risk. The results of the research will be the scientific basis for developing risk-based infection control policies. In addition, the results are expected to improve safety standards for patients and health workers in the ICU.

MATERIALS AND METHODS

Type of Research

The type of research used in this study is observational, with a cross-sectional study design and the QMRA risk assessment model. This study involves the simultaneous observation and measurement of variables on subjects whose environmental samples take Aerosol air in the intensive care unit (ICU) room at RSUP. Dr Wahidin Sudirohusodo was measured at three locations, three times a day. This research process begins with interviews with respondents related to factors that influence the calculation of QMRA, and then anthropometric measurements are taken. Furthermore, air sampling was carried out at a predetermined point, which then calculated the large number of aerosol bacteria. It was then carried out to identify bacteria and fungi and determine the types of bacteria and fungi found at the research location. After all the data is found, the next step is calculating QMRA and determining risk management.

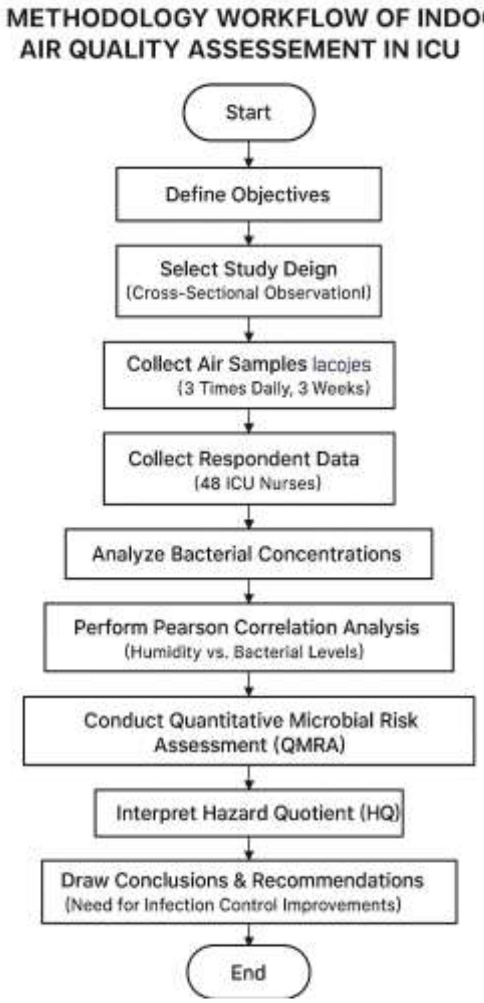

Figure 1. Flowchart of the research

Population and sampling technique

This study was conducted in the intensive care unit (ICU) at RSUP. Dr Wahidin Sudirohusodo. This study consists of two types of samples: environmental and human. The number of environmental samples is as many as three air sampling points, carried out as many as three measurements per day, carried out on three different days, so the number of air samples in this study is nine at each point. This study's human sample consisted of all health workers on duty in the intensive care unit (ICU) at RSUP: Dr Wahidin Sudirohusodo, namely 48 respondents.

Research Instrument

Corresponding Authors are responsible for identifying and declaring all funding sources received for the research submitted to the journal. During submission, Corresponding Authors will also be asked to provide the Funder, Award Number and Grant Recipient. If there are no funders to be identified the corresponding author must state "Funding information is not available." Funding information will be entered during the submission stage and will be included in the final publication. In this study, an interview and questionnaire filling stage was carried out to obtain data on the characteristics of respondents, average daily inhalation dose (frequency of exposure, exposure time), body weight, and identification data such as name, age, and gender.

Quantitative Microbial Risk Assessment (QMRA)

$$ADD_{inh}\ [CFU/(kg/day)] = \frac{C \times IR \times EF \times ET}{BW \times AT}$$

Notes :

ADD inh	=	Average Daily Dose (CFU/kg/day)
C	=	Concentration at exposure point (CFU/m^3)
IR	=	Inhalation rate (m^3/day)
EF	=	Exposure Frequency (day/year)
ET	=	Exposure Time (year)
BW	=	Body Weight (kg)
AT	=	Averaging Time

$$\mathbf{HQ} = \frac{\mathbf{ADD}}{\mathbf{RfD}}$$

Notes :

HQ	=	Risk magnitude of non-carsinogenic agents
ADD	=	Average exposure dose through the respiratory system (CFU/kg/day)
RfD	=	Reference dose (CFU/m^3) (5000 CFU/m^3)

After characterising the risk, which is said to be safe if RQ < 1, indicating there is no possibility of adverse effects, all conditions are maintained so that the RQ value < 1. The risk level is said to be unsafe if RQ ≥ 1, indicating the possibility of adverse effects (Apriyani et al., 2020). If a risk level with an unsafe category is found, risk management is carried out, including determining safe concentrations.

RESULTS

Table 1. Total Bioaerosol (Bacteria and Fungi) intensive room at RSUP. Dr Wahidin Sudirohusodo Makassar Year 2024

Point	**Pick-up time**		**Mushroom count (cfu)**	**Bacteria count (cfu)**	**Total bioaerosol (cfu/m^3)**	**Indonesian Minister of Health No.1204/Menkes/SK/X/2004, Standard 0-200)**
Point 1	Sunday	09.00	23	420	443	Not qualified
		15.00	18	296	314	Not qualified
		20.00	17	308	325	Not qualified
	Monday	09.00	35	672	707	Not qualified
		15.00	19	332	351	Not qualified
		20.00	27	368	395	Not qualified
	Thursday	09.00	20	904	924	Not qualified
		15.00	18	928	946	Not qualified
		20.00	21	2744	2765	Not qualified
Point 2	Sunday	09.00	51	872	923	Not qualified
		15.00	24	600	624	Not qualified
		20.00	24	412	436	Not qualified
	Monday	09.00	48	808	856	Not qualified
		15.00	27	660	687	Not qualified
		20.00	36	864	900	Not qualified
	Thursday	09.00	33	1352	1385	Not qualified
		15.00	28	1388	1416	Not qualified
		20.00	47	7540	7587	Not qualified
Point 3	Sunday	09.00	46	928	974	Not qualified
		15.00	22	524	546	Not qualified
		20.00	21	368	389	Not qualified
	Monday	09.00	42	1076	1118	Not qualified
		15.00	21	652	673	Not qualified
		20.00	31	624	655	Not qualified
	Thursday	09.00	42	1640	1682	Not qualified
		15.00	38	1188	1226	Not qualified
		20.00	35	7540	7575	Not qualified
Point 4	Sunday	09.00	42	808	850	Not qualified
		15.00	24	968	992	Not qualified
		20.00	29	388	417	Not qualified
	Monday	09.00	48	928	976	Not qualified
		15.00	23	984	1007	Not qualified
		20.00	22	688	710	Not qualified
	Thursday	09.00	36	2292	2328	Not qualified
		15.00	54	1352	1406	Not qualified
		20.00	24	7540	7564	Not qualified

Source: Primary data, 2024

Based on the measurement results listed in Table 1, it is known that the total bioaerosol consisting of bacteria and fungi at all measurement points (Point 1 to Point 4) showed consistent values exceeding the threshold set by the Decree of the Minister of Health No. 1204/Menkes/SK/X/2004, which is a maximum of 200 cfu/m³. The highest total bioaerosol concentration was found on Thursday at 20.00 at several points, with extreme values reaching more than 7500 cfu/m³, especially at Points 2, 3, and 4. This indicates the potential for serious health risks for patients and health workers due to high exposure to microorganisms in the air.

Table 2. Results of Examination of Environmental Samples (Temperature) in the Intensive Room at RSUP. Dr Wahidin Sudirohusodo Makassar

No.	Point of sample	Indoor Temperatue (^{0}C)	Description (Permenkes RI Number 7 of 2019, standard 22 ^{0}C - 23 ^{0}C)
1.	1	22,8	Meets the requirements
2.	2	22,2	Meets the requirements
3.	3	21,9	Meets the requirements
4.	4	22,12	Meets the requirements
	Average	**22,25**	**Meets the requirements**

Room temperature measurements, as shown in Table 2, show that all measurement points have temperatures within the standard range set by the Indonesian Minister of Health Regulation No. 7 of 2019, namely 22°C - 23°C. The recorded temperature values ranged from 21.9°C to 22.8°C. Thus, room temperature is not a contributing factor to the high concentration of bioaerosols found in this study.

Table 3. Results of Environmental Sample Testing (Humidity) in the Intensive Room at RSUP. Dr Wahidin Sudirohusodo Makassar

No.	Point of sample	Indoor Humidity (%)	Description (Permenkes RI Number 7 of 2019, standard 40% - 60%)
1.	1	67,89	Not qualified
2.	2	68,33	Not qualified
3.	3	71,44	Not qualified
4.	4	72	Not qualified
	Average	67,6	Not qualified

Source: Primary data, 2024

Table 3 shows that all humidity measurement points exceed the specified standard (40%-60%), with humidity values ranging from 67.89% to 72%. This high humidity is thought to be one of the factors that facilitates the growth and proliferation of microorganisms in the air, considering that humid conditions are an ideal environment for the growth of bacteria and fungi.

Table 4. Results of Pearson Correlation Tests on the Effect of Temperature and Humidity Parameters on Bioaerosols in the Intensive Room at RSUP. Dr Wahidin Sudirohusodo Makassar

Parameter		r-value	p-value
Temperature		0,666	0,592
Humidity		0,092	0,000

Source: Primary data, 2024

Based on Table 4, the analysis results show that there is no statistically significant relationship between temperature and bioaerosol concentration ($r = 0.666$; $p = 0.592$). On the other hand, there is a statistically significant relationship between humidity and bioaerosol concentration ($r = 0.092$; $p = 0.000$), although the strength of the correlation is very weak. This finding strengthens the suspicion that high humidity plays an important role as a risk factor for increasing bioaerosol contamination in intensive care rooms.

Risk Assesment

Hazard Identification

Hazard identification is the first step in the environmental health risk analysis (EHRA) process, which is conducted to identify the types and properties of agents that can cause adverse effects on organisms, systems, or (sub) populations (Djasfar & Pradika, 2023). The types of risk agents in this study are microorganism aerosol pollution, consisting of bacteria and fungi found in intensive care rooms at Dr. Wahidin Sudirohusodo General Hospital in Makassar, as presented in Table 3.

Exposure Assessment

ADD_{inh} (Average Daily Dose Inhalation) is part of exposure, defined as the average daily dose over a lifetime that can be estimated individually for exposure through inhalation. The unit of ADDinh is CFU/kg/day. The ADDinh studied is the average daily inhalation dose from indoor aerosols in the intensive care unit at Dr. Wahidin Sudirohusodo General Hospital in Makassar, which poses a risk to individuals in the room, particularly healthcare workers exposed to aerosols. The exposure dose (intake) can be calculated using the following equation:

$$ADD_{inh}[CFU/(kg.day)] = \frac{C \times IR \times EF \times ET}{BW \times AT}$$

Table 5 Minimum, Maximum, and Mean Values of ADDinh Respondents for Exposure to Total Aerosol Bacteria in the Intensive Care Unit at Dr. Wahidin Sudirohusodo Hospital, Makassar

Point	Concentration (CFU/m^3)			ADD inh		
	Min	Max	Mean	Min	Max	Mean
1	314	2765	796.67	3.13	66.39	25.70
2	436	7587	1646	6.47	137.18	53.10
3	389	7557	1648.67	6.48	137.40	53.18
4	417	7564	1805.56	7.09	150.47	58.25

Source: Primary data, 2024

Based on Table 5 in the ADDinh calculation related to total aerosol bacteria conducted on 48 respondents at four points in the intensive care unit at Dr. Wahidin Sudirohusodo General Hospital in Makassar, the highest average ADDinh value was found at point 4, which was 58.25, and the lowest was at point 1, which was 25.70.

Dose Respons

Dose-response analysis is aimed at estimating whether a risk agent has the potential to cause adverse health effects in a population at risk. In estimating infections caused by exposure to risk agents . In QMRA, the most crucial part is the appropriate dose-response model for estimating infections caused by exposure to risk agents. Exposure to infectious agents can be calculated using the following Beta-Poisson equation:

$Pt(d) = 1 – (1+ d/\eta)-r$

Dose calculation via the inhalation route must consider factors such as inhalation rate (IR), exposure time (t), and airborne pathogen concentration. The inhalation dose can be calculated as follows:

Table 6. Probability of Total Airborne Aerosol Infection in the Intensive Care Unit at Dr. Wahidin Sudirohusodo Hospital, Makassar, 2024

Point	**P_{inf} Aerosol Total**		
	Min	**Max**	**Mean**
1	0.864	0.9999	0.990
2	0.961	0.9999	0.997
3	0.961	0.99999	0.997
4	0.968	0.99999	0.998

Source: Primary data, 2024

Based on the results of the dose-response analysis in Table 6 conducted on the total number of aerosol bacteria (bacteria and fungi) through inhalation at each research point in the intensive care unit of Dr. Wahidin Sudirohusodo General Hospital in Makassar, the highest mean infection probability was found at point 4, which was 0.998, and the lowest was at point 1, which was 0.990.

Risk Characteristics

Risk characteristics are expressed using the Hazard Quotient (HQ) for non-carcinogenic effects. The QMRA approach at this stage determines whether the risk agent (microbes) will cause harm to healthcare workers in the intensive care unit at Dr. Wahidin Sudirohusodo General Hospital in Makassar. Risk characteristics are the final stage of risk assessment. Risk characteristics are efforts to determine whether the exposed population is at risk from risk agents entering the body. The level of health risk from exposure to microorganisms is categorised as a non-carcinogenic health risk using the following equation:

$$HQ = \frac{ADD}{RfD}$$

The distribution of bioaerosol (airborne bacteria) exposure risk in the intensive care unit of Dr. Wahidin Sudirohusodo General Hospital in Makassar is as follows:

Table 7. Distribution of Respondents' Risk to Total Aerosols (Bacteria and Fungi) in the Intensive Care Unit of Dr. Wahidin Sudirohusodo Hospital in Makassar

Hazard Quetient	Point 1		Point 2		Point 3		Point 4	
	n	%	n	%	n	%	n	%
≥1	46	95.8	48	100	48	100	48	100
<1	2	4.2	0	0	0	0	0	0

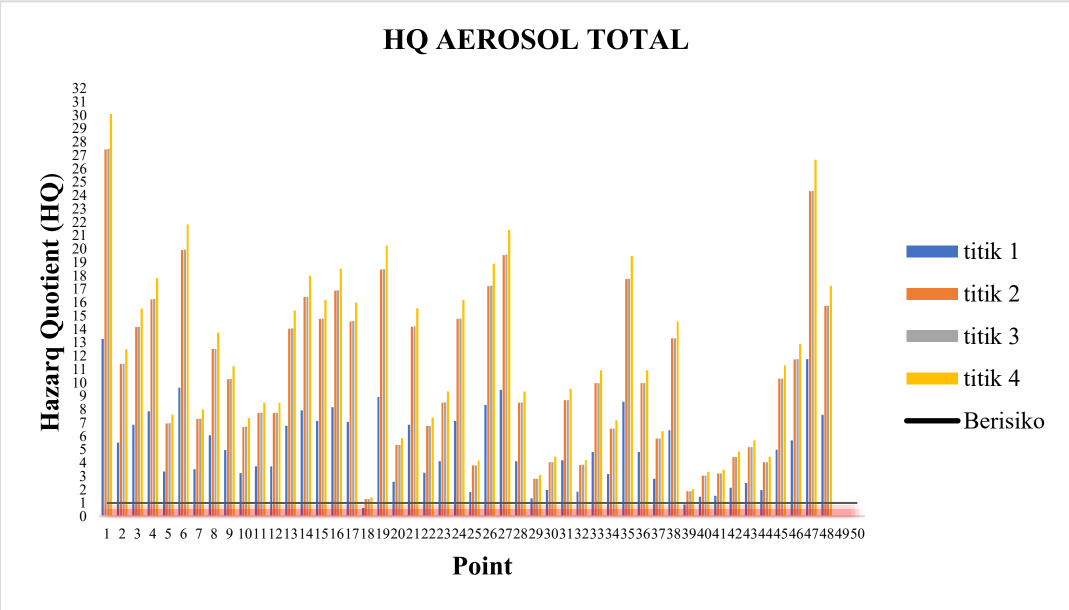

Figure 2. Hazard Quotient (HQ) Aerosol Total

Figure 2 shows the distribution of risk of exposure to total aerosol bacteria (bacteria and fungi) in the intensive care unit of RSUP. Dr. Wahidin Sudirohusodo Makassar at point 1, 46 respondents (95.8%) had HQ > 1, indicating that these 46 respondents were at risk of exposure to total bacteria at that point. HQ < 1 was found in 2 respondents (4. At points 2, 3, and 4, the HQ results from the 48 respondents were the same, with 100% having HQ > 1, indicating that all respondents at those points were at risk of health effects from exposure to bacterial aerosols at each respective point.

Risk Management

Determining safe concentrations is one of the risk management measures when exposure patterns and times cannot be changed. The results of the calculation to determine the safe concentration of microbial aerosol exposure risk agents are as follows:

$$C_{aman} = \frac{RfD \times Wb \times tavg}{R \times tE \times fE \times Dt}$$

$$C_{aman} = \frac{5 \times 55 \times 10950}{0.83 \times 8 \times 295 \times 30}$$

$$C_{aman} = \frac{3011250}{58764}$$

$$C_{aman} = 51.24 \text{ CFU/m}^3$$

Based on the results of the safe concentration calculations, the recommended safe concentration limit in this study is 51.24 CFU/m^3.

DISCUSSION

Conccentrate Total Bioaerosol

Bioaerosols are dust particles that consist of living organisms (bacteria and fungi) (Mahmood Ajaj et al., 2023). Fungi and bacteria are microorganisms that can pollute the air. Fungi are one of the microorganisms that can cause air pollutants and are often poorly understood by most people. Fungi are found in all places; their spores are found in dust, air, surfaces, and water, which can cause human disease (Datau et al., 2020). The quality of microorganisms in the air describes the environmental health conditions of hospital facilities. It is considered to have pathogenicity that can cause human infections, such as hospital-associated infections (HAIs) (Ashuro et al., 2022). Microorganisms in the room are spore-shaped organisms carried by air through air vents or by humans going in and out of the room. Bioaerosols are mobile because they have a tiny size and light weight, so that they can be easily carried and spread to the environment by air (Kim et al., 2018).

In this study, bioaerosol measurements were carried out in the intensive care unit at RSUP. Dr Wahidin Sudirohusodo Makassar. The results of indoor bioaerosol measurements in Table 1 can be concluded from the results of sampling conducted at four research points carried out for three consecutive days, where three studies were carried out at each point each day. The results of these measurements show that all measurements show results that do not meet the requirements based on the Decree of the Minister of Health of the Republic of Indonesia Number 1204 / MENKES / SK / X / 2004 concerning ‘Hospital Environmental Health Requirements’, where the total number of bioaerosols in the air for the required intensive care room is 0-200 CFU / m^3.

This research is in line with research conducted by (U.P et al., 2019), which showed that in his study, the results of the average air germ number in the inpatient room of RST Wijayakusuma Purwokerto are for class I 2,833.33 CFU/m3, class II 2,150 CFU/m3, and class III 29,000 CFU/m3. In contrast, the average air germ number as a whole class I, II, and III RST Wijayakusuma Purwokerto is 7871.43 CFU/m3, which shows these results do not meet the requirements. A thorough monitoring program carried out by another study by (Mirhoseini et al., 2017) revealed notable variation in airborne bacterial counts throughout several wards, including the intensive care unit, with a reported range of 1 to 423 CFU/m^3.

In recent years, investigations into microbial contamination in indoor environments, particularly in hospital settings such as intensive care units (ICUS), have gained increasing relevance due to their implications for patient safety and infection control (Tselebonis et al., 2020). The rise in bacterial colonies in hospitals, especially in ICUS and operating rooms, correlates with increased nosocomial infection cases. Nosocomial infections are responsible for increased morbidity and mortality among patients receiving care in ICUS (Napoli et al., 2012).

Hospitals can improve air quality standards through a comprehensive approach focused on microbiological monitoring and infection control, and provide a safer environment for patients, especially in ICUS. Getachew et al.'s research demonstrates that monitoring polluted surfaces and air quality is essential to lowering the prevalence of nosocomial infections linked to microbes (Getachew et al., 2020). Studies carried out in different hospitals also show that specific bacterial species, namely Gram-negative bacteria, predominate in bioaerosol exposure. For instance, Biglari et al.'s survey revealed that most bacteria in hospital air were Gram-positive. However, the detection of Gram-negative bacteria, including Pseudomonas aeruginosa and Klebsiella pneumoniae, also indicated a notable frequency. This emphasises how important it is to keep an eye on and manage microbes in vital locations like ICUS to lower the risk of infection (Biglari et al., 2020).

Analysis of Physical Parameters of Bioaerosol Pollution Risk

Research on bioaerosol pollution in intensive care units (ICUS) in hospitals includes analysis of physical parameters that can affect the risk of microbial contamination. Bioaerosols include particles dispersed in the air, containing bacteria, fungi, and other pathogens. Health risks associated with bioaerosols in ICUS are primarily caused by humidity, temperature, and air circulation, essential factors in determining air quality and the potential for nosocomial infections. One factor that can cause Sick Building Syndrome (SBS) is physical factors in the air, namely air temperature and humidity. Some health issues that excessively high room temperatures can cause include dehydration, stress, skin irritation, and headaches. Meanwhile, humidity levels exceeding 60% can lead to respiratory infections, which are often caused by fungal infections that can grow and thrive in humid air (Datau et al., 2020).

Based on Table 4 from the Pearson Correlations test results, only one parameter has a significant value: humidity. Based on the humidity test results, a p-value of $0.000 < 0.05$ was found, which means that the parameter has a significant effect, and the calculated r value for the humidity parameter indicates a positive direction of influence. The positive influence means that the higher the humidity, the greater the number of bacteria in the room.

According to health standards, the ideal air humidity in an ICU should range between 40% and 60%. Humidity above 70% not only supports mould and bacteria growth but can also contribute to health issues such as respiratory tract irritation and sinus infections. Air quality in ICU rooms is influenced by humidity; Pratiwi et al. found that humidity levels not in line with standards can promote the growth of bacteria and mould, increasing hospital infection rates (Pratiwi et al., 2024).

Research by Zeng et al. further confirmed the relationship between environmental conditions and the incidence of infections caused by Gram-negative bacteria. Their data showed that as temperature and humidity increased during the summer, diseases such as peritonitis associated with peritoneal dialysis also increased sharply, reinforcing that climatic conditions can facilitate the spread of pathogenic organisms (Zeng et al., 2020). Additionally, Konno et al. noted that humidity and temperature significantly influence frequently touched surfaces in hospital environments. Their findings suggest that maintaining surfaces at a warm temperature can help reduce bacterial presence, with the study indicating that surface temperatures resembling human skin can inhibit pathogen growth (Konno et al., 2023). This suggests that regulating the temperature of the surrounding environment may lessen the amount of germs present on ICUS surfaces that are often touched. According to a thorough investigation by Jalili et al., operating rooms and intensive care units frequently have lower microbial counts than other wards. They attribute this discrepancy to improved environmental conditions and ventilation (Jalili et al., 2021).

Hazard Identification

Aerosols are one of the most essential air pollutants produced by natural processes and human activities. Human exposure to bioaerosols in indoor air causes many problems in healthcare centres. Hospitals have high concentrations of bioaerosols. Harmful health effects, such as the transmission of infectious diseases, acute toxic effects, and respiratory syndromes like asthma and allergies, are associated with exposure to bioaerosols (Tolabi et al., 2019). To understand the dangers of aerosol bacteria in hospital ICUS, it is essential to understand the risks of nosocomial infections and develop effective ways to prevent them. Aerosol bacteria dispersed in the air can spread harmful pathogens to patients and medical staff, increasing the likelihood of infection.

Health issues caused by poor indoor air quality can lead to discomfort for staff working in the room. The first stage of MRA is hazard identification. This stage aims to identify risks through environmental health risk analysis. As a result, the presence of microorganisms in the air can pose a threat to human health, particularly for employees working in specific areas.

Hazard identification in intensive care units at Dr. Wahidin Sudirohusodo General Hospital, Makassar. The results of the hazard identification presented in Table 3.1 conclude that the intensive care unit does not meet the requirements outlined in the Ministry of Health of the Republic of Indonesia Regulation No. 1204/MENKES/SK/X/2004 on ‘Health Environmental Requirements for Hospitals’ regarding the threshold limit value for total bioaerosols, which is 0-200 CFU/m³. The hazard identification results of various bioaerosols found in the intensive care unit include several bacteria and fungi classified as potential pathogenic microorganisms.

Hospital-acquired infections or Healthcare-Associated Infections (HAIs), according to the Centre for Disease Control and Prevention, are systemic or localised conditions that are a reaction to exposure to infectious agents or toxins, which arise without evidence that the infection was present or in the incubation period when the patient was admitted to the intensive care unit. Bacteria commonly involved in HAIS include Streptococcus spp., Acinetobacter spp., Enterococcus, Pseudomonas aeruginosa, coagulase-negative Staphylococcus, Staphylococcus aureus, Bacillus cereus, Legionella, and the Enterobacteriaceae group, which includes Proteus mirabilis, Klebsiella pneumoniae, Escherichia coli, and Serratia marcescens. Pseudomonas aeruginosa, Staphylococcus aureus, and Escherichia coli are the primary causes of HAIS (Santri et al., 2019).

A study conducted in 2019 on bacterial patterns causing nosocomial infections in the Intensive Care Unit (ICU) of GMIM Pancaran Kasih Hospital in Manado reported several bacteria, including Vibrio cholerae, Escherichia coli, Klebsiella pneumoniae, and Gram-positive cocci. Staphylococcus sp. is a Gram-positive coccus bacterium, part of the normal human flora, found in environments in contact with humans and air. These bacteria are one of the leading causes of infections in hospitals (Waleleng et al., 2024). This study begins with research conducted by (Habibi et al., 2021) where the results show that various bacteria were found in udara samples from a sick home, indicating that common pathogens such as Staphylococcus aureus, Pseudomonas aeruginosa, and Acinetobacter baumannii were detected.

Exposure Assessment

Exposure assessment or exposure analysis is conducted to determine the route, frequency, duration, and magnitude (amount) of exposure to microbial hazards in a population (EPA, 2012). Bioaerosol levels indoors are higher than outdoors. Inhalation is the primary route of exposure to bioaerosols. Bioaerosol levels indoors are at least ten times higher than outdoors, with exposure routes including ingestion or swallowing, direct contact, and inhalation or breathing (Wang et al., 2018). Analysis of bacterial aerosol exposure through the inhalation route is essential in understanding the spread of infection and the health impacts of exposure to aerosol particles in the environment. Bacteria dispersed in aerosols can have profound implications, particularly in respiratory tract infections, which often occur through inhalation of small particles.

Based on Table 5 of the ADDinh calculation results for total aerosol bacteria conducted on 48 respondents at four points in the intensive care unit at Dr. Wahidin Sudirohusodo General Hospital in Makassar, the highest average ADDinh value was found at point 4, which was 58.25, and the lowest was at point 1, which was 25.70.

Bacteria in hospital environments often exhibit varying patterns of presence depending on the time of observation, environmental conditions, and environmental activities. Studies in several hospitals have shown that bacterial concentrations, particularly those of antibiotic-resistant Gram-negative species, tend to be higher in the afternoon, especially on weekdays (Saadoun et al., 2020). Research by (Asrianto et al., 2022) indicated that hygiene management, ventilation, and interactions in patient care areas directly influence microbial contamination levels. They also found that samples taken during higher activity, such as in the afternoon during weekdays, had higher bacterial levels.

Dose Response

Dose-response analysis is intended to estimate whether a risk agent has the potential to cause adverse health effects in a population at risk. In estimating infections caused by exposure to risk agents, the dose-response relationship describes the likelihood of an individual becoming ill after coming into contact with a microbe (Ningrum Baharuddin et al., 2023). Based on the calculation of infection probability for total aerosol bacteria in Table 3.6, which was conducted using the total number of aerosol bacteria (bacteria and fungi) through the inhalation route at each research point in the intensive care unit of RSUP. Dr. Wahidin Sudirohusodo Makassar found the highest mean infection probability at point 4 (0.998) and the lowest at point 1 (0.990).

Risk Characterization

Risk characterisation is a component that integrates the risk assessment process by characterising or describing health risks to microbes, which is calculated using a formula based on the US EPA. Air pollution caused by bacteria is categorised as a non-carcinogenic effect. The results of risk characterisation are expressed in the Hazard Quotient (HQ). The Hazard Quotient (HQ) for total aerosol bacterial exposure in Table 3.7 shows that only two respondents had an HQ value <1, meaning they were still within safe limits, but 46 other respondents had an HQ value >1, meaning they had a high exposure risk that was deemed unsafe or had a potential health risk. The high number of respondents with HQ > 1 indicates the presence of serious potential health risks that must be addressed promptly. Individuals with high risk, such as patients in intensive care units or those with certain health conditions, may be more susceptible to infection.

Risk characterisation related to the concentration of bacteria found in the Intensive Care Unit (ICU) air indicates that the higher the number of bacteria, the greater the risk of nosocomial infection among staff in the ICU. This has been supported by various studies showing a direct relationship between bacterial concentration in the air and the risk of infection. A study by Li et al. monitored aerosol concentrations in the ICU, revealing significant levels of Pseudomonas aeruginosa and Acinetobacter baumannii. A risk quotient (RQ) > 1 indicates that the probability of infection among patients and healthcare workers is relatively high due to the high presence of these pathogenic microorganisms in the air (Li et al., 2017).

According to a study by (Zhang et al., 2019) that carefully examined the properties of bacterial aerosols, germs can multiply under favorable conditions, increasing the risk of infection in hospital settings. The study demonstrated that when high pollutant levels coexist with favourable atmospheric conditions, bacteria such as Acinetobacter lwoffii and Bacillus sp. exhibit high survival and growth probabilities, which correlate with an RQ significantly greater than 1 in environments exposed to high concentrations of particulate matter (PM), thereby increasing patient vulnerability. Strict control measures must be implemented because of the known dangers of bacterial aerosols. Techniques including enhanced ventilation systems, personal protective equipment (PPE) guidelines, and the use of high-efficiency particulate air filters (HEPA) are crucial for lowering exposure (Bryant & Tobias, 2020).

Risk Management

Risk management is needed to reduce potential risks. Based on the results of the Hazard Quotient (HQ) calculations in this study, air pollution caused by bacteria categorised as non-carcinogenic was identified. The risk level (HQ) results for healthcare workers in the intensive care unit of Dr. Wahidin Sudirohusodo General Hospital in Makassar at all study sites indicated that these risk agents pose harmful effects on the health of healthcare workers in those areas.

Health risk management involving the control of aerosol bacteria in hospital environments must be conducted using an evidence-based approach and comprehensive strategies. In this context, two primary methods exist to align potential dose intake values with Reference Dose (Rfd) values: reducing microorganisms' concentration (C) or minimising exposure time. Based on the calculation results to determine safe concentration limits in this study, a recommended value of 51.24 CFU/m³ was identified as the maximum permissible concentration of bacteria in the air. Reduction of bacterial concentration can be achieved through various microbial control methods aimed at reducing the number of bacteria in the hospital environment. The following are some methods that can be applied:

a. Desinfection and sterillisation

Disinfection is the destruction, inhibition or removal of microbes that can cause disease or other problems such as decay. This is usually achieved by using chemicals. Disinfection can be carried out in various ways: spraying, wiping, mopping, submersion, fogging and fumigation. For large areas of air, spraying with steam or smoke can be used.

b. Apliication of UV-C technology

Ultraviolet-C (UV-C) light has been proven effective in killing microorganisms, including bacteria and viruses, in hospital environments. According to research conducted by Totaro et al., applying UV-C light in heating, ventilation, and air conditioning (HVAC) systems in surgical and intensive care areas reduced the total microbial count significantly (Sahli et al., 2021).

c. Microbial control through filtration

Filtration is a valuable technique for managing microorganisms, particularly airborne bacteria. Filtration in air conditioners (AC) is essential for preserving air quality since it eliminates pollutants and germs. To stop the spread of pathogens in hospitals, particularly in patient isolation rooms, air filtering by air conditioners is crucial. However, we did not find any references directly supporting the claim that air treatment using filtration methods can reduce microbial contamination in hospital wastewater. Therefore, this claim needs to be revised. In this context, using appropriate filters, especially in negative-pressure rooms, can help maintain air quality and reduce the risk of nosocomial infections (Asrianto et al., 2022).

d. Ventilation management and indoor air quality

According to research, hospital rooms can lessen the transmission of aerosol bacteria by having a well-maintained atmosphere with sufficient ventilation and an effective air filtering system. The incidence of nosocomial infections can be decreased by installing HEPA filters in the intensive care unit's ventilation system, which can assist in filtering air particles like bacteria and fungi. Effective ventilation system settings are crucial in controlling bacterial and fungal levels within the ICU (Ningrum Baharuddin et al., 2023).

e. Temperature and humidity control

Maintaining optimal temperature and humidity levels in the ICU can limit the growth of microorganisms. One study found that Bacterial aerosol survival was impacted by controlled humidity and lower temperatures. Temperature and humidity monitoring equipment must be utilized to maintain suitable environmental conditions in the intensive care unit (Li et al., 2017; Zhang et al., 2019). Microorganism growth can be inhibited by controlling humidity and temperature. Ecological conditions where temperature is controlled between 20-24 °C and relative humidity is 40-60% have a positive impact on reducing bacterial and fungal counts in the room. According to research findings (Tselebonis et al., 2020), regular temperature and humidity contribute to a decrease in microorganism levels in the room, so policies to regulate and monitor these conditions regularly in the ICU must be implemented.

f. Routine monitoring and evaluation

Monitoring the number of microbes and air quality in the ICU is very important. Regular environmental evaluations and audits can be conducted to measure bacterial aerosol levels. This can help identify high-risk areas and evaluate the effectiveness of existing controls (Bryant & Tobias, 2020). Hospitals can modify their policies and procedures based on data collected from these evaluations. Kurniyanto et al. demonstrated that the presence of a monitoring system can help hospitals identify and respond to fluctuations in microbial levels (Arıkan et al., 2022; Sahli et al., 2021).

CONCLUSION

The conclusion of this study confirms that bacterial concentrations at several sampling points in the ICU room exceeded the established safe limits, indicating the potential for significant microbial exposure for health workers and patients. Pearson correlation analysis showed that air humidity played an important role in increasing bacterial aerosol concentrations, where increasing humidity was significantly correlated with high bacterial counts ($p = 0.000$). These findings emphasize the importance of controlling environmental parameters in intensive care facilities, especially regarding air humidity regulation, which has so far perhaps received less attention as a major risk factor in the spread of microorganisms through the air.

Furthermore, the results of the Quantitative Microbial Risk Assessment (QMRA) analysis showed that almost all respondents exposed in the sampling area were at significant health risk. At point 1, 95.8% of respondents showed a Hazard Quotient (HQ) value > 1, while at points 2, 3, and 4, all respondents (100%) had HQ > 1. These data quantitatively confirm that exposure to bacterial aerosols in the ICU environment can pose a real health risk, which not only endangers patients with weak immunity but also increases the vulnerability of health workers who work long-term in the environment.

Therefore, the results of this study emphasize the urgency of strengthening environmental-based infection control protocols in the ICU. A comprehensive mitigation strategy, including optimizing ventilation systems, controlling humidity, using advanced air filtration technology, and increasing health workers' awareness and compliance with infection control procedures, is are strategic step that must be implemented immediately. A multidisciplinary approach involving microbiologists, environmental engineers, and public health practitioners is essential to ensure a safe ICU environment with minimal risk of aerosol microbial exposure, for maximum protection of all healthcare facility residents.

DECLARATIONS

Author Contribution

Conceptualization, R. and A.M. ; methodology, R., A.M., and A.S. ; formal analysis, R. and A.M.; investigation, R., A.M., and A.S.; resources, A.M., A.B.B. , and S.K.A. ; data curation, R.; writing—original draft preparation, R.; writing—review and editing, A.M., A.B.B., S.K.A., A.I.S. , and M.N.M. ; visualization, R. and A.M. All authors have read and agreed to the published version of the manuscript.

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Informed Consent Statement

All participants involved in this study provided informed consent prior to participation. The purpose of the study, procedures involved, potential risks, and benefits were thoroughly explained to all participants, who voluntarily agreed to participate in the research.

Declaration of Competing Interest

The author declares that there is no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancies have been completely observed by the authors.

Ethical Approval: Ethical approval for this study was obtained from [Hasanuddin University], under approval number [Approval Number].

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