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ORIGINAL RESEARCH PAPER

Risk assessment of fine particulate matter exposure attributed to the presence of the cement industry

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ABSTRACT

BACKGROUND AND OBJECTIVES: Chronic exposure to fine particulate matter may cause adverse health impacts on humans. The impact of fine particulate matter collected in the industrial area was explored. Therefore, this study aimed 1) to assess the levels and spatial distribution of fine particulate matter and 2) to estimate the health risks due to the exposure of fine particulate matter in the population surrounding the Maros cement industry. A Monte Carlo Simulation model with 10.000 iterations was used for risk analysis through the inhalation pathway.

FINDINGS: The average fine particulate matter concentration was 23.68 micrograms per cubic meter, above the air quality guidelines of the World Health Organization. However, the Monte Carlo Simulation to assess the health risk with the 95th percentile demonstrated that children and adults are at low risk for developing adverse health effects. The result of sensitivity analysis showed that duration of exposure (27.0%) and concentration of fine particulate matter (25.7%) were the most contributing factors to health risks in adults and children, respectively. This new approach determines the critical factors with major effects on reducing the health risk of the vulnerable population

CONCLUSION: Fine particulate matter poses health risks to adults and children, despite the calculated risks are still acceptable. Thus, limiting exposure duration and maintaining fine particulate matter levels in the residential area are needed.

NUMBER OF REFERENCES	NUMBER OF FIGURES	NUMBER OF TABLES
78	5	1

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INTRODUCTION

In recent decades, air pollution cases have been broadly recognized as a potential hazard to public health and a threat to economic growth. Approximately, there are 4.2 million deaths annually caused by ambient air pollution (Shaddick *et al.*, 2020). Based on World Health Organization (WHO) data, one out of every nine deaths in 2012 was related this pollution (WHO, 2016). The cement industry is one of the largest contributors to air particulate and 5% of global CO_2 emissions (Abu-Allaban and Abu-Qudais, 2011). There are various pollutants from cement plants, such as sulfur dioxide, radioactive dust, hydrogen chloride, hydrogen fluoride, organic compounds, dioxins, furans, nitrogen oxide, hydrocarbon, heavy metals, and carbon monoxide, which are related to health problems and environmental impacts (Astuti *et al.*, 2021c; Emetere and Dania, 2019; Mallongi *et al.*, 2019; Ogunkunle and Fatoba, 2014; Rauf *et al.*,2021a, 2021b). Primarily, the air pollutants in cement factories come from the clinker (Schuhmacher *et al.*, 2004). Dust is released from quarrying, stockpiles, raw material transportation, clinker cooler, crusher, grinders, materials-handling equipment, kilns operation, and milling proces (Abu-Allaban and Abu-Qudais, 2011; Mishra and Siddiqui, 2014). It may easily be transported by wind to different places from point sources. Greenhous gases (GHG) such as nitrogen, carbon, and sulfur oxides are mainly produced by fossil fuel combustion for power generation, kiln, and drying. SO_2 is emitted from the oxidation process of limestone as the cement raw material (Abu-Allaban and Abu-Qudais, 2011). The cement factory is one of the main sources of particulates based on many studies (Fell and Nordby, 2017; Kholodov *et al.*, 2020; Mallongi *et al.*, 2021; Mehraj *et al.*, 2013; Mishra and Siddiqui, 2014; Nkhama *et al.*, 2017; Rauf *et al.*, 2021b, 2022). Particulate matter (PM) consists of fine and coarse particles (Mekasha *et al.*, 2018) sourced from cement mills, packaging, fuel combustion and preparation, stacks, and road cleaning in the form of carbon and dust (Mishra and Siddiqui, 2014). Particulate matter is also produced when raw material processing (quarrying, crushing, hauling, grinding of limestone and clay) and clinker. Particles suspended in ambient air have various sizes, grouped to TSP (Total Suspended Particle) up to 100 microns in size, PM_{10} (particles with a size of < 10 microns) and $PM_{2.5}$ (particles with a size of < 2.5 microns). PM_{10} and $PM_{2.5}$ can enter and cause irritation and damage to the respiratory system. Particulate matter (PM) can contain potentially toxic heavy metals such as Pb, Cd, Cr, As, Ni, Mn, Zn, Mo, Cu, and Ba posing adverse health problems (Ahmad *et al.*, 2013). In addition, $PM_{2.5}$ can absorb organic compounds such as nitro-PAH and PAHs, ammonium, nitrate, sulfate, organic carbon, and element carbon from vehicles (Motesaddi Zarandi, 2019). The low concentration of $PM_{2.5}$ is still dangerous to human humans due to its adverse health effects. This emission is toxic because it contains mutagens, immunotoxins, respiratory toxins, neurological toxins, and carcinogenic agents. $PM_{2.5}$ can freely enter the respiratory tract and get deposited in the lungs' alveoli before entering the bloodstream. The dust may enter the human body through the gastrointestinal tract through contaminated foods (Mishra and Siddiqui, 2014). $PM_{2.5}$ is more dangerous to human health than PM_{10} (Ahmad *et al.*, 2013). Short-term exposure to $PM_{2.5}$ may increase the risk of respiratory and cardiovascular disease. $PM_{2.5}$ is positively related to coronary heart disease mortality (Ahmad *et al.*, 2013). Around 3% and 5% deaths cases are associated with cardiopulmonary disease and lung cancer, respectively which are from $PM_{2.5}$ exposure (Mekasha *et al.*, 2018). Several studies showed that the exposure may significantly reduce lung functions and cancer in cement workers and the community surrounding the plant (Fell and Nordby, 2017; Kholodov *et al.*, 2020; Nkhama *et al.*, 2017 The recent study by Nkhama *et al.* (2017) showed that people exposed to $PM_{2.5}$ had lower lung capacity. Other study by Novirsa and Achmadhi, (2012) showed that several points exceed the US-EPA quality standard of 0.03 mg/m3 based on the findings of ambient air study near the cement industrial area of Padang City. Sampling point at ring 2, 4 and 5 with a distance of 500 - 1000 m, 1,500–2,000 m, and 2,000 – 2,500 m from the center of the factory has $PM_{2.5}$ concentration of 0.041 mg/m^3, 0.038 mg/m^3 and 0.037 mg/m^3 (Novirsa and Achmadi, 2012). In the study by Kholodov *et al.* (2020) adverse health impacts due to cement dust and its related substances exposure are skin irritation and allergic dermatitis, respiratory track (asthma, silicosis, and chronic bronchitis), nasopharyngeal mucosa, and the oral cavity, and digestive tract disorders. Various materials contained in in $PM_{2.5}$ can cause various respiratory disorders such as infections acute respiratory infection (ARI), lung cancer, cardiovascular disease, premature death, chronic obstructive pulmonary disease (COPD). Correia *et al.* (2013) showed that a decrease in $PM_{2.5}$ concentrations was associated with an increase in life expectancy of 0.35 years. Another study by Sánchez-Soberón, (2017) stated that heavy metals concentration such as Cr(VI) may cause cancer among cement workers which are exposed from indoor activities (working /leisure and sleeping). WHO recommends a safe level of $PM_{2.5}$ exposure of 25 µg/m^3 in a 24-h period (not exceeding 3 days a year) and 10 µg/m^3 annually (Nkhama *et al.,* 2017). Meanwhile, the United States Environmental Protection Agency (USEPA) recommends 35 µg/m^3 in 24-h exposure to $PM_{2.5}$ (Nkhama *et al.,* 2017). Maros Regency has a potential limestone mining area surrounding the karst area. The cement industry is one of the largest companies in Maros regency, producing 1.8 million/tons of cement annually. The plant is near a residential area (< 50 m), which may expose the people surrounding it to health hazards (Rauf *et al.,* 2021a). According to Rauf *et al.* (2021b), TSP emitted by the Maros Cement Plant exceeded the minimum safe level by ambient air quality. As a result, the people living near the plant are at risk of non-carcinogenic cases (HQ>1). This may be caused by heavy metals bound in particulate. Based on annual health data in Maros Regency, cough, dermatitis, influenza, and acute respiratory infection are the major morbidity cases in Maros regency (Dinkes Maros, 2015). Morbidity cases are suspected due to exposure to $PM_{2.5}$ and dust in the air produced by the cement industry in Maros Regency. Therefore, a study related to $PM_{2.5}$ exposure and health risk assessment is needed in this area to predict health risks due to air pollution from the cement factory. A recent study also showed that exposure to heavy metals, which are bounded to dust through inhalation, oral and dermal, may cause non-carcinogenic (HQ>1) and carcinogenic cases (TCR > 10^{-6}) (Rauf *et al.,* 2021b). Several studies showed that the presence of the cement industry surrounding the karst area is attributed to an increase in ecological and human health risks (Astuti *et al.,* 2022; Mallongi *et al.,* 2022; Rauf *et al.,* 2021b) due to the accumulation of heavy metals in the environment. Study associated with $PM_{2.5}$ pollution and its contribution to human health in South Sulawesi Province is limited. Previous study in Maros regency showed a health risk due to exposure to TSP (Total Suspended Particle) from the cement industry in Maros (Rauf, 2021a). Furthermore, the Monte Carlo Simulation (MCS) model is still limited to identify health risks due to hazardous substances from ambient air. The model has just been carried out to identify uncertainty in the point estimate of exposure from the conservative human health risk assessment method by USEPA and sensitivity of exposure parameters analysis. Most of the MCS method was used in several studies on the chemical exposure from the soil, water, and food (Astuti, *et al.,* 2022; Jimenez-Oyola *et al.,* 2021; Rajasekhar *et al.,* 2018). Few studies used MCS to rank exposure pathways, locations, and contaminants from air pollution, particularly $PM_{2.5}$ exposure. Previously, the MCS model estimated health risks from air pollutants such as heavy metals (Chen *et al.,* 2022; Chen *et al.,* 2022; Dehghani *et al.,* 2021; Rauf *et al.,* 2021b; Wang *et al.,* 2019); sulphate, nitrate, ammonium, organic carbon (OC)-bounded to $PM_{2.5}$ (Wu *et* al., 2021); polycyclic aromatic hydrocarbon (Mo *et al.,* 2019; Motesaddi Zarandi *et al.,* 2019); O_3 (de Souza Silva *et al.,* 2016). High uncertainty may appear in the risk assessment process when using deterministic parameters. The probabilistic assessment method such as Monte Carlo Simulation can diminish risk assessment uncertainties by analyzing the concentration of pollutants and other toxicity factors (USEPA, 1997). Jimenez-Oyola *et al.,* (2021) mentioned that human health risk assessment problems lack information about exposure in the population and often use default values from the literature that cannot describe the real condition, leading to under or overestimation of health risks. Probability risk assessment using the MCS method can overcome these constraints. This method is useful for risk assessors making future management actions (USEPA, 1997). Therefore, the MCS method is used to assess health risks from $PM_{2.5}$ exposure to people surrounding the cement industry of Maros Regency. This is the first study that used this method to assess $PM_{2.5}$ exposure in an industrial area. The study purposes are 1) identification of $PM_{2.5}$ concentration in ambient air environment surrounding area near the largest cement industry in Maros Regency, and 2) estimation of health risk due to $PM_{2.5}$ exposure using Monte Carlo Simulation method. This study may be useful to make environmental risk management in the future. It was carried out in Maros Regency, South Sulawesi Province, Indonesia, in 2022.

MATERIALS AND METHODS

Sampling process

The $PM_{2.5}$ level was measured for 10 days in March 2022. The total concentrations in the outdoor environments were measured in four major sub-districts of Salenrang, Baruga, Bungaeja, and Tukamasea. The meteorological data (i.e, temperature, relative humidity, and wind speed) and the daily concentration during the sampling period were applied. In this study, 5 selected residences were selected as they were the nearest location to industrial activities. In 2020, total resident in the sampling sites was 30,488 (BPSSMR, 2020). Sites 1, 2, 5, 11, 16 and 18 are within the Lau area, around 2.1 km from the cement factory and 700 m – 2.5 km from traditional rock mining. This area is in the west and southwest regions, where the air quality is influenced by heavy-duty trucks' transportation of raw materials and industrial products distribution as well as vehicles fume from the main road. Sites 6, 7, 12, and 17 are the distinct village areas occupied by residents before the industrial activities began. This area is located in the southwest, Mattoangin region, about 2 - 3.5 km from the main industrial activities in the north. There is always yellow and white dust on residents' terraces, even when the wind does not blow predominantly in this direction, specifically in the morning. Sites 3, 8, 9, 13, 18, and 19 are located in the Baruga area, where the cement factory is in the south, approximately 500 m - 3.4 km from a cement plant and 3.77 km from a marble factory in the southeast. This area was one of the most densely populated residences working as farmers. Sites 4, 10, 14, 15, 20, and 21 are located in Tukamasea and Leang-Leang areas which residents in the east

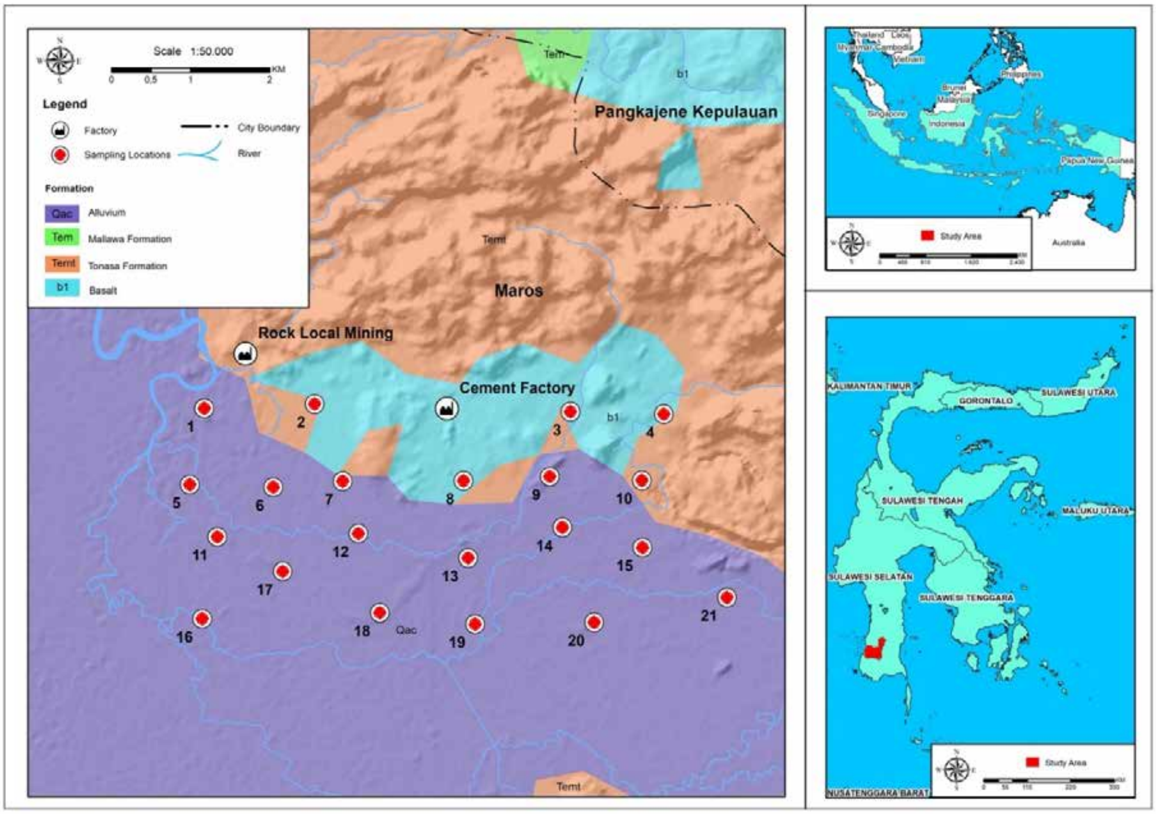


Fig. 1: Geographic location of the study area along with the sampling locations of $PM_{2.5}$ in the in four major sub-districts in Indonesia

and southeast inhabit. In this area, traffic volume was relatively low. The residents mostly worked as blue-collar workers and farmers. No sampling was carried out in the north, northeast, or northwest of the factories, as these areas were uninhabited and surrounded by karst hill (Tonasa limestone Formation). Measurement of $PM_{2.5}$ concentration was carried out at 21 stations, namely 2 points at the front gate, the next 6 points each 100 m from the main gate, then 3 points at the entrance to the residential area, and 10 points inside the settlement (Fig. 1). $PM_{2.5}$ sampling was carried out using direct reading HAZ-Dust EPAM 5000. That equipment uses a laser analyzer to measure particulate. The measurement result or time-weighted average (TWA) value can be directly read after the measurement process is conducted. The meteorological data was collected from Indonesia Agency for Meteorology, Climatology, and Geophysics online database. Fig. 2 showed the wind directions or model dispersion of $PM_{2.5}$ in the cement industry of Maros during the sampling process. That model was carried out using wind rose plot software (WRPLOT 4.0.1 for PM2.5 concentration).

Data analysis

Human health risk analysis by USEPA was used to estimate health risk of $PM_{2.5}$ exposure in people surrounding cement factory. Inhalation is the main route for $PM_{2.5}$, thus health risk analysis was focus to this route. The equation for inhalation route non-carcinogenic risk analysis is shown in Eqs. 1 and 2 (Edlund *et al.,* 2021; Rauf *et al.,* 2021a, 2021b; USEPA, 2001, 1989).

$$ADD_{inh} = \frac{C \times Inh_{rate} \times EF \times ED \times ET}{BW \times AT} \quad (1)$$

$$HQ = \frac{ADD_{inh}}{RfC} \quad (2)$$

Where, ADD is the average daily doses of $PM_{2.5}$ (µg/kg/day), C is ambient $PM_{2.5}$ concentration (µg/m^3); Inh_{rate} is inhalation rate of people, USEPA default value 14.9 m^3/day (adult) and 9 m^3/day (children) (USEPA, 1989), EF is $PM_{2.5}$ exposure frequency 350 days/year for residential exposure (USEPA, 1991), ED is exposure duration, USEPA default value for adult 24 years and 6 years (Rauf *et al.,* 2021b), BW is body weight for adult 63.01 kg (adult) and 34.55 (children) (Rauf *et al.,* 2021b), AT is averaging time (ED x 365 days/years for non-carcinogenic risk estimation), RfC is reference concentration for $PM_{2.5}$ inhalation is 10 µg/kg/day (Novirsa and Achmadi, 2012). If HQ value exceeds 1, it indicated that the chronic $PM_{2.5}$ exposure is not safe for the population. It is potentially cause non-carcinogenic health impacts in the future. Otherwise, when the HQ value is lower than 1, there is no non-carcinogenic risk to population or the risk is negligible. Monte Carlo Simulation (MCS) model was used in this study to estimate uncertainty or distribution of probability risk and contribution of variable to non-carcinogenic risk in the Maros cement industry population. The MCS model has been used in many risk estimation study (Astuti *et al.,* 2022; Gao *et al.,* 2019; Mallongi *et al.,* 2022; Pelletier *et al.,* 2017; Rauf *et al.,* 2021b; Saha *et al.,* 2016; Tajdar-oranj *et al.,* 2018) and is recommended by USEPA, (1997) for health risk estimation process. Based on the previous study, default value such as inhalation rate and other variables to estimate health risk is potentially rise the ambiguity and uncertainty of risk (Rauf *et al.,* 2021b). Thus, using MCS to estimate the distribution of probability risk is need to be done. The MCS was performed with 10000 repetitions to examine uncertainties related to non-carcinogenic risk. In this study, the variables that were analyzed for sensitivity test using MCS are ED, EF, C, and BW. This model investigating the distribution of random variables by simulating random numbers (Millard, 1998). Usually the random number expressed as *Y*, variables in health risk assessment. In this case, the random vector *X* may represent observations from several kinds of distributions that characterize exposure and dose response. The distribution of the main variables was used to find the correlation between $PM_{2.5}$ exposure and the probability of health risk in human. The function of the selected variables in the Monte Carlo simulation is expressed in Eq. 3.

$$Y = h(X) = h(X_1, X_2, \ldots, X_n) \quad (3)$$

The result was presented in graphic of probability risk (uncertainty) and sensitivity of variables. The MCS was carried out using the Oracle Crystall Ball software (11.1.12 ver) in Microsoft excel 2019 add-in. In this study, the mean concentration of $PM_{2.5}$ and risk calculation were performed using Microsoft

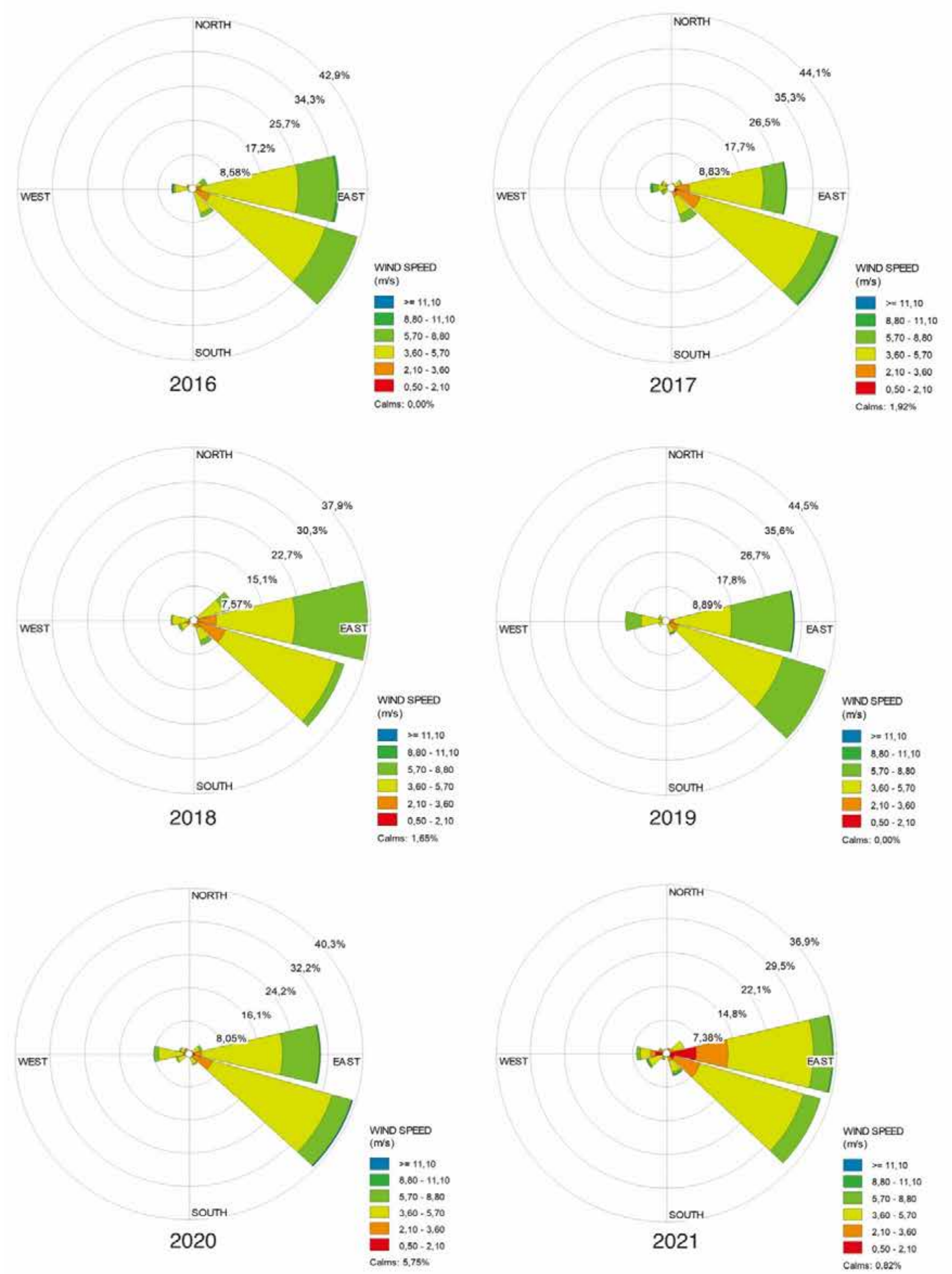


Fig. 2: Annual wind condition around the cement plant complex in 2016 – 2021

Excel version 2019. Spatial distribution of $PM_{2.5}$ concentrations was carried out by ArcGIS.

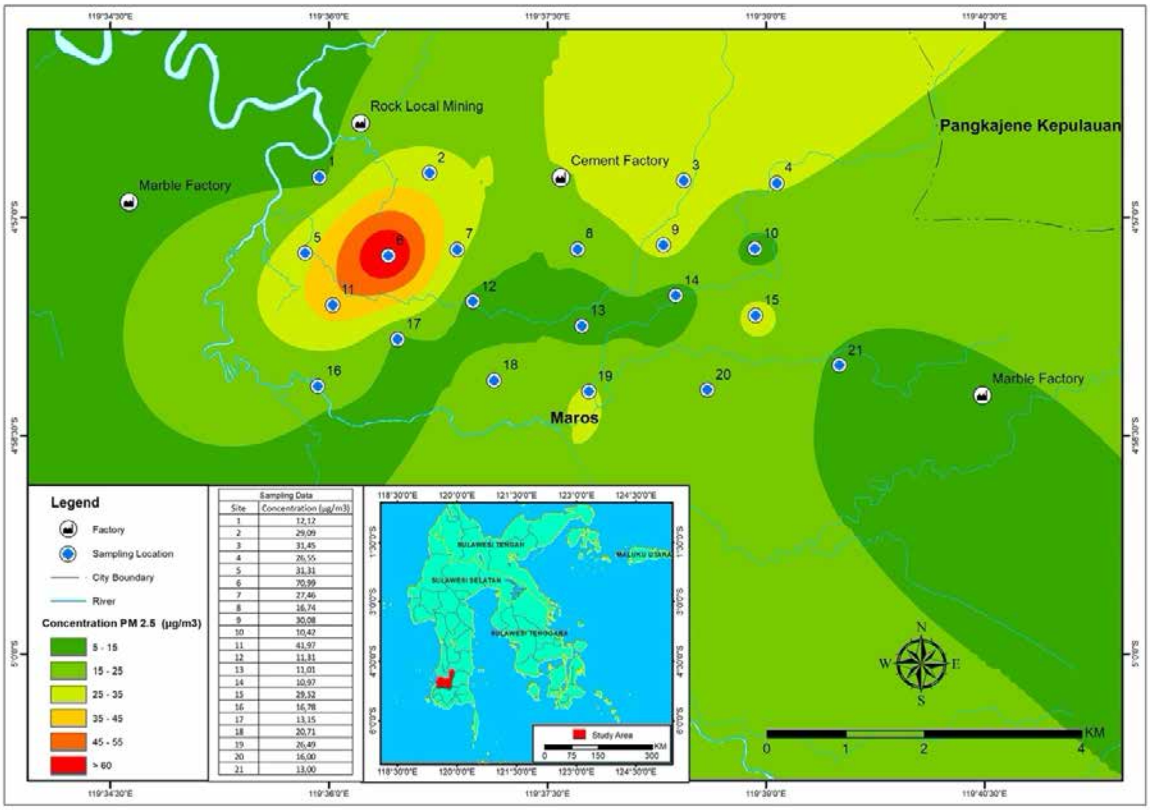
RESULTS AND DISCUSSION

Meteorological data

Meteorology is an important factor in the distribution and accumulation of particulates. It is the main component in determining the dilution effect of the atmosphere because the released substances are carried by the wind (Goudarzi *et al.*, 2018; Kim *et al.*, 2015). Temperature, wind speed, direction, and humidity were compiled from the Indonesian Meteorological, Climatological and Geophysical Agency (BMKG) online database. During the sampling days, temperatures ranged between 25.6 and 31.08°C, with an average value of 29.02°C, relative humidity ranged between 71.11% and 87%, average 81.6%, and wind speed ranged between 1.8 and 4.0 m/s, average 2.8 m/s. Fig. 2 indicates that the wind was heading Southeast and East. These locations are the main residential area in Tukamasea and Bungaeja Villages, with a resultant vector of this visualization at 109°. For six years, wind patterns were fairly consistent despite daily changes in direction (2016– 2021). The windrose plot was processed with Microsoft Excel software and WRPLOT 4.0.1 from Lakes Environmental Software. It was confirmed that the particulate concentration near cement plant areas in Southeast and East was higher than in others. Therefore, the residents will continuously be exposed to more particulates due to the wind direction.

$PM_{2.5}$ mass concentration

Direct measurements were carried out from morning to evening. The results showed that the concentration of PM varied at each point. The spatial distributions are presented in Fig. 3, while the differences in $PM_{2.5}$ concentration in Maros Regency and other countries are depicted in Table 1. The average concentration of 23.68 µg/m^3 was



Sampling Data	
Site	Concentration (µg/m3)
1	12,12
2	29,09
3	31,45
4	26,55
5	31,31
6	70,99
7	27,46
8	16,74
9	30,08
10	10,42
11	41,97
12	11,31
13	11,01
14	10,97
15	29,52
16	16,78
17	13,15
18	20,71
19	26,49
20	16,00
21	13,00

Fig. 3: The spatial distribution of $PM_{2.5}$ levels around the residential areas

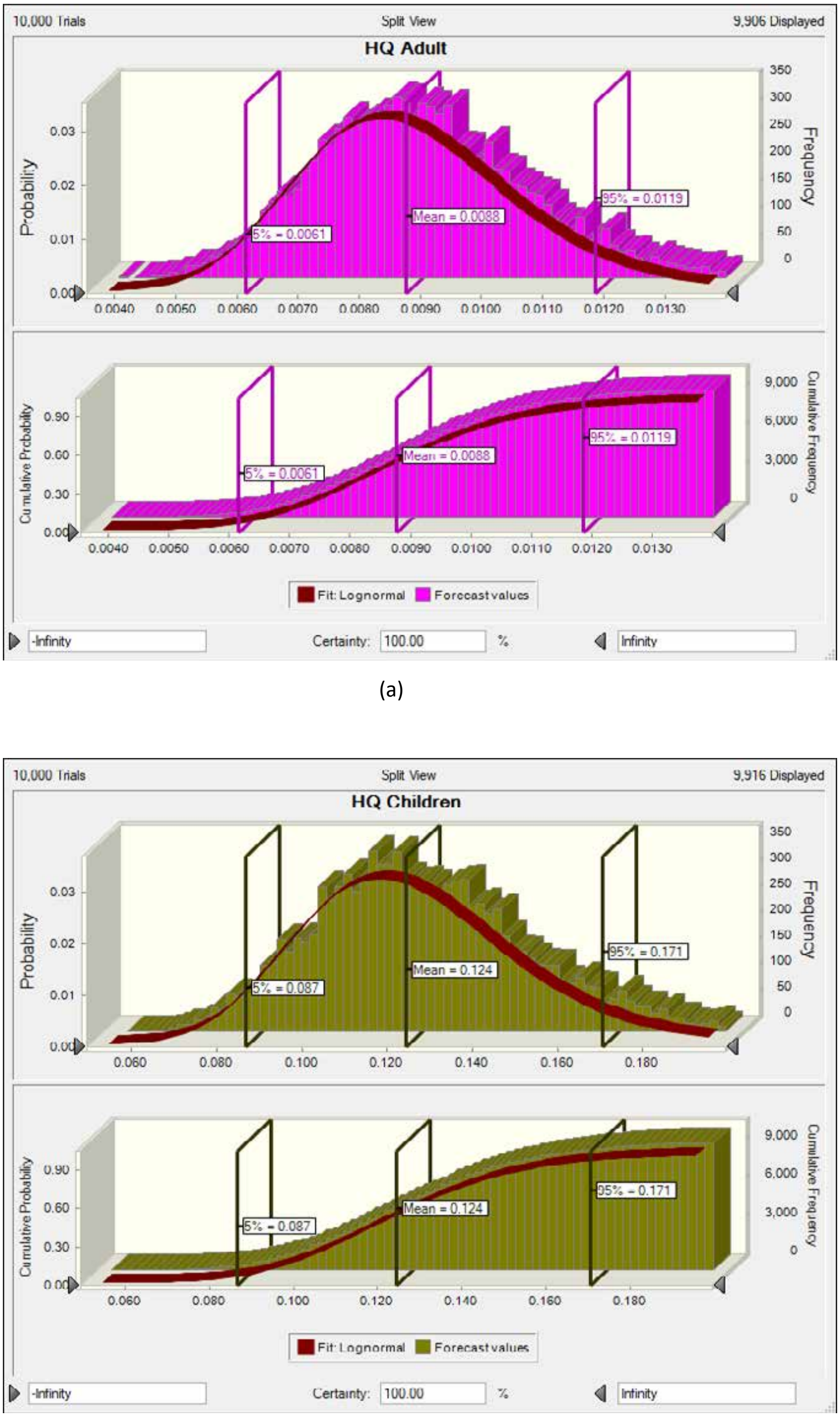
found for this study, which was higher than WHO Air Quality Guideline (AQG). WHO-AQGs of $PM_{2.5}$ for short-term (24-h average) and long-term (annual average) exposures are 15 µg/m^3 and 5 µg/m^3 (WHO, 2021). Alternatively, this concentration is still below the Indonesian standard for air quality (Indonesian government, 2021). The highest concentration of $PM_{2.5}$ found in station 6 (70.99 µg/m^3) is located in the south-eastern part of the cement plant, precisely in Tukamasea Village. This area is flat, quite lower, placed on alluvial plain and inhabited by most residents who work as farmers. The distribution of particulates originating from industrial activities from the direction of the Karst mountains in the north may increase $PM_{2.5}$ concentrations. The result was under a previous study, where the highest total suspended particulate (TSP) bound to metals was recorded at this location (Rauf *et al.,* 2021a; Rauf *et al.,* 2021b). According to the literature, $PM_{2.5}$ pollution might be affected by meteorological conditions, anthropogenic activities, and soil resuspension (Nkhama *et al.,* 2017; Peng *et al.,* 2016; Shahri *et al.,* 2019).

Maros karst area is surrounded by karst quarries, cement, and marble factories operating for the last two decades. The majority of industry in this region involves dry processes and high temperatures in their production activity. In cement factories, the particulates generated from the stacks may carry toxic particulates such as PAHs, heavy metals, and organic matters that are harmful to the surrounding population (Astuti *et al.,* 2021b; Mallongi *et al.,* 2022; Naeini *et al.,* 2019; Rauf *et al.,* 2021b). In addition, the use of coal in industry releases heavy metal ions involving high temperatures, which are likely to increase the risk to human health (Kim *et al.,* 2015). This indicates the higher the mass of particulates produced from industrial chimneys, the possibility of a high accumulation of toxic elements in other media such as soil and water bodies will increase (Han *et al.,* 2015; Kurt, 2018; Rauf *et al.,* 2022). Based on Table 1, the concentration of $PM_{2.5}$ around cement plants mostly exceeds WHO's standard (WHO, 2021).

Natural enrichments around karst areas are likely to occur where the wind will consistently blow and move the dust to residential areas (Ayanlade and Oyegbade, 2016; Han *et al.,* 2021; Rauf *et al.,* 2020b). Anthropogenic origin (mostly attributed to secondary particle formation) and natural sources (dust) contribute 17% and 16% to ambient PM in European and Central Asia urban areas (Almeida *et al.,* 2020). In Indonesia, limestone and marble are the main minerals of cement production. The conversion into cement by heat releases carbon dioxide and metals as a waste product (Rauf *et al.,* 2020a). In a study conducted in the Districts of Chelyabinsk, Russia, $PM_{2.5}$ concentrations were higher around industrial areas at 303 ng/m^3 than in non-industrialized areas at 192 ng/m^3. This is because the area has more intense activities and uses coal-fired stations (Krupnova et al., 2021). In non-industrial areas, the accumulation of $PM_{2.5}$ is mostly caused by vehicle fumes and burning waste. According to the United

Table 1: The comparison between average concentration of $PM_{2.5}$ from Maros cement, other studies and air quality standards.

Region/ country	Concentration (µg/m^3)	References
Maros, Indonesia	23.68	Present study
Chilanga. Zambia	10.21	(Nkhama *et al.,* 2017)
Thohoyandou, South Africa	11.00	(Edlund *et al.,* 2021)
Barcelona, Spain	15.20	(Sánchez-Soberón *et al.,* 2015)
Riyadh, Saudi Arabia	21.00	(Al-Zboon *et al.,* 2021).
Ewekoro, Nigeria	112.14	(Saheed Bada *et al.,* 2013)
Khash, Iran	14.34	(Shahri *et al.,* 2019)
Penglai, China	58.00	(Xue *et al.,* 2022)
Chuncheon and Yeongwol, South Korea	23.00 and 19.70	(*Han et al.,* 2015)
Antofagasta, Chile	42.00	(Jorquera and Barraza, 2013
Kongo Central Province, Democratic Republic of the Congo (DRC)	48.80	(Mbelambela *et al.,* 2020)
WHO-AQG	5 (annual) 15 (24-h)	(WHO, 2021)
Indonesian Standard for air pollution	15 (annual) 55 (24-h)	(Indonesian government, 2021)



-Infinity   Certainty: 100.00 %   Infinity

(a)

-Infinity   Certainty: 100.00 %   Infinity

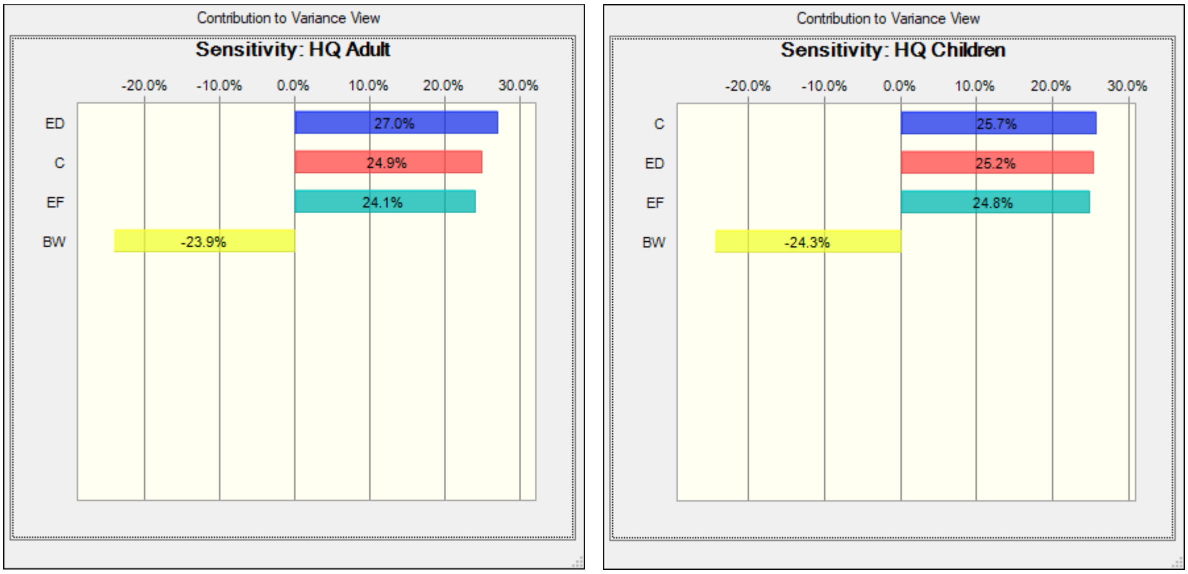
(b)

Fig. 4: The HQ of adult (a) and children (b) from $PM_{2.5}$ exposure

States Geological Survey, Indonesia produced 75,200 and 74,000 cement in 2017 and 2018. This number outperformed the production in Brazil (53,000), Iran (58,000), Japan (55,300), Republic of Korea (55,000), Russia (57,300) and Turkey (72,500) (USGS, 2020). The possibility of increasing cement factory activity and production will still occur in the next few years. This is worrying because the increase and demand for production can cause air pollution when it is not balanced with environmental protection policies and efforts to protect human health.

Health risk

In this study, PM$_{2.5}$ and health risk implications were assessed. The risk quotient was calculated to estimate the toxicological risk where the average dose of PM$_{2.5}$ was released to the reference. Fig. 4 depicts a health risk analysis with 95 percentile. The result indicates that children face greater risk (HQ = 0.171) than adults (HQ = 0.011) in the year. This result implies that the health risk posed by exposure to ambient air PM$_{2.5}$ around the industrial area was below the USEPA standards (HQ <1). However, long-term exposure can accumulate toxic substances bound to PM$_{2.5}$. Children's potential health risk is higher than adults due to their daily activities, inhalation rate, body weight ratio, and immature physiological system (Al-Zboon *et al.*, 2021; de Oliveira *et al.*, 2012; Mallongi *et al.*, 2020). There are likely other groups with higher vulnerability and susceptibility, such as the elderly or people with diseases, at higher risk for the relevant adverse health effects (Alsafran *et al.*, 2021; Astuti *et al.*, 2021a; Celo *et al.*, 2021). This is similar to a previous study conducted in Thohoyandou, South Africa, where children and infants experienced a greater carcinogenic and non-carcinogenic risks from PM$_{2.5}$ exposure than adults (Edlund *et al.*, 2021). Among 185 countries, the population-weighted median decrement in life expectancy from PM$_{2.5}$ (ΔLE) was 1.22 years (IQR of 0.67− 1.51 years) (Apte *et al.*, 2018). The high HQ of adults and children is attributed to the dusty weather in Indonesia for most of the year. Furthermore, the monitoring was conducted in March, which is considered the month with the windiest days (Astuti *et al.*, 2021a; Rauf *et al.*, 2022). Prevailing wind greatly contributes to particulate distribution in the air. Therefore, settlements that experience innate winds will accumulate more dust, particularly when they are located near industrial activities or roads (Han *et al.*, 2021; Kim *et al.*, 2015). This is in accordance with previous studies where the nearest area to cement will experience a higher



(a) (b)

Fig. 5: The sensitivity analysis of the main variables in health risk assessment using Monte Carlo Simulation (MCS)

accumulation of dust/ash and metals in ambient air, deposited to surface soil and bodies of water. Residents who inhabit this area are threatened with respiratory diseases and skin disorders (Astuti *et al.,* 2022; García-Pérez *et al.,* 2015; Kridin *et al.,* 2016).

In Fig. 5, the sensitivity chart revealed the exposure duration (ED) was the most significant factor for increasing the health problem in adult is exposure duration (ED) (27.0%), followed by concentration (C) of $PM_{2.5}$ (24.9%). Whereas in children, the highest contribution was the concentration (C) of $PM_{2.5}$ (25.7%), followed by ED (25.2%). It means that the exposure to pollutants and their concentration had the highest impact on developing adverse health effects in humans. Therefore, the most suitable scenarios focus on periodic industrial emissions monitoring near residential areas and limiting exposure duration. This indicates the more often discrete exposure events occur, the higher the possibility that residents will be at risk. Hence, children and adults should reduce their activities and use protection to decrease their contact with the air pollution that possibly contains harmful materials. The contribution of body weight (BW) was negative, indicating a low effect and can be ignored.

CONCLUSION

This study measured the outdoor level of $PM_{2.5}$ samplings continuously over 24 hours in 21 different sites. The focus was on the residential area around the cement industry in Maros Regency. The dominant wind direction, which blows from the northeast to the southeast, causes the Tukamasea region to experience a higher accumulation of particulates from factory production. As a result, the average concentration of $PM_{2.5}$ was higher than WHO-AQG for the short-term (24-h average) and the long-term standard (annual average). A health risk assessment was conducted through Monte Carlo Simulation (MCS) to determine the uncertainty. The proposed method identifies the potential health risks from $PM_{2.5}$ exposure through the inhalation pathway. The 95th percentile and 10.000 trials simulation showed that adults' and children's hazard quotient (HQ) were still tolerable and within safe limits. In sensitivity analysis, exposure duration and pollutant concentration are the most influential variables in the health risks of residents in the study area. This indicates that long-term exposure duration will still threaten human health, specifically for those close to factories. For the regulations to effectively protect the health of all age groups, the accepted levels and contact need to be reduced. This study recommends that $PM_{2.5}$ concentration around the residential areas be maintained. Personal protective equipment such as masks is suggested. For future analysis, integrating the MCS model and health risks assessment can be considered appropriate tools for monitoring air pollution and a scientific basis to predict health risk estimation. The MCS model can assess health risks due to $PM_{2.5}$ emissions in industrial areas and overcome the uncertainty related to health risk assessment. It may not apply to everyone, but the right scenarios and policies can go a long way toward ensuring that everyone's health is protected. Future study should focus on measuring the concentration of other pollutants bound to $PM_{2.5}$ and its health risks.

AUTHOR CONTRIBUTIONS

A. Mallongi performed the experimental design, prepared the manuscript text and conceptualization. S. Stang did the statistical analysis and validation. R.D.P. Astuti helped the literature review, sample collection, manuscript preparation and visualization. A.U. Rauf performed the project administration, sample collection, and data analysis. M.F. Natsir performed the sample collection and reviewing.

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CONFLICT OF INTEREST

The author declares that there is no conflict of interests 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 redundancy have been completely observed by the authors.

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ABBREVIATIONS

^oC	Celcius degree
$\mu g/m^3$	Microgram per meter cubic
µg/kg/day	Microgram per kilogram per day
%	percent
24-h	24 hours
ΔLE	Life Expectancy
ADD	Average daily dose
AQG	Air quality guideline
ARI	Acute respiratory infection
As	Arsenic
AT	Averaging time
Ba	Barium
BMKG	Indonesian Meteorological, Climatological, and Geophysical Agency or Badan Meteorologi, Klimatologi dan Geofisika
BW	Body weight
C	Concentration of $PM_{2.5}$
Cd	Cadmium
Cu	Copper
COPD	Chronic obstructive pulmonary disease
Cr	Chromium
Cr(VI)	Hexavalent Chromium
CO_2	Carbon dioxide
DRC	Democratic Republic of the Congo
ED	Exposure duration
EF	Exposure frequency
EPAM	Environmental particulate air monitoring
ET	Exposure time
GHG	Greenhouse gas
Inh_{rate}	Inhalation rate
IQR	Interquartile range
HQ	Hazard quotient
Mn	Manganese
m	Meter
m^3/day	Meter cubic per day
m/s	Meter per second
PAH	Polyaromatic hydrocarbon
Pb	Lead
PM	Particulate matter
PM_{10}	Particles with a size of < 10 microns
$PM_{2.5}$	Particles with a size < 2.5 microns
RfC	Reference concentration
SO_2	Sulphur dioxide
TCR	Total carcinogenic risk
TSP	Total Suspended Particle
TWA	Time weighted average
USEPA	United states Environmental Protection Agency
WHO	World Health Organization
WRPLOT	Wind rose plot
Zn	Zinc

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