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RESEARCH ARTICLE

Air and noise pollution analyses near oil and gas fields in the Mahakam Delta, Kalimantan, Indonesia

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Abstract. The Mahakam Delta is a strategic industrial area in East Kalimantan, Indonesia, in which oil and gas industries reduce ambient air quality and generate excessive noise. This research aimed to analyze the ambient air and noise pollution attributed to oil and gas production activities in the delta. Relevant parameters at five sampling points (UA-02 to UA-06) were measured and further analyzed in the laboratory, including total suspended particulate (TSP), SO_2, Pb CO, NO_2, O_3, temperature, humidity, wind direction, wind speed, and noise. Indonesia's air pollutant standard index (locally abbreviated as ISPU) with four parameters (CO, NO_2, SO_2, and O_3) was used to determine the ambient air quality, and provisions written in the Decree of the Minister of Environment No. 50 Kep-48/MENLH/11/1996 were consulted for the noise quality assessment. Results showed ISPU values in the range of 0–50 at the five sampling points, suggesting good ambient air quality and compliance with Government Regulation No. 22 of 2021. In addition, it was revealed that the noise parameter was lower than the upper threshold set in the Ministerial Decree, namely 65 dB. Nevertheless, monitoring air and noise quality at the main pollutant sources should be regulated through policies and implemented to protect the public from exposure to potential pollutants.

1. Introduction

Many anthropogenic activities are major sources of air pollutants and unwanted loud sounds. Air pollution occurs when the generated harmful substances exceed the air's ability to absorb them, declining the air quality. It can be attributed to volatile organic compounds (VOC) and nitrogen oxides (NOx) released by local and regional industries into the air, increasing ozone (O_3) production, as identified in Texas, Colorado, and Wyoming (Gilman et al., 2013). About 40–80% of air quality crises in developing and semi-industrialized countries are related to emissions of carbon (CO and CO_2), nitrogen oxides (NOx), sulfur oxides (SO_2 and SO_3), fluorine (F), O_3, hydrocarbons, toxins, particulate matter, and industrial pollutants from vehicles (Pope et al., 2015; Wellenius et al., 2013). In addition to downstream and upstream production, burning fossil fuels when operating heavy vehicles and engines in midstream operations also releases CO and NO_2 (Johnston et al., 2019).

Based on the Global Burden of Diseases Study 2015, ambient air pollution had increased significantly in the previous 25 years and contributed greatly to the global burden of diseases, particularly in low- and middle-income countries and territories (Cohen et al., 2017). As the industrial sector grows rapidly, more combustion engines emanate exhaust gas that contains large amounts of ultra-fine particles, nitrogen oxides, and other toxic substances (Field, 2014; Gilman et al., 2013). Furthermore, oil, gas, coal production and shipping industries can generate sound louder than the regulated thresholds. This noise pollution is known to increase the risk of several health problems, such as sleep disorders and cardiovascular disease. Additionally, recent studies in Pennsylvania and Texas found that people living near manufacturing facilities showed symptoms of depression due to repeated exposure to unwanted noise and reported reproductive health problems, congenital disabilities, and low birth weight associated with the emitted air and water contaminants (Tang et al., 2021; Willis et al., 2021). Also, research in California linked increased exposure to downstream oil production to higher risks of preterm birth and impaired pulmonary function (Gonzalez et al., 2020).

To evaluate and gain a better understanding of air pollution, air quality parameters can be quantitatively measured and expressed as an index. Accordingly, despite the inherent complexity in creating environmental quality indices that are specific, accessible, understandable, and uniformly accepted (Longhurst, 2005), indices have been broadly used to assess and evaluate complex environmental quality and associated health impacts (Katsouyanni et al., 1993). Also, oil and gas extraction involves separating oil, water, and gas, which releases byproducts as isolated or secondary pollutants. In this case, index values can also pinpoint which aspect or stage of production endangers humans and the environment and determine appropriate reduction and mitigation actions. For example, a high level of SO_2 in and around a production plant can be reduced by a flue gas desulfurization system, i.e., neutralization and conversion to sulfate a natural compound found in seawater (Tang et al., 2021; Willis et al., 2021; Gonzalez et al., 2020). In addition, calculating multiple indicators can be used to examine the effects of industries on nearby areas without measuring pollutant concentrations and determining other potential hazards, such as air, water, and noise pollution. For instance, Indonesia uses the air pollutant standard index (locally abbreviated as ISPU) with four indicators (CO, NO_2, SO_2, O_3) to describe an area's ambient air quality from its potential impacts on human health, aesthetic values, and other living organisms (Government Regulation No. 14 of 2020).

The Mahakam Delta in East Kalimantan, Indonesia, is the center of oil, gas, coal, and shipping industries. The oil and gas production emits toxic substances into the air and generates unwanted sound, leading to air and noise pollution. Further, the industrial growth in the delta prompts rapid development of transportation infrastructure and facilities, increasing exposure to pollutants and adverse impact on the environment and the health of people close to the Mahakam Working Area (Cohen et al., 2017; Gilman et al., 2013). This transportation sector generates high levels of NO_2, likely leading to mortality and morbidity, as indicated by their strong exposure-response function (Hamra et al., 2015).

Nevertheless, air quality problems and public exposure to ambient air pollution on a local scale like the Mahakam Delta remain underresearched (Allen, 2016). Investigation at this scale provides more detailed information because the degree of severity of air and noise pollution varies not only temporally but also spatially. It also depends on several place-specific factors, including types and sources of pollutants (residential and industrial), distance to production areas, and topographic and meteorological characteristics that influence the distribution of contaminants in the atmosphere (Kumar & Goyal, 2011; Cohen et al., 2017). Therefore, this research was designed to determine the air quality and noise levels in the delta's oil and gas production areas using noise and ambient air parameters (CO, NO_2, SO_2, and O_3). Measuring and evaluating these pollutants create references for noise and air quality management in and around the oil and gas production areas. Management measures are needed to minimize the harmful impacts of industrial pollutants, contain the spread of CO, SO_2, NO_2, and O_3 emissions, and lessen the burden of diseases related to air pollution. Continuous air quality management that focuses on pollutant sources provides information on air and noise pollution that bases the making and implementation of policies on different levels (i.e., local, subnational, or national) to reduce exposure to toxic substances and risks of associated diseases.

2. Methods

2.1. Research sites

The research was conducted in an industrial area in Balikpapan, part of the Mahakam Delta in East Kalimantan, Indonesia, in 2022. It is where the exploration and production activities of oil, gas, and coal occur and several companies engaging in these sectors are located. As shown in Figure 1, air and sound sampling was conducted at five locations: UA-02 (Parapatan, Balikpapan Selatan District), UA-03 (Manggar, Balikpapan Timur District), UA-04 (Kuala Samboja, Samboja District), UA-05 (Handil III, Muara Jawa District), UA-06 (Sungai Meriam, Anggana District). These samples were selected based on different types of potential pollutants. UA-02 is located in coastal waters that receive waste from the oil and gas industry (extraction wells) and supporting industries in the Mahakam Delta. UA-03 is situated in a coastal region used as residential areas and ports as transit points for industrial workers during their commute. UA-04 represents a central processing area, i.e., a place to process oil and gas from offshore rigs, including the West Seno and Attaka fields. UA-05 is a coastal residential area close to supporting industries of oil and gas production activities, such as pipe maintenance workshops. UA-06 is situated in coastal settlements of fishers who harvest marine products.

2.2. Research methods

This research used a mixed-methods design for the data analysis and collected (1) primary data by field survey and laboratory tests and (2) secondary data from industrial companies. The parameters observed were total suspended particulate (TSP) or particulate matter (PM), SO_2, CO, NO_2, O_3, Pb, temperature, air humidity, wind direction, and wind speed for air quality and noise. These data were measured directly at five sampling sites in the Mahakam Delta from October 29 to November 2, 2022. In the field, temperature was measured with a thermometer, air humidity with a hygrometer, wind direction with a compass, and wind speed with an anemometer. Based on the Indonesian National Standard (SNI), the ambient air sampling technique was conducted by direct measurement, including using an impinger for gas and a dust sampler. The collected gas solution and air samples were analyzed at the Samarinda Lestari Laboratory from November to December 2022 using the methods recommended in the SNI: spectrophotometry and gas chromatography. The test parameters and methods used to analyze ambient air and noise are written in detail in Table 1.

Afterward, four ambient air data (CO, NO_2, SO_2, and O_3) were calculated or converted into air pollutant standard index (ISPU) values according to the Decree of the Head of Environmental Impact Management No.14/MENLHK/2020 (Regulation of the Ministry of Environment, 2020). ISPU is a dimensionless value that explains the state of ambient air quality (i.e., clean or polluted) in a given area using a range of values from 0 (good) to 500 (hazardous). Although ISPU is most suitable for cities, it can be applied virtually to any area. This index was selected to allow for quick understanding because public information on the ambient air quality of a location in a given time is expressed chiefly as ISPU (hence, convenience for users) and for easy comparison to make decisions on air pollution control (Kumar & Goyal, 2011). ISPU was calculated using the formula below:

$$I = \frac{Ia - Ib}{Xa - Xb}\,(Xx - Xb) + Ib$$

where I is the Air Pollutant Standard Index (ISPU, dimensionless), X is the ambient concentration (ppm, mg/m^3, or mg/L), a and b are the upper and lower limits, and Xx is the actual or measured ambient concentration (ppm, mg/m^3, or mg/L). Ia, Ib, Xa, and Xb were determined using Table

2. For instance, the SO2 concentration in the last 24 h is 90 µg/Nm3 (Xx). Because 90 is located between 80 and 365 (see the first and second row of the second column, “24 h SO_2”), this means Xb=80 and Xa=365. Consequently, based on their corresponding upper limits in the first column, “ISPU value”, Ib=50 and Ia=100.

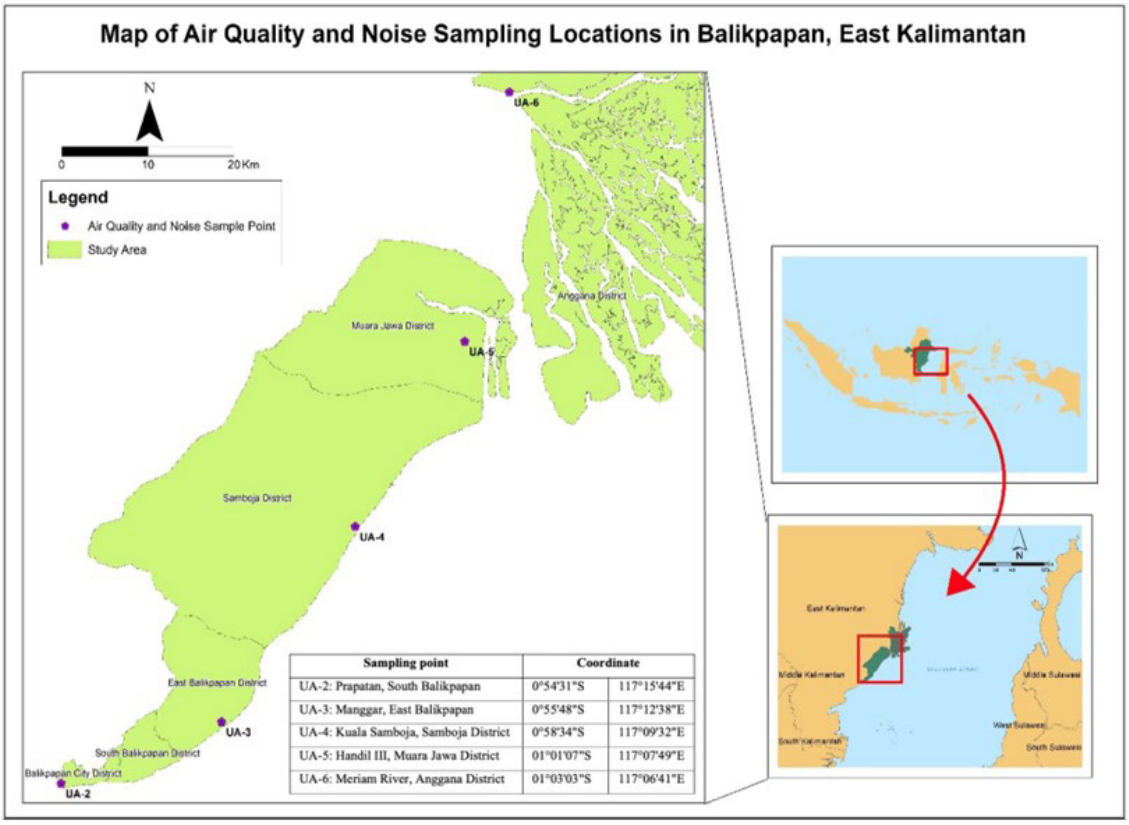

Figure 1. Air quality and noise sampling sites

Table 1. Parameters and methods of ambient air quality and noise analyses

Parameter	Analysis Method	Equipment	Quality standards (µg/Nm^3, measurement period)
Ambient air			
Sulfur dioxide (SO_2)	Pararosaniline	Spectrophotometer	150 (1 h)
Carbon monoxide (CO)	NDIR spectroscopy	NDIR analyzer	10,000 (1 h)
Nitrogen Dioxide (NO_2)	Griess Saltzman method	Spectrophotometer	200 (1 h)
Ozone (O_3)	Chemiluminescent	Spectrophotometer	150 (1 h)
Dust (TSP)	Gravimetry	Analytical balance	230 (24 h)
Lead (Pb)	Ash extraction	Atomic absorption spectrometer	2 (24 h)
Noise	Statistics	Sound level meter	55 dB(A) (24 h, 12 h)

Source: Attachment VII on Implementation of Environmental Protection and Management and Ambient Air Quality Standards of Government Regulation No. 22 of 2021 and Decree of the Minister of Environment No. Kep-48/MENLH/11/1996 on Noise Level Standards.

* = Maximum permissible noise level in housing and settlement

Table 3. Conversion table for ISPU parameter value to determine *Ia*, *Ib*, *Xa*, and *Xb*

ISPU value	24 h SO_2 (µg/m^3)	8 h CO (µg/m^3)	1 h O_3 (µg/m^3)	1 h NO_2 (µg/m^3)
0 -50	80	5	120	(2)
51-100	365	10	235	(2)
101-200	800	17	400	1130
201-300	1600	34	800	2260
301-400	2100	46	1000	3000
401-500	2620	57.5	1200	3750

Source: Decree of the Minister of Environment No. Kep-45/MenLH/10/1997

Afterward, the ISPU value (*I*) of each parameter was categorized according to the national standard for ambient air quality, i.e., Decree of the Head of Environmental Impact Management Agency No. 14 of 2020 (Table 3). The standard or upper limit indicates the highest amount of pollutants or elements the air can tolerate. The table also explains the air quality category, from good to hazardous, based on the degree of severity of potential impact on human health, aesthetic values, and other living organisms. As for the noise levels, the laboratory test results were compared with the standard set in the Decree of the Minister of Environment No.14/MENLHK/2020 (see Table 1). Recommendations on air and noise pollution controls were then given for any parameter values that exceeded their respective standards so as to reduce potential health impacts on people living close to the Mahakam Working Area.

3. Result and Discussion

3.1. Air Parameters of the Mahakam Delta Area

Figure 2 presents the climatic parameter values, air quality measurement results, and the regulated upper limit for each parameter at the five sampling points. The temperature ranged from 31.4°C in UA-02 to 34.2°C in UA-04, and the humidity varied from 56.8% in UA-02 to 64.5% in UA-06. These correspond to the tropical climate of the Mahakam, Southerly, northerly, and south-westerly winds were predominant throughout the year due to the influence of monsoon winds (Pertamina, 2021). Specifically, the wind directions were 180° in UA-06 and 155° in UA-02 and UA-03. The wind speeds varied between 0.3 and 0.5 m/s. In addition, the highest level of TSP was detected at 24 μg/Nm^3 in UA-02 or below the regulated upper limit, 230 μg/Nm^3. Meanwhile, lead (Pb) was found at the highest concentration (0.04 μg/Nm^3) in UA-06, followed by 0.03 μg/Nm^3 in UA-03, 04, and 05, and 0.02 μg/Nm^3 in UA-02. All these concentrations were lower than the regulated upper limit for Pb, 2 μg/Nm^3.

There are numerous standards used to measure air quality and determine the degree of pollution in the world, such as the Air Quality Index (AQ) used in several countries like the United Kingdom and China, Standard Pollutant Index (PSI) in the United States and Singapore, Composite Air Quality Index (CAI), and Common Air Quality Index (CAQI) in European countries. However, Indonesia creates and relies on different air pollution measurements, namely the Air Pollutant Standard Index (locally abbreviated as ISPU), which uses four main ambient air parameters: CO, SO_2, NO_2, and O_3 (Fahmi et al., 2012).

As Figure 2 and Table 4 show, SO_2, NO_2, CO, and O_3, concentrations meet the air quality standards regulated by the central government. The five air samples contained a similar amount of sulfur dioxide (SO_2), <9.3 μg/Nm^3 or below the upper limit (150 μg/Nm^3). SO_2 is a major pollutant, accounting for over 90% of global air pollution, that can cause oil and gas industry workers to experience adverse health effects due to short-term exposure (Wahab et al., 2012). The highest nitrogen dioxide (NO_2) presence was identified at 15 μg/Nm^3 in UA-03, with other sampling points showing NO_2 concentrations of lower than13.7 μg/Nm^3, which were all below the maximum allowable presence of this compound in the air (200 μg/Nm^3). If present in high concentrations, NO_2 can produce an odor and cause injuries to plants, allergic reactions or infections in the respiratory tract (e.g., allergic rhinitis, local dermatitis, and asthma) if inhaled (Wang et al., 2020; Wellenius et al., 2013), and even increased likelihood of depression (Szyszkowicz et al., 2016).

Meanwhile, the highest carbon monoxide (CO) concentration was recorded at 360 μg/Nm^3 in UA-03, followed by 243 μg/Nm^3 in UA-02, 242 μg/Nm^3 in UA-04, 124 μg/Nm^3 in UA-05, 123 μg/Nm^3 in UA-06. These levels were below the maximum permissible presence of CO in the air, 10,000 μg/Nm^3. CO is an odorless, tasteless, and colorless gas, meaning that CO contamination in the air cannot be seen with the

Table 3. Numbers and Categories of Air Pollutant Standard Index (ISPU)

Kategori	Rentang	Karbon Monoksida (CO)	Nitrogen (NO_2)	Ozon (O_3)	Sulfur Dioksida (SO_2)	Partikulat
Category	0 – 50	No effect	Slightly smelly	Damage to various types of plants by mixing with O3 (within 4 hours)	Damage to various types of plants with SO_2 (within 4 hours)	No effect
Currently	51 – 100	Changes in blood chemistry, but not detected	smelled	Injuries in several types of plants	Injuries in several types of plants	There is a decrease in visibility
Not healthy	101 – 199	Increased cardiovascular disease among smokers with heart disease	loss of smell and color. Increased reactivity of neck veins in asthmatics	Decreased ability in athletes who train hard	Odor, increased plant damage	The visibility was getting worse, and dust was everywhere
Very Unhealthy	200 – 299	Improvement of the cardiovascular system	Increase the sensitivity of patients with asthma and bronchitis	can affect the airways in patients with chronic lung disease	Increase the sensitivity of patients with asthma and bronchitis	Increase the sensitivity of patients with asthma and bronchitis
Dangerous	300 - more	Risk levels for all exposed populations				

Source: Decision of the Head of the Environmental Impact Control Agency, 2020

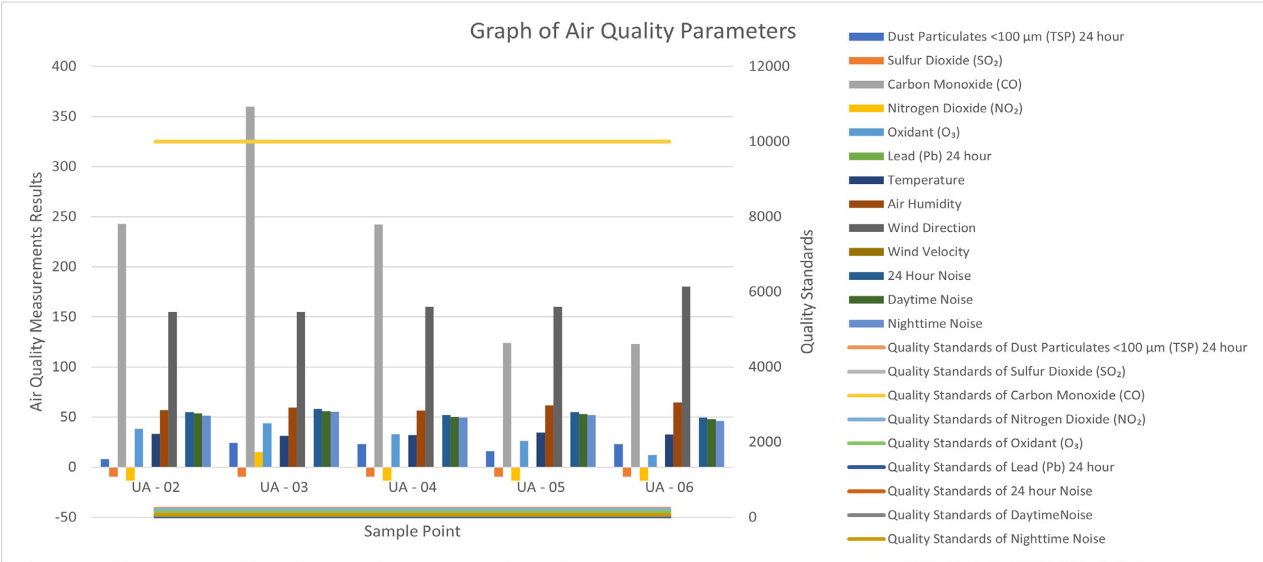

Figure 2. Air quality parameter values at the five sampling points and their regulated standards

Table 4. Parameters of Ambient Air (5 Types of Parameters)

No	Parameter	Unit	Quality standards	Prapatan Balikpapan (UA - 02)	Manggar Balikpapan Timur (UA - 03)	Kuala Samboja (UA - 04)	Handil (UA - 05)	Sungai Meriam (UA - 06)
1	Sulfur Dioksida (SO_2)	$\mu g/Nm^3$	150	< 9.3	< 9.3	< 9.3	< 9.3	< 9.3
2	Karbon Monoksida (CO)		10000	243	360	242	124	123
3	Nitrogen Dioksida (NO_2)		200	< 13.7	15	< 13.7	< 13.7	< 13.7
4	Oksidan (O_3)		150	38	44	33	26	12
	Environmental conditions		Bright	Bright	Bright	Bright	Bright	Bright

Table 5. ISPU values and categories of the four ambient air parameters at five sampling points

Parameter	UA-02		UA-03		UA-04		UA-05		UA-06	
	Value	Category	Value	Category	Value	Category	Value	Category	Value	Category
SO_2	9	Good	9	Good	9	Good	9	Good	9	Good
CO	3	Good	5	Good	3	Good	2	Good	2	Good
NO_2	9	Good	9	Good	9	Good	9	Good	9	Good
O_3	16	Good	18	Good	14	Good	11	Good	5	Good

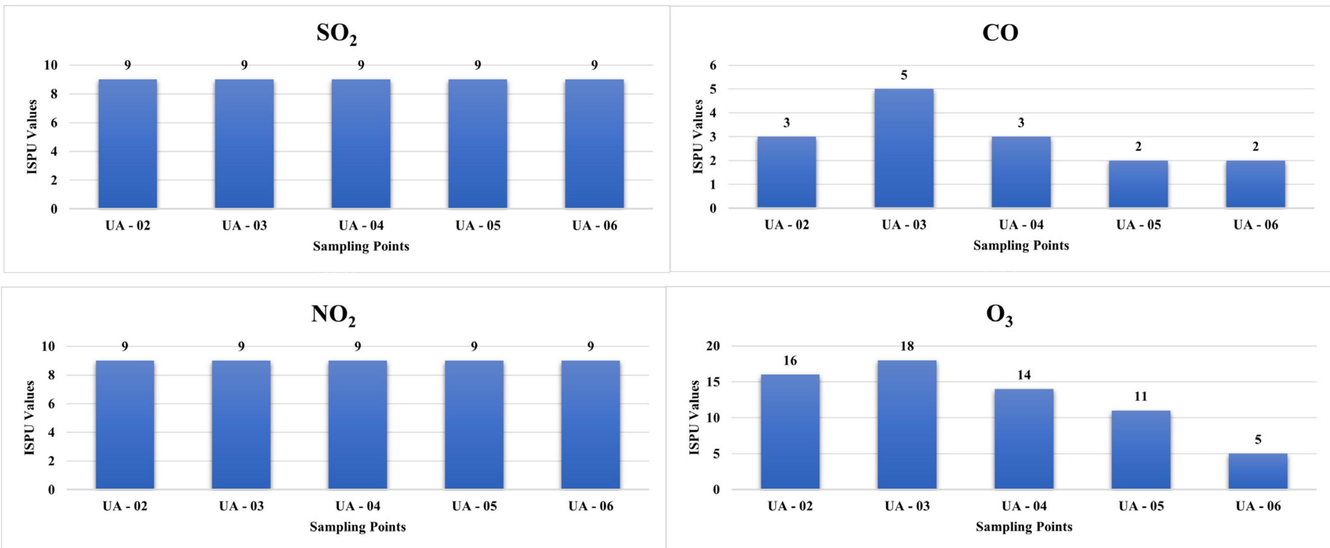

Figure 3. ISPU value of SO_2, CO, NO_2, and O_3

naked eye (Chelani et al., 2002). Most CO is formed due to incomplete combustion of carbon materials used as fuel and is sourced from heating, industrial processes, and wastes (Kunzli et al., 2000). Like NO_2, the highest ozone (O_3) level was detected at 44 µg/Nm^3 in UA-03. This was followed by 38 µg/Nm^3 in UA-02, 33 µg/Nm^3 in UA-04, 26 µg/Nm^3 in UA-05, and 12 µg/Nm^3 in UA-06. O_3 is a secondary pollutant formed in the atmosphere and is a strong oxidant that can react with various cellular components and biological materials (McConnell et al. 2006). If present in excessive amounts, O_3 can increase health risks in several groups of the exposed population and lead to depression and breathing difficulty (Zhao et al., 2018).

Table 5 and Figure 3 show the ISPU calculation results for SO_2, CO, NO_2 and O_3 and their categories. The index values varied from 9 to 18, suggesting good air quality. At the five sampled locations, SO_2 and NO_2 shared the same ISPU value, 9, indicating good air quality (ISPU = 0–50) based on the Decree of the Head of Environmental Impact Management Agency No. 107 of 1997. The ISPU values of CO were different across the five locations, ranging from 2 in UA-05 and UA-06 to 5 in UA-03, which fell into the category of good air quality. The last parameter, O_3, had the highest ISPU values, ranging from 5 in UA-06 to 18 in UA-03. Nevertheless, like the first three pollution indicators, these index values suggested good air quality. From these results, it can be inferred that the ambient air quality in the Mahakam Delta was generally good.

3.2. Noise Analysis Result

In addition to air quality, noise was observed as an environmental pollution and measured at the same sampling points as the air quality analyses. The noise analysis results at UA-02 to UA-06 are summarized in Table 6 and presented in a bar chart in Figure 4. Noise levels were measured using three different times: 24-h, first 12-h (06:00–22:00), and second 12-h (22:00–06:00). The loudest noise at each sampling point was 54.8 dB in UA-02, 58 dB in UA-03, 52.1 dB in UA-04, 54.8 dB in UA-05, and 49.4 dB in UA-06. The noise is believed to come from activities related to the oil and gas industry, particularly transportation from and to the industrial areas. Based on the Decree of the Minister of Environment No. 50 Kep-48/MENLH/11/1996, these decibels were lower than 65 dB and thus met the standard for noise level in industrial areas. However, the decree also regulated that the noise level in residential areas should not exceed 55 dBA, meaning noise pollution was detected in UA-03 (Manggar, Balikpapan Timur District). This sampling point is a coastal residential area close to ports with busy traffic with traditional motor boats, *ketinting*, as the most commonly used means of transportation by commuter workers. In addition, UA-03 is located at least 5 km from the Mahakam Working Area. This situation corresponds to the noise pollution in Sepatin, Muara Pantuan, and Tani Baru in Kutai Kertaneggara, East Kalimantan (Pertamina, 2021).

3.3. Discussion and Recommendation

The air pollutant standard index (or ISPU) analysis showed that the Mahakam Delta had overall good air quality because the ambient air parameter values (NO_2, SO_2, CO, and O_3) did not exceed their maximum permissible concentrations according to the Government Regulation No. 22 of 2021. This contradicts the results of previous studies that identified air pollution in Malaysia using PM_{10} as an additional parameter to NO_2, SO_2, CO, and O_3 (Awang et al. 2000) and in Italy (Rome), where the upper limits of NO_2, NOx, O_3, SO_2, C_6H_6, CO, and PM_{10} regulated in the Directive 2008/50/EC for ambient air quality were exceeded (Batista, 2017; Famoso et al., 2015). Decreased air quality has been linked to the downstream activities of the oil and gas industrial facilities, which emit hydrocarbons (Collett and Ham., 2016), benzene, toluene, ethylbenzene, xylene, formaldehyde, hydrogen

Table 6. Noise analysis results at five sampling points

No	Parameter	Unit	Quality Standars	Prapatan Balikpapan (UA - 02)	Balikpapan Manggar (UA - 03)	Kuala Samboja (UA - 04)	Handil III (UA - 05)	Meriam River (UA - 06)
1	24 Hours (LSM) 06.00 – 06.00	dB (A)	65	54.8	58	52.1	54.8	49.4
2	Afternoon (LS) 06.00 – 22.00			53.7	56	50.4	52.8	48.1
3	Evening (LM) 22.00 – 06.00			51.4	55.3	49.3	52.2	46.2

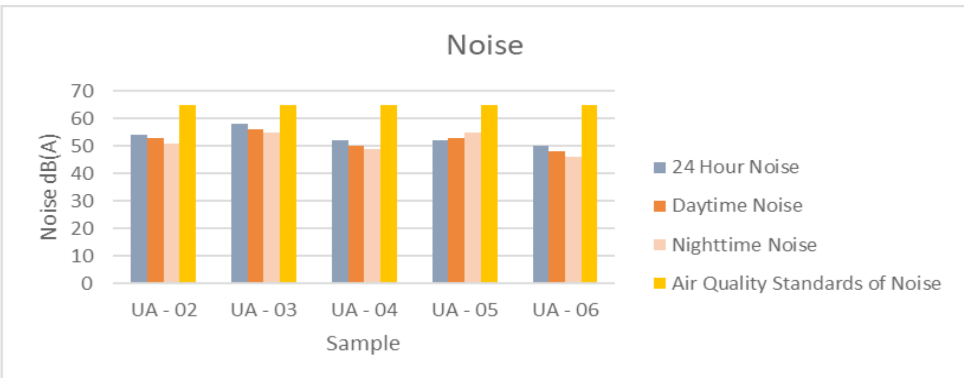

Figure 4. Graph of noise levels measured at three different times

sulfide, methylene chloride (Field et al. 2014), and other toxic substances that contribute to ambient air pollution (Petron et al., 2012).

Even though the air quality meets the regulated standards, the oil and gas production activities have raised health concerns among coastal communities closest to industrial sites (Baptiste & Nordenstam, 2009). These concerns are not without reasons, considering that potential adversities attributed to industrial pollutants have been extensively investigated and documented in the literature. Air pollution has been identified as the cause of shortness of breath, skin rashes, eye irritation (Kunii et al., 2002), and various chronic health problems, including respiratory and cardiovascular diseases and cancers (Liu al., 2019). High particulate concentrations also significantly reduce life expectancy in Bangladesh, Egypt, Pakistan, Saudi Arabia, Nigeria, and China (Alam et al., 2014; Apte et al., 2018; Farahat et al., 2016; Zhang et al., 2016). Most of the chemicals identified in natural gas research can affect respiratory, digestive, and sensory organs, remain in the human body for a long time (Colburn et al., 2011), and cause severe problems if inhaled (Adgate et al., 2014). Poor birth outcomes, congenital heart defects, and infant mortality are common in pregnant women living near oil and gas wells (Chay and Greenstone, 2003; McKenzie et al., 2014).

From the environmental perspective, the oil and gas industry generates CO_2, which is the primary driver of climate change (Cohen et al., 2017; Liu al., 2019). The resulting atmospheric condition can have widespread environmental impacts (Gladka et al., 2018; Wu et al., 2016). Climate change has also been shown to increase emissions from energy systems (e.g., vehicles) that are correlated with surface temperatures (Motallebi et al., 2008).

Furthermore, the Mahakam Delta is an outlet of the by-products of numerous constantly growing industries. Prapatan, Balikpapan Timur (UA-02), receives more industrial waste from the oil and gas industry because many oil and gas wells and other supporting facilities are concentrated in this area. The other sampling points are residential areas, schools, and hospitals located only 500 m from oil and gas processing factories. Proximity to the epicenter of oil and gas activities significantly exposes more than one million people in the region to harmful waste (McKenzie et al., 2018). It is thereby necessary to monitor the concentrations of major pollutants periodically and keep them under control to prevent the negative impacts of otherwise contaminated air on the human body, animals, and plants. This measure can help achieve environmental sustainability and ecological balance (Ghose and Majee, 2001).

In addition to contaminants, the daily operations of this industrial sector and movements from and to its facilities also produce unwanted loud noise (Ramanathan et al., 2020; Thompson et al., 2017). Based on the Decree of the Minister of Environment No. 50 Kep-48/MENLH/11/1996, the noise levels were within the acceptable range for industrial areas, i.e., <65 dB, but exceeded the upper limit for residential areas, i.e., 55 dB, in several locations. Noise exposure is a biological stressor and a potential public health hazard in various contexts, for it alters the function of human organs and systems (Münzel et al., 2014). Noise may contribute to developing and worsening stress-related health conditions (e.g., high blood pressure) (Dratva et al., 2012). Several large-scale epidemiological studies have identified associations between exposure to environmental noise and adverse health outcomes, such as cardiovascular diseases (Babisch et al., 2013). Different complex phases of oil and gas development are sources of transient and chronic noise. These sounds can be intermittent or continuous, with various intensities. Certain sound generators, such as compressor stations, produce low-frequency noise (LFN) usually heard as a low rumbling sound (Leventhall, 2003). Many source-dependent and subjective factors can influence health outcomes, such as noise sensitivity (Hill et al., 2014), noise reduction technologies, and the synergistic effects of noise and air pollution.

There are a number of factors to consider when assessing the health risks of exposure to air and noise pollution to inform decision-makers. These include population distance to oil and gas operations, mitigation techniques, and differences in noise sensitivity between individuals, which may be driven by age and pre-existing health conditions. Depending on the location of oil and gas operations, topography, and infrastructure, residents living in areas with active oil and gas development may not be informed of noise levels (dB(A) readings) and estimates of ambient air quality. Nevertheless, governments or related stakeholders have implemented preventive measures through policies and practices designed to limit exposure. Air monitoring in the oil and gas production sites in the Mahakam Delta uses sensors to measure pollutants periodically, which are cost-efficient but effective for measuring ambient air quality. For better control, governments are encouraged to consider potential noise and air pollutant levels when determining minimum surface distances of residents and sensitive recipients (e.g., schools, hospitals, etc.) to industrial facilities. Previous studies found a spatial relationship between health problems and distance to oil and gas industries: people living near active wells are more exposed to gas emissions and noise and thus experience more adverse health impacts than those residing farther away (Balazs & Morello-Frosch, 2013; Denham et al., 2022; Hays et al., 2017). Therefore, nearby communities should be provided with education on these deleterious impacts to reduce health risks from short- and long-term exposure to ambient air pollution due to oil and gas development (Al Mutairi et al., 2023). In addition, considering the spatial dimension, remote sensing technology and satellite imagery that covers the area of interest can help provide effective measurement and monitoring of relevant data (Al Mutairi et al., 2023).

Over the past decade, networks of sensors have proven helpful in assessing air quality on a local scale. The following efforts are lessons learned from previous research in different cities in the world that can also be implemented to reduce air pollution in the Mahakam Delta. In the city of Florence (Italy), a low-cost air quality monitoring unit (Arduino technology) with a high-resolution sensor equipped with road traffic density monitoring (camera sensors and video analysis to calculate the number of vehicles, speed categories, and density) was used to measure and monitor three parameters: CO, CO_2, and NO_2 (Gualtieri et al., 2017). Several other studies further demonstrated the ability of low-cost sensors to measure pollutants of interest in ambient concentrations (CO, NO, and NO_2). Other examples demonstrated the feasibility of collecting CO, NO_2, O_3, and CO_2 exposure data using portable instruments (Landrigan et al., 2018; Thompson, 2017). These sensors can be installed within or close to residential areas in the vicinity of industrial facilities (Wang et al., 2020); hence, they are applicable for pollutant control in the Mahakam Delta. However, for optimal results, sensor application must be integrated with mitigation measures to decrease emissions of hazardous substances by switching from fossil fuels to renewable energy, such as solar and wind power. Also, prohibiting biomass burning lowers sulfate and black carbon production, as well as NOx emissions by more than 80% (Ramanathan et al., 2020).

Furthermore, noise exposure can be reduced using perimeter sound walls, sound control systems, acoustic and building envelopes, and sound-absorbing materials. Natural terrain (e.g., hills) and elevated objects (e.g., a fence made of trees) can also intercept noise propagation. Non-structural prevention may include imposing regulations restricting nighttime activities to minimize sleep disturbance and factoring in the location and noise sensitivity of different groups of the general public, who may be more vulnerable to noise exposure than others, into determining maximum permissible noise levels.

Numerous government-regulated actions, policies, and plans have been introduced and have succeeded in reducing air and noise pollution and their adverse impacts (Wan et al., 2022), including restructuring industrial and energy infrastructure and formulating and implementing action plans to prevent and control air pollution. However, structural and non-structural management measures require an integrated multidisciplinary approach before they can be applied in the Mahakam Delta. This is to combine formulation and implementation of relevant regulations, standards, and policies with adequate monitoring, law enforcement, and compliance to achieve progressive air quality improvements and reduced noise exposure, which will benefit the environment and people living in the Mahakam Delta.

4. Conclusion

This research measured the air and noise pollution near oil and gas fields in the Mahakam Delta, East Kalimantan, Indonesia, using the Air Pollution Index (locally abbreviated as ISPU) direct measurement of noise levels, and comparison against government-regulated standards. The Mahakam Delta is in a tropical region with temperatures of 31.4–34.2°C and 56.8 to 64.5 % humidity. The winds are influenced by monsoons and blow at 0.3–0.5 m/s, predominantly in the direction of 155° and 180°. The ISPU values of four parameters (SO_2, NO_2, CO, and O_3) in these areas vary between 9 and 18, which, according to the Government Regulation No. 22 of 2021, are categorized as good air quality (ISPU=0–50). From the five sampling locations (UA-02 to 06), UA-03 in Kuala Samboja has the highest ISPU value of 18 for O_3. This point is located in a coastal residential area close to ports serving as transit points for oil and gas industry workers. The noise levels vary between 49.4 dB in UA-06 to 58 dB in UA-03, which meet the standard set in the Decree of the Minister of Environment No.50 Kep-48/MENLH/11/1996 for industrial area (<65 dB) but exceed the maximum allowable level in residential areas.

Considering that more than one million people live close to the oil and gas fields and that this industry generates substances harmful to public health and the environment, it is necessary to monitor the air quality and noise parameters regularly and keep them under control to reduce the risk of exposure. A multidisciplinary approach that integrates structural and non-structural measures is believed to help achieve environmental sustainability, ecological balance, and public welfare. An example of structural measures is installing a network of sensors, which provides a cost-efficient alternative for assessing air quality and noise levels on a local scale. Non-structural measures include governments that consider pollutant spread and noise propagation patterns when deciding minimum surface distances of residents and sensitive groups of the general public to the oil and gas production facilities. This multidisciplinary approach is expected to combine formulation and implementation of relevant regulations, standards, and policies with adequate monitoring, law enforcement, and compliance to achieve progressive air quality improvements and reduced noise exposure, which will benefit the environment and people in the Mahakam Delta.

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