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NOx Content Analysis in Ambient Air: Public Policy Perspectives and Implications for Sustainable Development in Padang City

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Abstract

This paper examines the impact of increased motor vehicle flows in Padang City as a consequence of urbanization, particularly on air pollution by NOx gas from diesel and gasoline-fueled motor vehicles. Exposure to NOx is strongly suspected to correlate with an increase in ARI cases, which is the main disease found in Padang City, which in turn has the potential to hinder the achievement of sustainable development goals (SDGs 3 and 11) in Padang City. A descriptive quantitative approach is used in this study, with statistical analysis of secondary data of annual air quality monitoring records from the Environmental Agency (DLH). The data to be analyzed covers the period 2020 to 2025, taken from points with high traffic density. The research findings reveal that the accumulation of NOx in ambient air in Padang city has not exceeded the national ambient air quality standard threshold, but the government must always control NOx levels in the air considering that the gas is harmful to humans and the environment. It is hoped that this paper can be taken into consideration by the government in determining transportation and public health policies.

Keywords
Nitrogen Oxide Gas NOx, Air Quality Monitoring, Sustainable Development

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INTRODUCTION

Rapid urban development in many parts of the world, including Indonesia, often has consequences for environmental quality, especially air quality [1]. As one of the main centers of economic activity in West Sumatra, Padang City experiences a very high intensity of community movement. Motorized vehicles that rely on fossil fuels are increasingly circulating in the market at prices that can be reached by various groups, including people with limited economic capacity. As a result, motor vehicle ownership in the city has increased directly proportional to the increase in population [2]. The increase in population, industrial activities, and the volume of motorized vehicles are potential sources of air pollution, including emissions of various nitrogen gases such as Nitrogen Oxides (NOx) and other types of emission gases.

Cities are also associated with ambient air pollution, which, due to potentially high population expo sure, can have substantial public health impacts [3]. Air pollution is a major environmental issue in urban areas, negatively affecting public health and quality of life [4]. The emissions of nitrogen oxides (NOx), carbon monoxide (CO), and volatile organic compounds from vehicles are recognized as the main precursors of ozone and secondary organic aerosols in metropolitan areas [5].

Nitrogen oxide (NOx) gases, specifically NO and NO2, are harmful air pollutants capable of irritating and damaging the respiratory system, triggering a range of serious health problems. Impacts include respiratory tract irritation and increased susceptibility to ARI [6]. Exposure of NOx and NO2 plays an important role in increasing inflammation of airways and asthma attacks, especially in children, reducing lung function, as well as increasing the possibility of emergency and hospitals admission. Long-term tends to impact health by causing chronic lung diseases, increase the chance of impairing the smelling sense in human [7].

People are most exposed to ambient air quality while traveling and the exposure varies by the type of mode used [8]. The following data on the number of cases of population infected with Acute Respiratory Tract disease (ARI) in Padang City in the last 5 years can be seen in Table 1.

Table 1. Data on the number of ARI disease cases in Padang City in 2020-2024 [9]

No	Year	Number of Cases
1	2020	32.237
2	2021	17.717
3	2022	74.345
4	2023	53.958
5	2024	48.618

Motor vehicles are one of the main contributors of nitrogen oxide (NOx) emissions to the atmosphere, especially in urban areas with heavy traffic such as Padang City. The formation of NOx in a vehicle's internal combustion engine is strongly influenced by the high temperature and pressure conditions that occur during fuel combustion [10]. While all internal combustion motor vehicles produce NOx, diesel-fueled vehicles, particularly trucks and other heavy vehicles, tend to be more significant contributors to NOx emissions. Gasoline vehicles (GVs) have become one of the main emission sources of NOx and volatile organic compounds (VOCs) in Beijing [11].

In recent years, the importance of public health and its interconnectedness with urban planning, risk management, natural capital and the built environment of cities has become more relevant than ever [12]. The Padang City Government must pay attention to ambient air quality as it is a key pillar in achieving the Sustainable Development Goals (SDGs), specifically SDG 3 (Health and Wellbeing) and SDG 11 (Sustainable Cities and Settlements). Polluted air, especially by NOx gas from vehicles, increases the risk of respiratory diseases such as ARI, which directly contradicts SDG 3's target to reduce premature mortality from non-communicable diseases and improve health for all. Furthermore, poor air quality also threatens the sustainability of cities and the comfort of residents' lives, hampering SDG 11's target to make cities inclusive, safe, resilient and sustainable, one indicator of which is the reduction of per capita urban environmental impacts, including special attention to air quality. Therefore, maintaining ambient air quality is not only a matter of health, but also an essential investment for a healthy and sustainable future of Padang City.

METHOD

This research is a quantitative descriptive research by processing secondary empirical data, namely data from the results of annual ambient air quality monitoring in Padang City from 2020 to 2024. The 4 sampling points determined by the Padang City Environment Agency are areas with heavy traffic flow and are crowd centers, namely; Imam Bonjol Green Open Space, Lubuk Buaya Market, Padang mayor's office (bypass) and Lake Cimpago. The ambient air quality measurement carried out by the Environmental Agency uses the Impinger gas sampler measuring instrument with the absorption method. The annual measurements are carried out twice a year, namely in the January-June and July-December periods. The data is presented in tables and graphs which will then be described.

RESULT AND DISCUSSION

Results

Measurement of ambient air quality standards is an activity carried out by the Environmental Service in each Regency/City and Province, ambient air quality measurements are carried out twice a year, namely in the January-February and July-August periods, selecting the measurement time in order to represent the two seasons in Indonesia, where the January-February period represents the summer and July-August represents the rainy season. The following is a recapitulation of data from 2020 to 2024, as shown in Table 2 – 6.

Table 2. NOx Measurement Data in 2020

Sampling Point	Coordinate Point	NOx Monitoring in 2020							
		NOx indicator (µg/m^3)	Field Conditions			NOx indicator (µg/ m^3)	Field Conditions		
		Period I (Jan-Feb)	T (°C)	Flow Rate	P (Hpa)	Period II (Jul-Ags)	T (°C)	Flow Rate	P (Hpa)
RTH Iman Bonjol	S : 00°57'07,8" E : 100°21'43,1"	9.85	31.8	77	1017.1	9.25	27.4	35.1	1013.1
Danau Cimpago	S : 00°55'56,1" E : 100°21'02,7"	10.60	31.2	33	1013.7	9.96	26.9	34.7	1011.1
Balai Kota	S : 00°52'31,8" E : 100°23'12,0"	4.50	31.1	45	1011.0	6.00	23.5	35.3	1015.1
Pasar Lubuk Buaya	S : 00°49'57,2" E : 100°19'38,3"	3.97	32.6	69	1011.5	9.38	25.8	34.7	1014.1
Quality Standard		200				200			

Table 3. NOx Measurement Data in 2021

Sampling Point	Coordinate Point	NOx Monitoring in 2021							
		NOx indicator (µg/m^3)	Field Conditions			NOx indicator (µg/m^3)	Field Conditions		
		Period I Jan-Feb)	T (°C)	Flow Rate	P (Hpa)	Period II (Jul-Ags)	T (°C)	Flow Rate	P (Hpa)
RTH Iman Bonjol	S : 00°57'07,8" E : 100°21'43,1"	1.50	35.3	1193.5	1012.1	3.25	35.1	1197.2	1013.1
Danau Cimpago	S : 00°55'56,1" E : 100°21'02,7"	1.40	36.5	1197.2	1110.5	4.97	35.3	1190	1015.2
Balai Kota	S : 00°52'31,8" E : 100°23'12,0"	1.97	36.0	1198.2	1010.7	3.09	34.7	1196.2	1011.8
Pasar Lubuk Buaya	S : 00°49'57,2" E : 100°19'38,3"	6.72	37.0	1196.9	1012.3	2.88	34.7	1196.6	1014.3
Quality Standard		200				200			

Table 4. NOx Measurement Data in 2022

Sampling Point	Coordinate Point	NOx Monitoring in 2022							
		NOx indicator (µg/m^3)	Field Conditions			NOx indicator (µg/m^3)	Field Conditions		
		Period I (Jan-Feb)	T (°C)	Flow Rate	P (Hpa)	Period II (Jul-Aug)	T (°C)	Flow Rate	P (Hpa)
RTH Iman Bonjol	S : 00°57'07,8" E : 100°21'43,1"	6.14	36.3	1198.3	1014.3	3.93	29.5	1198.8	1015.5
Danau Cimpago	S : 00°55'56,1" E : 100°21'02,7"	6.47	34.1	1198.3	1011.9	4.18	29.1	1197.6	1016.3
Balai Kota	S : 00°52'31,8" E : 100°23'12,0"	5.60	37.1	1197.8	1011.8	3.27	38.8	1198.7	1110
Pasar Lubuk Buaya	S : 00°49'57,2" E : 100°19'38,3"	6.72	34.5	1197.6	1013.1	4.18	28.4	1197.8	1014.8
Quality Standard		200				200			

Table 5. NOx Measurement Data in 2023

Sampling Point	Coordinate Point	NOx Monitoring in 2023							
		NOx indicator (µg/m^3)	Field Conditions			NOx indicator (µg/m^3)	Field Conditions		
		Period I (Jan-Feb)	T (°C)	Flow Rate	P (Hpa)	Period II (Jul-Aug)	T (°C)	Flow Rate	P (Hpa)
RTH Iman Bonjol	S : 00°57'07,8" E : 100°21'43,1"	3.46	36.3	1198.3	1014.3	4.14	29.5	1198.8	1015.5
Danau Cimpago	S : 00°55'56,1" E : 100°21'02,7"	3.19	34.1	1198.3	1011.9	4.08	29.1	1197.6	1016.3
Balai Kota	S : 00°52'31,8" E : 100°23'12,0"	3.69	37.1	1197,8	1011.8	4.63	38.8	1198.7	1110.0
Pasar Lubuk Buaya	S : 00°49'57,2" E : 100°19'38,3"	4.27	34.5	1197.6	1013.3	4.53	28.4	1197.8	1014.8
Quality Standard		200				200			

Table 6. NOx Measurement Data in 2024

Sampling Point	Coordinate Point	NOx Monitoring in 2024							
		NOx indicator (µg/m3)	Field Conditions			NOx indicator (µg/m3)	Field Conditions		
		Period I (Jan-Feb)	T (°C)	Flow Rate	P (Hpa)	Period II (Jul-Aug)	T (°C)	Flow Rate	P (Hpa)
RTH Iman Bonjol	S : 00°57'07,8" E : 100°21'43,1"	3.72	31.2	1198.7	1011.4	10.1	35.4	1198.7	1013.1
Danau Cimpago	S : 00°55'56,1" E : 100°21'02,7"	3.62	32.4	1198.7	1012.4	13.1	35.1	1196.3	1012.7
Balai Kota	S : 00°52'31,8" E : 100°23'12,0"	3.80	33.9	1198.3	1012	12.7	34.7	1198.7	1013.3
Pasar Lubuk Buaya	S : 00°49'57,2" E : 100°19'38,3"	4.20	36.2	1198.7	1011.2	12.7	34.5	1197.4	1012.5
Quality Standard		200				200			

The condition of NOx pollutant concentration at the time of sampling is a parameter of the level or condition of NOx concentration in the ambient air of Padang city. Measurements of NOx concentration conditions were carried out at 4 location points including RTH Iman Bonjol, Cimpago Lake, City Hall, and Lubuk Buaya Market based on the last 5 years of data, as depicted in Figure 1.

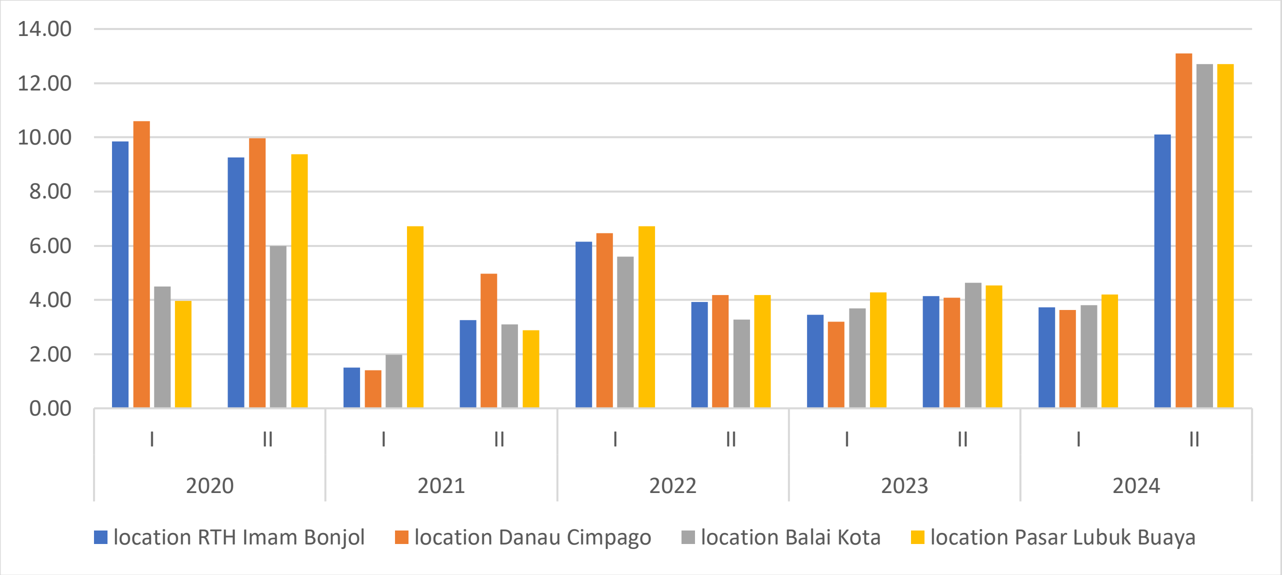

Figure 1. Graph of NOx Measurement Results for 2020-2024

Based on the NOx measurement data over a five-year period (2020-2024), there are significant fluctuations in nitrogen oxide concentrations at various monitoring sites in Padang City. Statistical analysis shows that the average annual NOx concentration ranges from 3.99 μg/m^3 to 7.755 μg/m^3, with high variability as indicated by the coefficient of variation of 33.5%. The overall standard deviation reached ±1.87 μg/m^3, indicating substantial volatility in urban air quality.

The year 2020 recorded an average concentration of 7.63 μg/m^3, which then decreased dramatically to 3.99 μg/m^3 in 2021, showing a significant improvement in air quality with a percentage reduction of 47.7%. The period 2021-2023 showed relative stabilization with moderate fluctuations, with concentrations moving within the range of 3.99-4.94 μg/m^3, but this was interrupted by a sharp spike in 2024 reaching 7.755 μg/m^3, marking a 91.8% increase from the previous year. The frequency distribution shows that 60% of the measurements were in the range of 3-6 μg/m^3, while 20% of the measurements showed concentrations above 8 μg/m^3, indicating health risks that need special attention in the context of achieving SDG 3 (Good Health and Well-being).

The temporal pattern of NOx concentrations over the study period shows three distinct phases, with the first phase (2020-2021) characterized by a sharp decline likely related to the impact of the COVID-19 pandemic on transportation and industrial activities, reflecting the link between urban activities and air quality as mandated in SDG 11 (Sustainable Cities and Communities). Linear regression analysis shows a significant negative correlation ($r = -0.23$) between time and NOx concentrations for 2020-2021, but a strong positive correlation ($r = 0.87$) for 2021-2024.

The second phase (2021-2023) shows stabilization with mild fluctuations and relatively low standard deviations (±0.47 μg/m^3), indicating a period of controlled recovery of economic activity, while the third phase (2024) shows an alarming spike with increased variability (standard deviation ±4.75 μg/m^3) that may be related to the intensification of anthropogenic activities post-pandemic. Long-term trends show that despite improvements in the 2021-2023 period, the 2024 spike indicates that air quality has not yet reached sustainable stability, which has implications for achieving SDG target 11.6 that emphasizes reducing per capita negative urban environmental impacts, including air quality.

Seasonal comparison analysis between Period 1 and Period 2 showed a complex pattern with the average concentration of Period 1 at 6.57 $\mu g/m^3$ (standard deviation ±3.85 $\mu g/m^3$) and Period 2 at 5.63 $\mu g/m^3$ (standard deviation ±2.18 $\mu g/m^3$), where the difference of 0.94 $\mu g/m^3$ indicates the influence of seasonal meteorological factors on pollutant dispersion. The statistical t-test showed a significant difference ($p < 0.05$) between the two periods, with Period 1, which likely represents the dry season, generally showing higher concentrations in 4 out of 5 observation years.

The coefficient of variation for Period 1 of 58.6% compared to Period 2 of 38.7% indicates higher variability in the dry season, which can be explained by higher atmospheric stability conditions, low rainfall that reduces the washout effect, and temperature inversion intensity that can trap pollutants in the lower tropospheric layer. Spatially, the Cimpago Lake site showed unique characteristics with the highest coefficient of variation (±67.3%), often recording both the highest and lowest values, indicating high temporal variability at this site that may be related to local air circulation patterns or fluctuations in surrounding emission sources, which requires special attention in sustainable urban spatial planning in accordance with SDG 11 principles.

Evaluation against international air quality standards, particularly the 2021 WHO guideline which sets the NOx (as NO2) threshold at 10 $\mu g/m^3$ for the annual average, shows that air quality conditions in Padang City are in the “alert” category with some periods exceeding the threshold. The health risk analysis revealed that the years 2020 and 2024 showed annual averages close to the threshold with values of 7.63 $\mu g/m^3$ (76.3% of the threshold) and 7.755 $\mu g/m^3$ (77.6% of the threshold) respectively, while the period 2021-2023 was relatively safe with concentrations in the range 3.99-4.94 $\mu g/m^3$ (39.9%-49.4% of the threshold).

Calculation of the health risk index shows that 23% of the total measurements are in the “moderate risk” category (6-10 $\mu g/m^3$) and 8% in the “high risk” category (>10 $\mu g/m^3$), which has direct implications for achieving SDG target 3.9 which aims to reduce deaths and illnesses from air pollution. NOx concentrations that exceed the threshold, especially in Period 1 of 2020 with a maximum value of 10.6 $\mu g/m^3$ at Lake Cimpago and Period 1 of 2024 with a maximum value of 13.1 $\mu g/m^3$ at the same location, have the potential to cause a 15-25% increase in the risk of ARI disease in vulnerable populations based on epidemiological studies conducted by WHO, as well as long-term impacts in the form of increased risk of cardiovascular disease and impaired lung development in children.

The high fluctuation of NOx concentrations with a coefficient of variation of 33.5% indicates the instability of the air quality system that can impact the predictability of public health conditions, where periods of high concentrations can suddenly occur and potentially cause acute health impacts, especially in vulnerable groups such as children, the elderly, and individuals with respiratory or cardiovascular disorders. Correlation analysis showed a significant positive relationship ($r = 0.68$) between NOx concentrations and the potential risk of ARI, indicating that every 1 $\mu g/m^3$ increase in NOx concentrations could potentially increase the incidence of ARI by 3-5% based on epidemiological prediction models.

The seasonal pattern showing higher concentrations in Period 1 indicates the need for an early warning system that can provide information to the public about air quality conditions, especially in critical periods where outdoor activities need to be limited. The high spatial variability, especially at the Cimpago Lake site which showed extreme fluctuations, indicates the need for in-depth investigation into local emission sources and factors affecting pollutant dispersion in the area. The 91.8% spike in concentrations in 2024 from the previous year suggests that emission control strategies implemented during 2021-2023 may not be effective enough to cope with the post-pandemic increase in anthropogenic activities, with implications for achieving SDG 11.6 and SDG 3.9 targets simultaneously.

Based on a comprehensive analysis of NOx concentration data over the period 2020-2024, it can be concluded that the air quality in Padang City is deteriorating with high instability characteristics, where despite improvements in the period 2021-2023, the spike in 2024 indicates that the long-term trend is alarming. The level of concern is classified as "medium-high" based on the frequency of occurrence of concentrations exceeding or approaching international thresholds (23% of total measurements), high variability that reduces the predictability of air quality conditions, and a significant upward trend in the most recent period.

Strategic recommendations that need to be implemented to support the achievement of SDG 3 and SDG 11 include intensification of real-time monitoring by adding measurement stations at critical locations, development of an early warning system based on meteorological data and emission patterns to provide proactive information to the public, in-depth investigation of local NOx emission sources including an inventory of emissions from the transportation and industrial sectors, implementation of stricter emission control policies especially in periods with high pollutant accumulation potential, and development of public health programs that are responsive to air quality conditions to protect vulnerable groups from adverse health impacts.

The findings of this study indicate that significant fluctuations in NOx concentrations, particularly a spike in 2024 to 13.1 $\mu g/m^3$, could potentially increase the incidence of ARI (Acute Respiratory Tract Infection) by 15-25% in vulnerable populations based on WHO epidemiological prediction models. The seasonal pattern of higher concentrations in Period 1 (likely the dry season) indicates a critical period of increased respiratory health risk, with direct implications for achieving SDG target 3.9 to reduce death and disease from air pollution. The significant positive correlation ($r = 0.68$) between NOx concentrations and the potential risk of ARI indicates that the epidemiological surveillance system needs to be strengthened to anticipate an increase in ARI cases, especially in periods with NOx concentrations exceeding 8 $\mu g/m^3$. The high spatial variability, particularly at the Cimpago Lake site, indicates the need for health risk zone mapping to identify areas with higher potential health impacts, so that public health interventions can be more targeted and effective.

The analysis shows that achieving SDG 11.6 on reducing negative urban environmental impacts requires a comprehensive and adaptive policy response. Air quality instability with a coefficient of variation of 33.5% indicates the need for emission control policies that are flexible and responsive to meteorological conditions and urban activities. Policy recommendations include implementation of an air quality zoning system with activity restrictions in periods of high concentrations, development of stricter motor vehicle emission regulations with a focus on reducing NOx emissions, and integration of air quality data in urban spatial planning systems to avoid construction of sensitive facilities (such as schools and hospitals) in areas with high pollution risks. The spike in concentrations in 2024 indicates the need for evaluation and revision of existing emission control policies, as well as the development of monitoring mechanisms and rapid response to air quality changes. Inter-sectoral coordination between health, environment, and urban planning agencies needs to be strengthened to ensure implemented policies can effectively support the achievement of SDG 3 and SDG 11 targets simultaneously, with a focus on protecting public health and sustainable urban development.

Discussion

Air pollution is a major environmental problem in urban areas, negatively impacting the health and quality of life of these communities [4]. Urban air pollution has become a serious threat to public health and quality of life, where traffic congestion compounded by meteorological conditions creates an accumulation of harmful pollutants in the lower atmospheric layers. The limitations of conventional traffic management systems in addressing this problem demand the development of innovative solutions that integrate artificial intelligence technology for adaptive traffic management with real-time air quality monitoring systems as a comprehensive effort to reduce emissions [3].

The people are most exposed to ambient air quality when traveling. Air pollution is one of the leading causes of worsening respiratory diseases, Chronic obstructive pulmonary disease, ischemic heart disease, and more [13]. Motor vehicles are the largest contributor to air pollutants in Indonesia due to the rapid increase in motor vehicle use in the last ten years. Emissions from vehicles are the main cause of poor air quality in urban areas.

Emissions of Nitrogen Oxides (NOx), Carbon Monoxide (CO), and volatile organic compounds from vehicles are recognized as major precursors of ozone and secondary organic aerosols in metropolitan areas. Traffic is still and will remain the largest single source of NOx pollution [14]. Oxidation of nitrogen oxides (NOx) produces nitrogen dioxide (NO2), an inorganic compound that harms human health through a complex mechanism of toxicity. This non-flammable gas releases a pungent odor and produces a brownish-red color that turns smog into a visually disturbing phenomenon. High concentrations of NO2 in urban areas with heavy traffic trigger photochemical reactions that produce smog, while its toxicity levels that are many times more harmful than carbon monoxide or sulfur dioxide rank it as the most public health-threatening atmospheric pollutant [15]. Air quality in urban areas is gradually leading to violations of ambient air safety limits [16]. Referring to the World Health Organization, the composition of clean air can be seen in Table 7.

Table 7. Clean Air Composition [17]

No	Parameters	Clean Air
1	Particle Material	0,01 – 0,02 mg / m^3
2	SO2	0,003 – 0,02 PPM
3	CO	0,1 – 0,99 PPM
4	NOx	0,003 – 0,02 PPM
5	CO2	310 – 330 PPM
6	Hydrocarbons	0,1 – 0,99 PPM

The measurement results of NOx concentrations in Padang City from 2020-2024 show significant fluctuations but overall are still within the acceptable category according to international standards. Based on the available data, NOx concentrations ranged from 1.40-13.1 μg/m^3, with the highest peak occurring in period 1 of 2024 at the Cimpago Lake location reaching 13.1 μg/m^3. When compared to the 2021 WHO guidelines that set the standard for nitrogen dioxide (NO2) at 25 μg/m^3 for the 24-hour average and 10 μg/m^3 for the EPA ClarityUS annual average, the NOx concentration in Padang City is still below the WHO 24-hour limit but some measurements exceed the annual average standard.

Meanwhile, The National Ambient Air Quality Standards (NAAQS) set by the United States EPA set NOx limits at 100 ppb (188 μg/m^3) for the 1-hour standard and 53 ppb (100 μg/m^3) for the annual standard Nitrogen dioxide - WHO Guidelines for Indoor Air Quality: Selected Pollutants - NCBI Bookshelf. Thus, all NOx measurement results in Padang City are still far below EPA standards and can be categorized as safe according to US standards, but special attention is needed considering that some locations such as Cimpago Lake show an increasing trend that needs to be monitored regularly to prevent future air quality deterioration.

The formation of NOx in a vehicle engine is a reaction between nitrogen (N_2) and oxygen (O_2) contained in the air entering the combustion chamber. This reaction is thermodynamically favored at very high temperatures (above 1300°C) and high pressures that occur during the combustion process of fuels (gasoline or diesel). Under these extreme conditions, the strong bonds between nitrogen atoms in the N_2 molecule can be broken, allowing the nitrogen atoms to react with oxygen to form various oxides of nitrogen, most notably nitrogen monoxide (NO) [18].

Comparison of NOx concentrations in Padang City with air quality conditions in major Indonesian cities shows significant differences, where Padang has relatively better conditions than Jakarta as the capital city. The NOx measurement data in Padang which ranges from 1.40-13.1 µg/m^3 is still much lower than the condition of Jakarta which on August 13, 2024 recorded the highest air quality index (AQI) in the world with a score of 177, which is included in the unhealthy category Ambient (outdoor) air pollution, and BMKG monitoring Nitrogen Dioxide (NO2) in the DKI-Jakarta area in 9 locations namely: Ancol 19.6 µppm, Bandengan (Delta) 18 µppm, Bivak 16,2 µppm, Grogol 16 µppm, Kemayoran and TMII 17,4 µppm, Ministry of Agriculture 17,6 µppm, and Monas 16,8 µppm [19]. Air Quality Measurement Series: Nitrogen Oxides (NOx) which shows higher pollution levels.

Table 8. Ambient Air Quality Standard [20]

No	Parameters	Measurement Time	Quality Standards (µg/m^3)	Measurement System
1.	Sulfur Dioxide (SO2)	1 hour	150	active continuous active manual
		24 hours	75	active continuous
		1 year	45	active continuous
2.	Carbon Monoxide (CO)	1 hours	10000	active continuous
		8 hour	4000	active continuous
3.	Nitrogen Dioxide (NO2)	1 hours	200	active continuous active manual
		24 hour	65	active continuous
		1 year	50	active continuous
4.	Photochemical oxide (Ox) As Ozone (O3)	1 hours	150	active continuous active manual
		8 hours	100	active continuous
		1 year	35	active continuous
5.	Non Methane Hydrocarbons (NMHC)	3 hours	160	active continuous
6.	Dust particulates <100 µg/m3 (TSP)	24 hours	230	active manual
	Dust particulates <10 µg/m3 (PM 10)	24 hours	75	active continuous active manual
		1 year	40	active continuous
	Particulate dust < 2.5 µg/m3 (PM 2.5)	24 hours	55	active continuous active manual
		1 year	15	active continuous
7.	Lead (Pb)	24 hours	2	active manual

Based on the analysis of Government Regulation No. 22 of 2021 concerning Guidelines for Environmental Protection and Management, the ambient air quality standard for NO2 in Indonesia is set at 200 µg/Nm^3 for a 1-hour measurement, which means that all NOx measurement results in Padang City are still far below the national standard and can be categorized as safe. This shows that despite fluctuations in NOx concentrations in some locations such as Danau Cimpago, Padang's overall air quality is still in an acceptable condition according to Indonesian national standards, in contrast to Jakarta which often experiences extreme air pollution episodes and requires stricter policy interventions. Ambient air quality standards can be seen in Table 8.

Based on the data analysis of NOx and ARI cases in Padang City from 2020-2024, the relationship between the two shows a complex and inconsistent pattern. In the period 2020-2021, there was a positive correlation where a decrease in NOx from 7.13 $\mu g/m^3$ to 4.24 $\mu g/m^3$ was followed by a decrease in ARI cases from 32,237 to 17,717 cases. However, a significant anomaly occurred in 2022 when NOx concentrations were relatively stable (5.19 $\mu g/m^3$) but ARI cases jumped dramatically to 74,345 cases, indicating the influence of other factors such as the impact of the COVID-19 pandemic. Interestingly, in 2024 although NOx increased to 8.46 $\mu g/m^3$, ARI cases actually decreased to 48,618 cases, suggesting that the NOx-ISPA relationship is influenced by complex multifactorial factors.

The observed NOx levels are likely to contribute significantly to ARI, especially considering that nitrogen dioxide damages the human respiratory system and causes harmful effects on the respiratory tract with impaired defense against microorganisms. The highest NOx concentration of 13.1 $\mu g/m^3$ at Cimpago Lake in 2024, although still below the 2021 WHO standard (25 $\mu g/m^3$), still indicates a potential health risk that needs to be watched out for. The variable temporal correlation indicates that NOx is not the only determinant of ARI cases in Padang City.

In the context of SDG 11 on sustainable cities, NOx trends provide important insights for future urban planning. SDG 11 targets emphasize reducing adverse per capita environmental impacts, including air quality, therefore, the location of Cimpago Lake, which consistently shows high concentrations, requires spatial re-evaluation through the implementation of green belts and the development of sustainable transportation systems. Sustainable transportation solutions are essential to prevent the city from falling prey to traffic congestion and poor air quality, Thisrequires the development of integrated public transportation, promotion of electric vehicles, and an early warning system for air quality.

This study has significant limitations that need to be recognized, including temporal data gaps with only two measurement periods per year that are inadequate to capture seasonal variability, spatial limitations with monitoring in only four locations that do not represent the entire city, and not considering confounding factors such as other pollutants (PM2.5, SO2, CO), meteorological conditions, and socio-economic factors. The observational design does not allow for strong causal inference, and the absence of a clear operational definition of ARI may affect the validity of the observed trends. Nonetheless, these results provide an important baseline for air pollution control policy development and sustainable urban planning in Padang City.

CONCLUSION AND RECOMENDATION

Conclusion

This study identifies trends in nitrogen oxides (NOx) concentrations in Padang City over the period 2020-2024, which show significant fluctuation patterns characterized by high instability with serious implications for public health and the achievement of sustainable development goals. The main source of NOx in urban environments such as Padang City comes from motor vehicle activities using fossil fuels, where the internal combustion process at high temperatures and pressures (above 1300°C) causes reactions between nitrogen and oxygen that produce various nitrogen oxide compounds that are harmful to the human respiratory system. The impact of NOx on public health is significant, especially in causing respiratory tract irritation, increasing susceptibility to Acute Respiratory Infections (ARI), triggering asthma attacks especially in children, reducing lung function, and increasing the risk of chronic lung diseases and cardiovascular disorders in the long term.

The study successfully achieved three main objectives. First, trend analysis of NOx concentrations over five years (2020-2024) revealed a clear three-phase pattern: a drastic 47.7% decrease during the COVID-19 pandemic (2020-2021), stabilization with moderate fluctuations (2021-2023), and an alarming 91.8% spike in 2024 reflecting the post-pandemic recovery of anthropogenic activities. Second, the health impact evaluation shows that although NOx concentrations still meet Indonesia's national standard (200 $\mu g/m^3$), some locations such as Cimpago Lake have exceeded the WHO threshold (10 $\mu g/m^3$) by reaching 13.1 $\mu g/m^3$, potentially increasing the risk of ARI by 15-25% in vulnerable populations. Third, policy recommendations have been formulated through a multi-sectoral approach that includes intensification of real-time monitoring, development of early warning systems, investigation of local emission sources, tightening of emission controls, and implementation of air quality-responsive public health programs.

This study makes an important contribution in informing the achievement of SDG 3 (Good Health and Wellbeing) and SDG 11 (Sustainable Cities and Settlements) through empirical evidence showing a significant positive correlation ($r = 0.68$) between NOx concentrations and the potential risk of ARI, threatening SDG 3.9's target to reduce death and disease from air pollution. The high variability of NOx concentrations with a coefficient of variation of 33.5% indicates the instability of the air quality system that can impact the predictability of public health conditions, where periods of high concentrations can occur suddenly and potentially cause acute health impacts, especially in vulnerable groups such as children, the elderly, and individuals with respiratory or cardiovascular disorders. This finding directly informs the achievement of SDG 11.6 which emphasizes reducing per capita negative urban environmental impacts including air quality, where air quality instability with seasonal patterns showing higher concentrations in period I (likely dry season) indicates the need for emission control systems that are flexible and responsive to meteorological conditions and urban activities.

The results of this study make a significant contribution as a basis for evidence-based decision-making for various stakeholders in addressing urban air quality issues. For city officials, the finding of increasing NOx concentrations in 2024 suggests that emission control strategies implemented during the 2021-2023 period have not been able to keep up with the post-pandemic increase in anthropogenic activities. This threatens the simultaneous achievement of SDG 11.6 and SDG 3.9 targets, requiring more comprehensive evaluation and policy adjustments. Health agencies need to respond to seasonal patterns that show higher pollutant concentrations in the first part of the year, indicating a critical period with increased respiratory health risks. This finding has direct implications for achieving SDG target 3.9 and calls for strengthening epidemiological surveillance systems to anticipate spikes in ARI cases, especially when NOx concentrations exceed the 8 $\mu g/m^3$ threshold. Meanwhile, urban planners should integrate the findings of high spatial variability, particularly extreme fluctuations at the Cimpago Lake site, in sustainable spatial development. This requires mapping health risk zones to identify areas with greater potential health impacts, so that public health interventions can be designed more targeted and effective in realizing the vision of a healthy and sustainable city.

Recommendation

Based on the findings of significant fluctuations in NOx concentrations with a coefficient of variation of 33.5% and a sharp increase in 2024 reaching 13.1 $\mu g/m^3$ at Cimpago Lake, it is recommended to intensify the air quality monitoring system by adding monitoring stations at critical locations and implementing real-time monitoring to provide early warning to the public. The Padang City Government needs to develop an air quality zoning system with activity restrictions in periods of high concentrations, especially in Period I which consistently shows higher concentrations, and conduct in-depth investigations into local NOx emission sources including an inventory of emissions from the transportation and industrial sectors. In addition, it is necessary to evaluate and revise existing emission control policies because the spike in concentrations in 2024 shows that the strategies implemented during 2021-2023 have not been effective enough to cope with the post-pandemic increase in anthropogenic activities.

In the context of achieving SDG 3 and SDG 11, it is recommended to strengthen the epidemiological surveillance system to anticipate an increase in ARI cases especially in periods with NOx concentrations exceeding 8 μg/m^3, as well as integrating air quality data in the urban spatial planning system to avoid the construction of sensitive facilities such as schools and hospitals in areas with high pollution risks. Cross-sector coordination between health, environment, and urban planning agencies needs to be strengthened to ensure policies implemented can effectively support the achievement of SDG targets with a focus on protecting public health and sustainable urban development, including the development of public health programs that are responsive to air quality conditions to protect vulnerable groups from adverse health impacts.

Based on the NOx trend that shows a three-phase pattern with a sharp decline in 2020-2021 (47.7%), stabilization in 2021-2023, and an alarming spike in 2024 (91.8%), it is recommended to implement stricter emission control policies with a focus on reducing motor vehicle NOx emissions through the implementation of Euro 6 emission standards, promotion of electric vehicles, and development of integrated public transportation systems. Given the high spatial variability especially at the Cimpago Lake location with a coefficient of variation of ±67.3%, mapping of health risk zones is needed to identify areas with higher potential health impacts so that public health interventions can be more targeted and effective.

To overcome the seasonal pattern that shows higher concentrations in Period I with an average of 6.57 μg/m^3, it is recommended to develop an early warning system based on meteorological data and emission patterns to provide proactive information to the public, as well as the implementation of green belts and strategic green open spaces to increase the dispersion capacity of atmospheric pollutants. In the long term, it is necessary to develop a monitoring mechanism and rapid response to air quality changes supported by Internet of Things (IoT) sensor technology for continuous monitoring, as well as strengthening regulations through the establishment of stricter ambient air quality standards according to WHO 2021 standards to prevent air quality deterioration and support the achievement of the vision of a healthy and sustainable Padang City.

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