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Analysis of SO_2, NOx, CO and $PM_{2,5}$ Pollutant Dispersion from The Combustion of Domestic Waste Incinerators

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Abstract
The population of Bandung City in 2024 reached 2,579,837 people with a total daily waste generation of 546,151.49 tons/year, with the largest composition of domestic waste (household waste). This high volume of waste puts serious pressure on the Final Processing Site (TPA). As a form of commitment to achieving the national waste management target, the Bandung City government continues to encourage the implementation of the Reduce, Reuse, and Recycle (3R) approach. One solution to the implementation of 3R is the incineration of residual waste using a tool with a waste incinerator installation, namely an incinerator. However, the composition of the waste greatly affects the quality of the resulting emissions. The content of organic materials, plastics, heavy metals, and water content in the waste can produce dangerous pollutants such as particulates, carbon monoxide (CO), nitrogen oxides (NOx), dioxins and furans if the combustion process does not take place optimally. Air quality monitoring using AERMOD software is necessary, considering that the effluent from waste combustion in the incinerator is dispersed into the ambient air.
Keywords: *kota bandung, domestic waste, incineration, composition of waste, AERMOD*

Abstrak
Jumlah penduduk Kota Bandung pada tahun 2024 mencapai 2.579.837 jiwa dengan total timbulan sampah harian sebesar 546.151,49 ton/tahun, dengan komposisi sampah terbesar sampah domestik (sampah rumah tangga). Tingginya volume sampah ini menimbulkan tekanan serius terhadap Tempat Pemrosesan Akhir (TPA). Sebagai bentuk komitmen dalam mencapai target pengelolaan sampah nasional pemerintah Kota Bandung terus mendorong penerapan pendekatan *Reduce, Reuse* dan *Recycle* (3R). Salah satu solusi dari penerapan 3R berupa pembakaran sampah residu menggunakan sebuah alat dengan instalasi pembakar sampah yaitu insinerator. Namun demikian, komposisi sampah sangat mempengaruhi kualitas emisi yang dihasilkan. Kandungan bahan organik, plastik, logam berat, dan kadar air dalam sampah dapat menghasilkan polutan berbahaya seperti partikulat, karbon monoksida (CO), nitrogen oksida (NOx), dioksin dan furan apabila proses pembakarannya tidak berlangsung secara optimal. Pemantauan kualitas udara disekitar perlu diperhatikan, mengingat efluen hasil pembakaran sampah pada insinerator terdispersi ke udara ambien menggunakan *software* AERMOD.
Kata Kunci: *kota bandung, sampah domestik, insinerator, komposisi sampah, AERMOD*

1. Introduction

The use of incinerators is expected to be optimized to reduce waste problems in Bandung City and its surrounding areas more efficiently and become a solution for environmental cleanliness, waste incineration design takes into account the amount of combustion air, combustion residues, and incinerator design. There are two types of continuous incinerators where waste is burned continuously at a constant ratio, while in batch incinerators, waste is added up to the upper limit and burned together [1]. Generally, the optimal combustion temperature ranges from 850°C to 1100°C, depending on the type of waste being processed and the incinerator system used [2]. Complete incineration requires a high temperature of 650°C or more [3].

The composition of waste greatly affects the efficiency and success of the incineration process because each type of material has different physical and chemical characteristics, including moisture content, calorific value, and combustible content. Wet organic waste such as food scraps and leaves has high moisture content and low calorific value, requiring additional energy to evaporate the water before it can burn completely. Conversely, dry waste such as plastic, paper, and wood has a high calorific value and supports an efficient combustion process [4]. The chemical composition of waste, especially the content of carbon (C), hydrogen (H), and oxygen (O), affects the temperature and composition of incineration exhaust

gases [5]. The physical and chemical characteristics of waste depend on the dominant composition of the waste. The dominant waste category for all socioeconomic levels is biodegradable waste (56%), mainly food waste, which produces high moisture content in MSW or municipal solid waste, nylon plastic bags (11%), and textiles (9%)[6]. Incomplete combustion can produce pollutant emissions such as Total Particulates (PM), Sulfur Dioxide (SO_2), Nitrogen Oxides (NO_x), Carbon Monoxide (CO), and other hazardous compounds such as Hydrogen Chloride (HCl), Hydrogen Fluoride (HF), heavy metals (e.g., Mercury/Hg), and toxic organic compounds such as dioxins and furans[7].

Various meteorological factors play an important role in increasing the amount of particulates. Changes in meteorological parameters can have a significant impact on the spread of pollutants and the diffusion of air pollution, both from the region itself and from other surrounding regions [8]. Wind speed affects the spread and concentration of pollutants in an area, strong winds will cause pollutants in the environment and human activities to be carried away by the wind. When wind speeds are low, pollutants will accumulate around the area [9]. Wind direction is a key meteorological parameter that has a major impact on horizontal transport and distribution of air pollutants as well as vertical mixing and dispersion in a region [10]. Air humidity can affect pollutant concentrations, when humidity is high, water vapor in the air can react with air pollutants, turning them into other harmful substances or secondary pollutants [11].

Temperature affects air density and the altitude of the atmospheric layer where pollutants are concentrated, low air pressure is generally associated with unstable air conditions (rising air), which triggers cloud and rain formation, rain can have a negative impact on the entry of pollutants into the environment, as some pollutants can dissolve in rainwater causing acid rain that damages the environment, solar radiation plays a role in photochemical reactions that produce secondary pollutants, such as tropospheric ozone and photochemical smog and Atmospheric stability refers to the tendency of air to rise or fall. An unstable atmosphere is air that tends to rise, helping to spread pollutants to the higher atmosphere [12].

Air quality monitoring or air pollution control can be determined by tracking the movement of pollutants through modeling, AERMOD is an air dispersion model developed by the United States Environmental Protection Agency (U.S. EPA). This model is capable of simulating air quality from various types of emission sources, including point, line, surface, and volume sources originating from different locations. AERMOD consists of three main components in its modeling, namely wind direction and speed modeling using WRPLOT View, meteorological modeling with AERMET View, and topographic data processing through AERMAP [13]. In terms of processing, AERMOD has two main pre-processing modules, namely AERMET which processes meteorological data, and AERMAP which processes surface or elevation data, before finally being analyzed by the main AERMOD module [14].

2. Material and Methods

Geography of TPS3R X

TPS3R X is located in Kelurahan X, which is the study area of this research with a land area of 140 hectares. TPS3R X service area is a central sports activity area, dominated by residential areas with a population of 9,300 in 2025, consisting of 9 RW. TPS3R X is managed by a Community Self-Help Group. And to reduce waste at TPS3R X using incinerators.

Methods

Initial steps before creating a dispersion model using AERMOD software involve calculating emission load. In this study, actual operational data on incinerators was obtained through direct observation of waste incinerator operations at TPS3R X by measuring the amount of waste based on the components burned over a period of 8 days. Calculations to determine waste composition using the following formula [15]:

$$\frac{\text{waste mass by type}}{\text{total waste mass}} \text{ x } 100\% \quad (1)$$

When calculating emissions from waste incinerators, a distinction must be made between the dry weight and wet weight of waste, as the water content of waste can be very high. Therefore, the dry content of waste or waste fractions is an important parameter that must be determined [16]. Formula for the dry content of incinerated waste [17]:

$$\%\ dry\ content = 100\% - \%\text{moisture content} \quad (2)$$

$$\text{Dm} = \text{WFi x dmi} \quad (3)$$

When:

Dm = total dry matter of MSW

WF_i = weight of waste per component MSW
dm_i = dry matter content per component of MSW

The method for calculating emissions uses emission factors for each pollutant. The incinerator at TPS3R X does not provide any explanation regarding emission control devices. Therefore, based on conservative estimates, the emission factor for open burning of municipal solid waste is used and are presented in **Table 1**. Emissions estimates represent the mass of municipal solid waste incinerated. Emissions are calculated as follows [18]:

$$Dm = WFi \text{ x } dmi \quad (4)$$

When:
Emi = Emissions of pollutant i
Ms = Amount of MSW burned (kg/year)
EFi = Emission factor of pollutant i (g/kg of dry weight burned)

Table 1: emission factors for open burning of municipal solid waste

Pollutants	EF (g/kg)
SO_2	0,5
NOx	3
CO	42
$PM_{2,5}$	9,8
CO_2	1,453

To calculate the release duration and convert the mass released per day into g/sec, the formula used [19]:

$$ERadj = ER/h \text{ x } 0{,}2778 \quad (4)$$

When:
ERadj = adjusted emission rate (g/sec)
ER = calculated emission mass (kg/day)
H = emission duration (hours/day)
0.2778 = conversion factor from kg/hour to g/second

Ambient Air Quality Standards

In Appendix VII of Government Regulation No. 22 of 2021, standard values are set for various air pollutant parameters, including sulfur dioxide (SO_2), carbon monoxide (CO), nitrogen dioxide (NO_2), and fine particulate matter ($PM_{2.5}$), with different average measurement times, such as 1 hour, 8 hours, 24 hours, and annually, provided in **Table 2** [20].

Table 2: Various Air Pollutant Parameters

No	Parameter	Measurement Time	Quality Standard
1	Sulfur Dioxide (SO_2)	1 hour	150 µg/m^3
		24 hour	75 µg/m^3
		1 year	45 µg/m^3
2	Carbon Monoxide (CO)	1 hour	10000 µg/m^3
		8 hour	4000 µg/m^3
3	Nitrogen Dioxide (NO_2)	1 hour	200 µg/m^3
		24 hour	65 µg/m^3
		1 year	50 µg/m^3
4	Photochemical oxides (Ox) as Ozone (O3)	1 hour	150 µg/m^3
		8 hour	100 µg/m^3
		1 year	35 µg/m^3
5	Non-Methane Hydrocarbons (NMHC)	3 hour	160 µg/m^3
6	Particulate matter< 100 µm (TSP)	24 hour	230 µg/m^3
	Particulate matter< 10 µm (PM_{10})	24 hour	75 µg/m^3
		1 year	40 µg/m^3

No	Parameter	Measurement Time	Quality Standard
	Particulate matter< 2,5 µm ($PM_{2,5}$)	24 hour	55 µg/m^3
		1 year	15 µg/m^3
7	Lead (Pb)	24 hour	2 µg/m^3

3. Results and Discussion

These emission load calculations actual operational by measuring the amount the dry content of waste based on the components burned over average of 8 days for SO_2, Nox, CO, $PM_{2,5}$ and CO_2 pollutants are presented in **Table 3** and **4**.

Table 3: Recapitulation of dry matter content per component of MSW

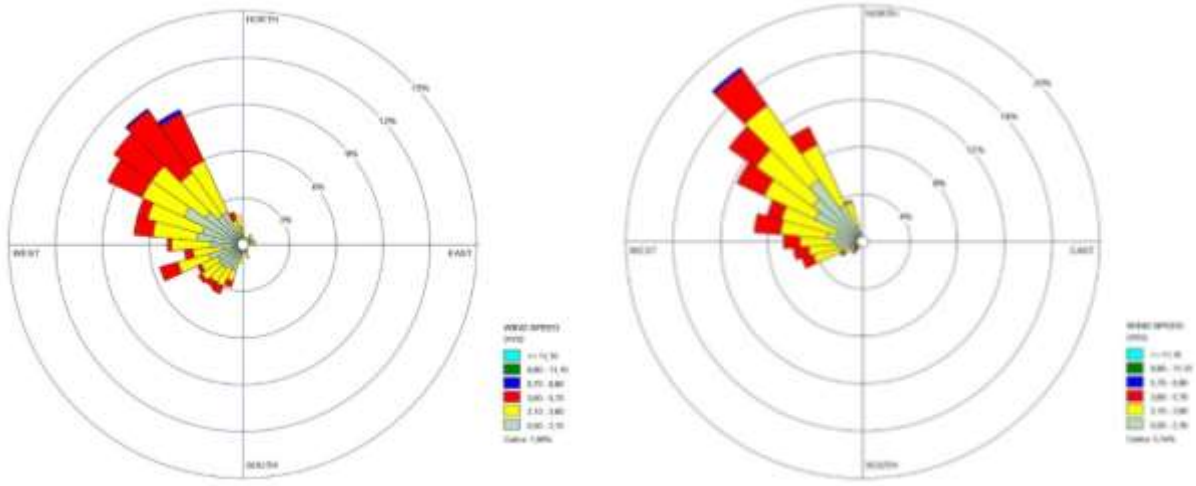
Type of waste	Dry matter (kg/day)							
	day							
	1	2	3	4	5	6	7	8
Garden waste	3802,81	3276,45	1425,52	1327,99		3151,15		3153,88
Food waste	196,28	168,67	146,80	239,18		194,62		442,51
Paper/cardboard	1373,23	193,60	1084,64	923,02	-	1326,13	-	1308,76
Plastic	1040,22	1786,41	757,65	795,05		1990,21		1206,58
Total	6412,54	5425,13	3414,62	3285,25		6662,12		6111,73

Table 3: Recapitulation of average emissions generated

Pollutants	ER adj (g/s)
	Average
SO2	0,08
NOx	0,46
CO	6,41
PM2,5	1,50

Dispersion result

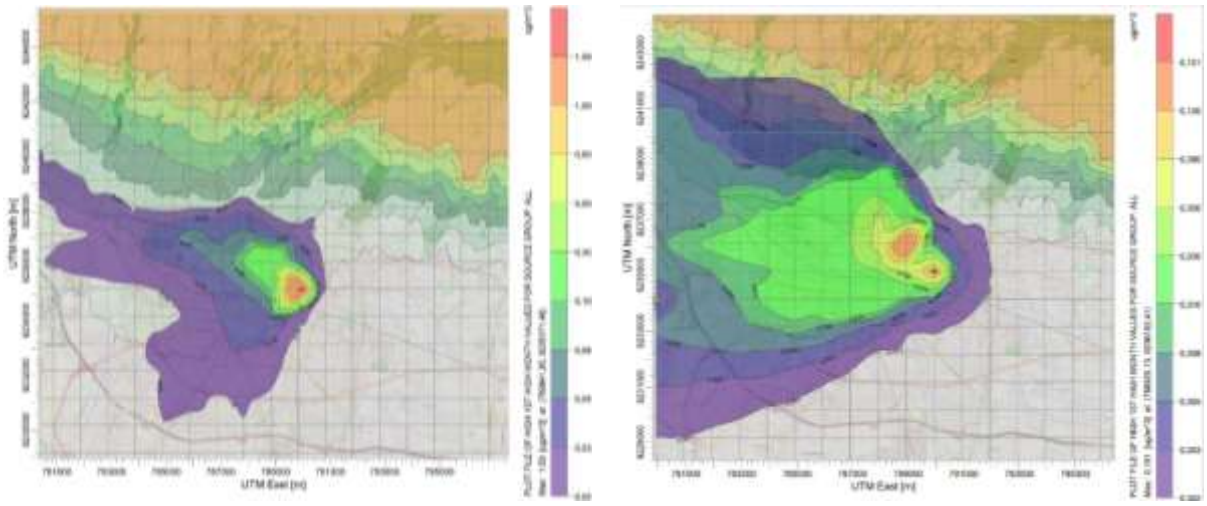
The dispersion results of SO_2, NOx, CO, and $PM_{2,5}$ pollutants during one month between the dry month (August) and the wet month (September) with characteristic wind speed conditions or movement in August not dominated by a particular speed category but almost balanced between moderate and slow wind speeds, while the characteristic wind speed or movement in September was dominated by a moderate wind speed category as shown in **Figure 1**.



(a) (b)

Figure 1: (a) Windrose in August (b) Windrose in September
Source: data processing results (2025)

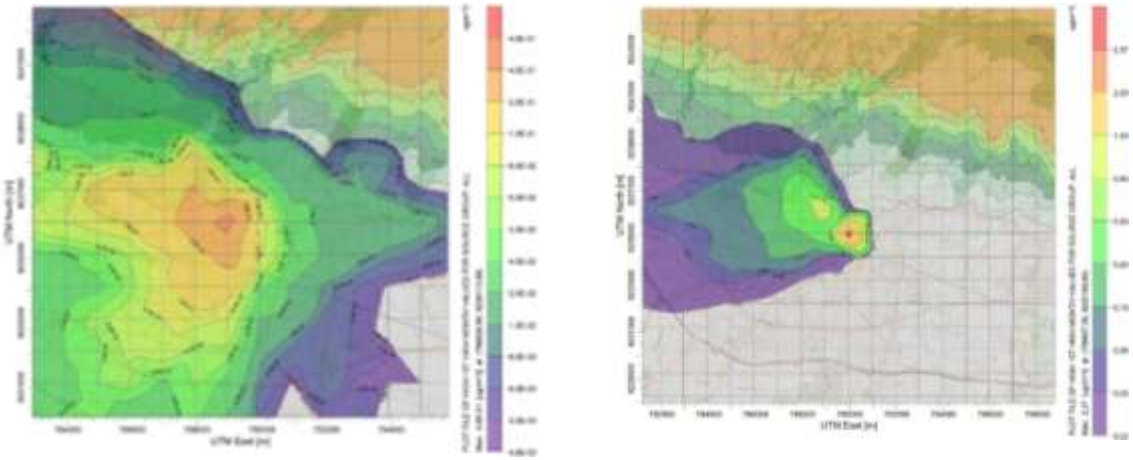
The difference in SO_2 pollutant concentrations in the AERMOD software results between the dry and wet seasons is due to weather variations in each period. In the dry season, there is minimal rainfall, making it difficult for SO_2 to be washed out, while weak and calm winds cause pollutants to accumulate near emission sources without dispersing widely, resulting in significantly higher minimum (0,02 µg/m³) and maximum (1,59 µg/m³) values. Similarly, the wet season, with higher rainfall intensity and predominantly moderate wind speeds, promotes wet deposition and the dispersion of SO_2 over a wide area, causing concentrations to drop significantly to a minimum of 0,002 µg/m³ and a maximum of 0,151 µg/m³, as shown in **Figure 2**.



(a) (b)

Figure 2: (a) SO_2 Dispersion in August (b) SO_2 Dispersion in September
Source: data processing results (2025)

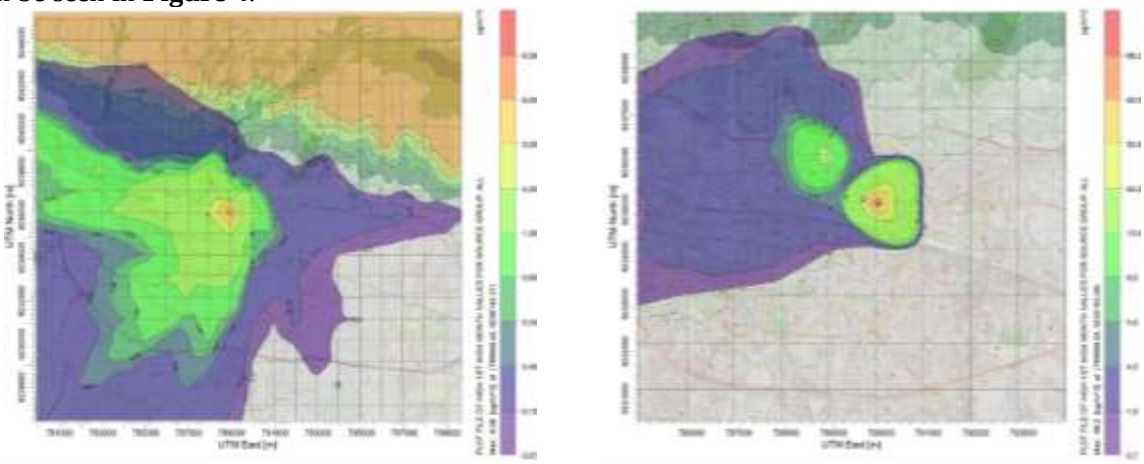
The difference in NOx concentrations in the AERMOD software results, which are lower in the dry season (minimum 0,0048 µg/m³ to maximum 0,48 µg/m³) compared to the wet season (minimum 0,02 µg/m³ to maximum 2,37 µg/m³), is due to weather variations that affect pollutant dispersion. During the dry season, stable winds with low speeds allow NOx to spread more evenly from emission sources without accumulating in one location, and the lack of rain actually supports better air mixing even without strong washing by rain, so that overall concentrations remain low. On the other hand, the wet season with high rainfall and strong prevailing winds often hinders upward dispersion and causes NOx to concentrate around the source due to changes in wind direction and humid air, which pushes the minimum and maximum values higher. These conditions can be seen in **Figure 3**.



(a) (b)

Figure 3: (a) NO_x Dispersion in August (b) NO_x Dispersion in September
Source: data processing results (2025)

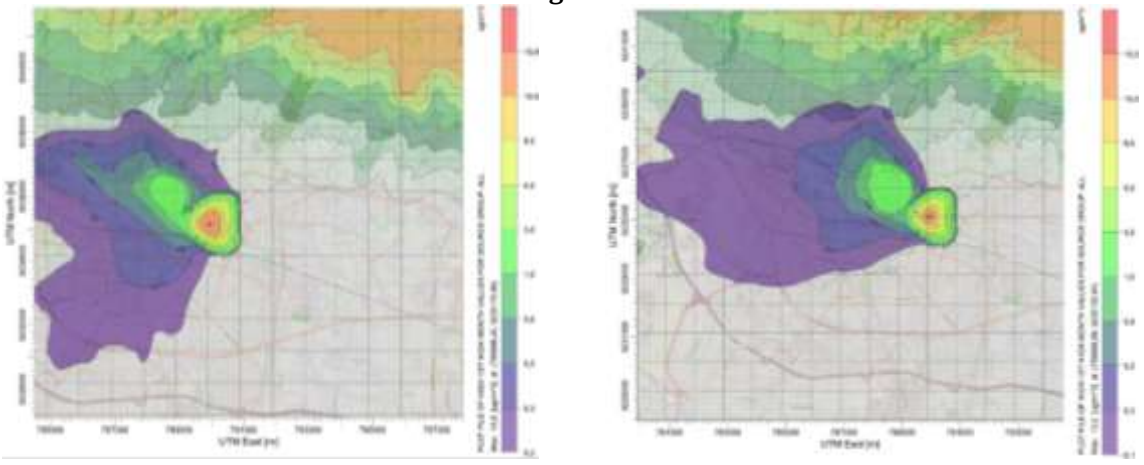
The difference in CO pollutant concentrations from the AERMOD software modeling results, which are much higher in wet months (minimum 0,7 µg/m³ to maximum 66,2 µg/m³) compared to dry months (minimum 0,07 µg/m³ to maximum 6,56 µg/m³), is due to weather conditions that affect how pollutants disperse in the air. During dry months, stable and dry winds allow CO to spread widely from emission sources without being trapped, so that the minimum and maximum concentrations remain low overall. Conversely, in wet months, high rainfall intensity and strong wind turbulence often limit vertical mixing and cause CO accumulation in areas near sources due to changes in wind direction and high humidity, causing concentration spikes of up to 10 times as seen in the maximum values. The moderate wind speeds that dominate during wet months are not strong enough for optimal dispersion like strong winds, causing pollutant accumulation under humid and rainy conditions that hinder effective washing. Both conditions can be seen in **Figure 4**.



(a) (b)

Figure 4: (a) CO Dispersion in August (b) CO Dispersion in September
Source: data processing results (2025)

The difference in PM2.5 pollutant concentrations calculated by the AERMOD software, which tend to be higher in dry months (minimum 0.2 µg/m³ to maximum 15.9 µg/m³) than in wet months (minimum 0.1 µg/m³ to maximum 13.2 µg/m³), occurs because dry weather prevents the washing away of pollutants by rain, causing particles to remain in the air longer and reach higher peak concentrations. During dry periods, the lack of rainfall reduces wet deposition, and air stability exacerbates the accumulation of primary PM2.5, SO2 concentrations (higher at 0.02–1.59 µg/m³), and NOx, which reacts to form secondary PM2.5 through chemical processes such as sulfate and nitrate formation. In wet months, rainfall effectively cleans PM2.5 through washout, suppressing total concentrations even though NOx tends to be higher during this period, because wet deposition has a greater effect than particle formation, resulting in lower concentrations. Both conditions can be seen in **Figure 5**.



(a) (b)

Figure 5: (a) PM2,5 Dispersion in August (b) PM2,5 Dispersion in September
Source: data processing results (2025)

The results of modeling the distribution pattern of SO2 over 24 hours in August and September compared to the ambient air quality standard for SO2 pollutants of 75 µg/m3 for a 24-hour measurement period show that the value is still below the applicable quality standard. The results of modeling the CO dispersion pattern for 8 hours compared to the ambient air quality standard for CO pollutants of 4000 µg/m3 for an 8-hour measurement period show that the value is still below the applicable quality standard. The results of the PM2.5 dispersion pattern modeling for 24 hours compared to the ambient air quality standard for PM2.5 pollutants of 55 µg/m3 for a 24-hour measurement period show that the value is still below the applied quality standard. All three conditions can be seen in **Figure 6**.

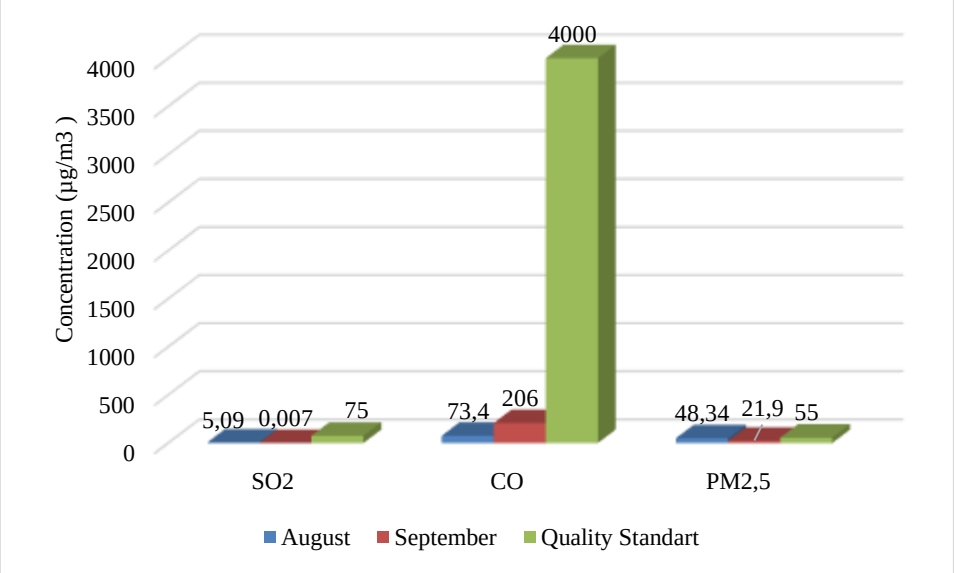


Figure 6: Comparison Chart of Modeling Results with Quality Standards
Source: data processing results (2025)

4. Conclusion

Based on the results of a study on the dispersion of SO_2, Nox, CO, $PM_{2,5}$ and CO_2 pollutants, the maximum concentrations of SO_2 and PM 2,5 pollutants are higher in dry months, while the maximum concentrations of NOx and CO pollutants are higher in wet months. These differences are influenced by meteorological factors, including wind direction and season. During dry months, stable and dry winds allow pollutants to spread widely from emission sources without being trapped, so that maximum concentrations remain low overall. Conversely, during wet months, high rainfall intensity and strong wind turbulence often limit vertical mixing and cause pollutant accumulation in areas near sources due to changes in wind direction and high humidity, which cause concentration spikes. The moderate wind speeds that dominate during wet months are not strong enough for optimal dispersion like strong winds, causing pollutant accumulation under humid and rainy conditions that inhibit effective washing. The concentration of pollutant dispersion modeling results for sulfur dioxide (SO_2), carbon monoxide (CO), and fine particulate matter ($PM_{2.5}$) compared to ambient air quality standards shows that the values are still below the quality standards.

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