

Article

Ambient Gaseous Pollutants in an Urban Area in South Africa: Levels and Potential Human Health Risk

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Abstract: Urban air pollution from gaseous pollutants is a growing public health problem in many countries including South Africa. Examining the levels, trends and health risk of exposure to ambient gaseous pollutants will assist in understanding the effectiveness of existing control measures and plan for suitable management strategies. This study determined the concentration levels and non-cancer risk of CO, SO₂, NO₂, and O₃ at an industrial area in Pretoria West, South Africa. We utilised a set of secondary data for CO, NO₂, SO₂, and O₃ that was obtained from a monitoring station. Analysis of the hourly monitored data was done. Their non-cancer risk (HQ) was determined using the human health risk assessment model for different age categories. The annual levels of NO₂ (39.442 µg/m³), SO₂ (22.464 µg/m³), CO (722.003 µg/m³) and the 8-hour concentration of CO (649.902 µg/m³) and O₃ (33.556 µg/m³) did not exceed the South African National Ambient Air Quality Standards for each pollutant. The HQ for each pollutant across exposed groups (except children) was less than 1. This indicates that the recorded levels could not pose non-cancer risk to susceptible individuals.

Keywords: gaseous pollutants; air quality; health risk assessment; South Africa

1. Introduction

Urban air pollution from gaseous pollutants is a growing environmental and public health problem in many cities of the world [1,2]. Carbon monoxide (CO), Nitrogen dioxide (NO₂), Sulphur dioxide (SO₂), and Ozone (O₃) are gaseous pollutants that have been internationally recognised as environmental priority air pollutants since they can constitute a threat to human health and the environment [3].

Reduction in lung function in children with a history of persistent asthma resulting from exposure to modest ambient concentrations of NO₂, NO, PM₁₀, and SO₂ has been reported in South Africa [4]. In addition, O₃, NO₂ and SO₂ can induce harmful effects such as increased bronchial reactivity [5,6], pulmonary and systemic inflammation [6], and protracted inflammatory and thrombotic responses in vulnerable individuals [7]. A possible association between short-term exposure to SO₂ and adverse endpoints, including gastrointestinal disorders and inflammation of the blood vessels, has been reported [8]. Also, association between day-to-day variations in NO₂ concentration and mortality, hospital admissions and respiratory symptoms was reported by the World Health Organization [9].

South Africa is among the world's foremost mining and mineral-processing nations, with large deposits of metals and coal. The country also possesses an energy and carbon-intensive economy [10].

Coal is an essential fuel for industrial processes in South Africa that is substantially used by coal-fired power stations. Most (91%) of the electricity generated in South Africa is from coal [11]. Although most power stations in South Africa use low-grade coal, the resultant emissions from coal burning such as CO, NO₂, SO₂, and Particulate matter (PM) have created huge environmental and health problems for communities sited in 'hot spot' areas with a large industrial presence [12]. South Africa often experiences high pollution levels that are injurious to human health, mainly in large industrial areas such as the South Durban Industrial Basin and the Vaal Triangle [13].

The Constitution of South Africa, 1996 Constitution of the Republic of South Africa (Act No. 108 of 1996) serves as the foundation for environmental regulation and policy in South Africa. The right to environmental protection and to live in an environment that is not harmful to health or well-being is clearly stated in Section 2.4 of Chapter 2 of the Bill of Rights. This fundamental right strengthens environmental policies and laws. In the year 2009, the South African government promulgated the National Ambient Air Quality Standards in terms of section 9 (1) of the National Management: Air Quality Act, 2004 [14]. This is to guard against adverse health effects in humans from exposure to ambient gaseous pollutants. In the year 2007, the National Framework for Air Quality Management (NFAQM) was formulated [15]. The establishment of the NFAQM ensured the emergence of new air quality and emission guidelines that target emissions emanating from industrial activities [15].

Understanding the trend in ambient concentration of gaseous pollutants and the non-cancer risks associated with short and long-term exposure to these pollutants in an industrial area has become an important field of air pollution health research [16]. This study will provide evidence-based knowledge on the impact of control measures instituted by governments in recent years, and for planning suitable risk assessment and management strategies for pollution control if need be. Therefore, this study examined the non-cancer health risk associated with exposure to concentrations of CO, SO₂, NO₂, and O₃ in an industrial area in Pretoria West, South Africa.

2. Methods

2.1. Study Area

The study was conducted in Pretoria West industrial area in the Gauteng province (Figure 1). It is positioned to the north of Johannesburg and extends from Centurion in the South to Temba in the North, encompassing an area of 2200 km² [17]. Within the Pretoria West industrial area, are industries with approved air emission licences, power plants and metallurgical industries and facilities with small boilers [18]. High pollution levels have been reported previously in this area [19]. The air quality monitoring station located in the industrial area is one of the seven monitoring air quality stations owned by the City of Tshwane. The stations are able to monitor priority pollutants such as SO₂, O₃, CO, NO₂, PM_{2.5}, PM₁₀, volatile organic compounds, benzene, toluene, and xylene effectively. Meteorological parameters such as wind speed, wind direction, temperature, relative humidity, precipitation, and solar radiation are also monitored. The detailed information on the study area has been reported in our earlier published works [18–21].



Figure 1. Google Earth image depicting Pretoria West industrial area. Source: Morakinyo et al. [20–22]. Red rings indicate some of the emission stacks in the study area.

2.2. Sampling

For this study, we utilised a set of data for CO, NO₂, SO₂, and O₃ that were obtained from the Environmental Management Services Department City of Tshwane. Ambient concentrations of CO, NO₂, SO₂, and O₃ were monitored by the data originators using a CO Analyzer (Model T300; S/N: 449), a NO_x Analyzer (Model T200; S/N: 1624), a Fluorescence SO₂ Analyzer (Model 100E; S/N: 2891), and an O₃ Analyzer (EC 9810; S/N: 08-1084) (Figure 2). The operational procedures for the samplers are described in their respective operational manuals [23–26]. Particulate matter of aerodynamic size 2.5 and 10, Benzene, Toluene, and Xylene were not included in the data analysis because there were so many missing data across different days due the malfunctioning of their monitors (Figure 3).

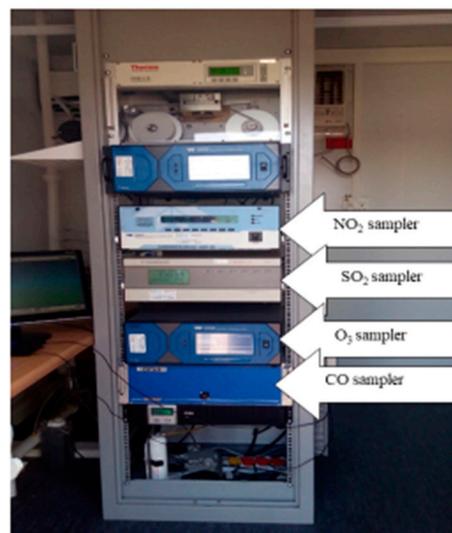


Figure 2. CO, NO₂, SO₂, and O₃ samplers.

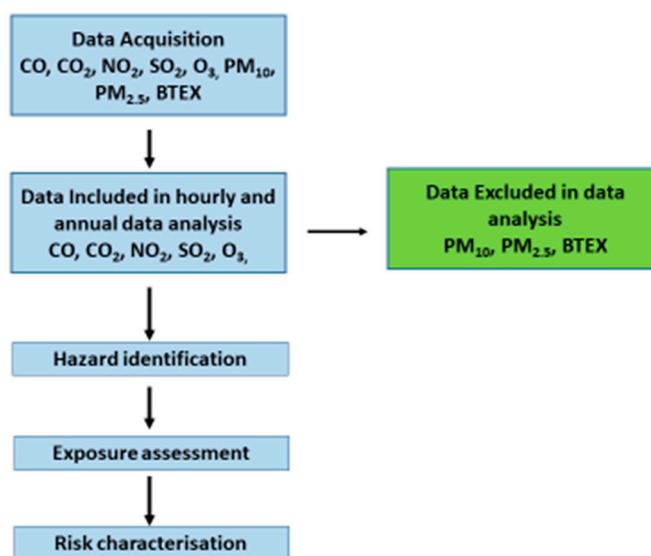


Figure 3. A flow chart of data type analysed and used for human health risk assessment.

Measurement of the air quality in Pretoria West industrial area is useful in estimating the levels of exposure to a pollutant that is considered to be safe for humans over their lifetime. To achieve acceptable air quality levels in the City of Tshwane (where Pretoria West industrial area is situated) and to minimise the impact of air pollution on both human health and the environment, the air quality management for Tshwane was developed in 2006 by the Environmental Management Division and the municipal health services [17].

In estimating the overall air quality in Pretoria West industrial area, we analyzed a 1-year (January 2016 to December 2016) long term ambient monitoring data of CO, SO₂, NO₂, and 8 h. The 24-h average concentrations of CO, SO₂, and NO₂ were estimated for days when they were valid data for not more than 20 h. Moreover, the 8 h average concentration of O₃ was calculated using the hourly concentration. The levels of the pollutants measured were compared with recommended guidelines as shown in Table 1. The most recent national air quality standards for PM₁₀, CO, SO₂, NO₂, and O₃ as stated in Schedule 32816 of the NEMA: AQA was gazetted by the then Minister of Water and Environmental Affairs on 24 December 2009 [27]. Air quality standards indicate the levels of exposure to air pollutants that are safe for human health over a set time span.

Table 1. Reference ambient standards for CO, NO₂, SO₂, and O₃.

Pollutant	Reference Standard Concentration			
	1 h (µg/m ³)	8 h (µg/m ³)	24 h (µg/m ³)	Annual (µg/m ³)
NO ₂	200*	-	188***	40*
SO ₂	350*	-	125*	50*
CO	29,770**	10,305**	-	-
O ₃	226***	120*	-	-

*NAAQS—National Ambient Air Quality Standards for South Africa; **Default value was in ppm; ***South Africa standards—Air Quality Act (Act 39 of 2004); NO₂: nitrogen dioxide, SO₂: sulphur dioxide, CO: carbon monoxide, O₃: ozone Source: South Africa [27].

The four seasons in South Africa are classified based on the months of the year as follows: summer (December, January and February), autumn (March, April and May), winter (June, July and August), and spring (September, October and November).

Analysis of hourly monitored data for monthly and annual concentrations of CO, NO₂, SO₂, and O₃ was done using IBM SPSS statistical software version 20 (SPSS Inc., Chicago, USA), while the graphical representation was done using Microsoft Excel 2013 spreadsheet. Graphical representation (wind rose and

polar plots) of the effects of wind speed and wind direction on the concentration of CO, NO₂, SO₂, and O₃ was done using R[®] (v.2.13.1) statistical software. This was used to deduce the dominant prevailing winds and the seasonal distribution and levels of the pollutants in the study area. Descriptive statistics such as mean, standard deviation and percentages were used to summarise the air pollution data in a meaningful way so that the hourly, weekly, monthly, and annual patterns of the pollutants in the study area emerged. Descriptive statistics give a summary of the data under consideration and together with graphics analysis form the basis of quantitative data analysis.

2.3. Health Risk Assessment

To estimate the possible health risks that exposure to CO, NO₂, SO₂, and O₃ could pose to residents of the study area, human health risk assessment (HHRA) of the inhalation exposure pathways was conducted. The HHRA is a tool used by regulatory agencies to assist in the formulation of policies that protect public health against the harmful effects of air pollution [28]. The HHRA framework used in this study has four components: hazard identification, dose-response assessment, exposure assessment, and risk characterisation.

2.4. Hazard Identification

Hazard identification is a process of recognising if a pollutant present in an environment is likely to induce adverse human health effects should exposure to that pollutant occur [29]. The identification of CO, NO₂, SO₂, and O₃ as injurious to human health in this study was achieved through a review of existing literature.

2.5. Dose-Response Assessment

The dose-response assessment detects the association between exposure level or dose and the severity of the health endpoints that are likely to occur [30]. Dose-response assessment was not calculated in this study. The amount of CO, NO₂, SO₂, and O₃ absorbed into the body was estimated from their concentration and the duration of exposure. The measured ambient concentrations was then compared with the South African National Ambient Air Quality Standards (NAAQS) [14].

2.6. Exposure Assessment

The exposure assessment describes the population exposed to the pollutant and the magnitude and duration of exposure to the pollutant. In this study, the human populations living in Pretoria West are the likely receptors of levels of the pollutants. The population consists of 23.2% young persons (0–14 years), 71.9% persons of working-age (15–64 years) and 4.9% elderly persons (65+ years) [31]. The study population was grouped into four categories: infants (birth–1 year), children (2–5 years), children (6–12 years), and adults (19–75 years). We have utilised this age classification in our previous study [22].

2.7. Risk Characterisation

Risk characterisation is the quantitative estimation of the health risk of exposure to a pollutant. It reflects the probability of an adverse health outcome occurring among healthy and/or sensitive individuals [32]. In this study, the risk of exposure to the pollutants was determined by estimating the Hazard Quotient (HQ) for non-carcinogens [29].

The health risk of exposure to CO, NO₂, SO₂, and O₃ through the inhalation route was estimated using Equations (1) and (2).

$$\text{ADD}_{\text{inh}} = \frac{C \times \text{InhR} \times \text{EF} \times \text{ED}}{\text{BW} \times \text{AT}} \quad (1)$$

$$\text{HQ} = \text{ADD}_{\text{inh}}/\text{RfC} \quad (2)$$

where:

- ADD is the average daily dose of CO, NO₂, SO₂, and O₃ through the inhalation route
- C is the concentration of CO, NO₂, SO₂, and O₃ in ambient air
- InhR is the inhalation rate (m³/day)
- ED is the exposure duration (days)
- BW is the body weight of the exposed group (kg)
- AT is the averaging time (days)
- EF is the exposure frequency (days/year)
- HQ is the hazard quotient
- RfC is the reference dose for pollutant (Table 1) [33].

The value used for computing each parameter is presented in Table 2. An HQ > 1.0 suggests the likelihood of sensitive individuals experiencing non-cancer health effects through exposure to a pollutant [34].

Table 2. Recommended values in equations of the daily exposure dose of CO, NO₂, SO₂.

Parameter	Definition	Value for Age Categories				Reference
		Infant (0–1 yr.)	Child (2–5 yrs.)	Child (6–12 yrs.)	Adult (19–75 yrs.)	
C	Mean concentration of CO, NO ₂ , SO ₂ in ambient air (µg/m ³)					
EF	Exposure frequency (days/year)	350	350	350	350	[19,35]
ED	Exposure duration (years)	1	6	12	30	[35,36]
AT	Averaging time (days); AT = ED X365 days	365	2190	4380	10,950	[35,36]
BW	Body weight (kg)	11.3	22.6	45.3	71.8	[35,36]
InhR	Inhalation rate (m ³ /day)	9.2	16.74	21.02	21.4	[35]

3. Results and Discussion

3.1. Mean Concentrations of NO₂, SO₂, CO and O₃

Table 3 shows the hourly, daily and annual concentration levels of pollutants in the ambient air of the study area. The mean 1-hour concentrations of NO₂, SO₂, CO, and O₃ are 18.345 µg/m³, 16.138 µg/m³, 295.410 µg/m³, and 26.840 µg/m³ respectively.

Table 3. Ambient concentrations of NO₂, SO₂, CO, and O₃.

Averaging Time	NO ₂ (µg/m ³)	SO ₂ (µg/m ³)	CO (µg/m ³)	O ₃ (µg/m ³)
	Mean	Mean	Mean	Mean
1 h	18.35	16.21	295.41	26.84
8 h	-	-	649.90	33.56
24 h	18.47	16.84	-	-
Annual	39.44	22.46	722.00	-

The recorded annual levels of NO₂ (39.442 µg/m³), SO₂ (22.464 µg/m³), and CO (722.003 µg/m³) and the 8-hour concentration of CO (649.902 µg/m³) and O₃ (33.556 µg/m³) did not exceed the NAAQS. However, the annual mean concentrations of NO₂ and SO₂ decreased from 39.442 µg/m³ to 11.50 µg/m³ and from 22.464 µg/m³ to 18.68 µg/m³ during the periods of 2014 and 2016 respectively [19]. The annual concentration of NO₂ recorded in this study was lower than that recorded in certain urban cities in Africa such as Dakar, Senegal (59.6 µg/m³; 31.7 ppb) [37] and Cairo, Egypt (66.74 µg/m³; 35.5 ppb) [38].

However, the annual means of NO₂ and SO₂ recorded in this study were higher than the annual means of 30.5 µg/m³ (16.2 ppb) and 9.4 µg/m³ (3.6 ppb) documented in Bamako, Mali [37], and the annual means of 9.1 µg/m³ (4.85 ppb) and 0.8 µg/m³ (0.29 ppb) reported in Kampala, Uganda [39]. Levels of NO₂ and SO₂ in urban areas have been linked to coal combustion in industries and biomass burning in residential areas [40,41]. Coal burning is the main contributor of SO₂ into the atmosphere [42].

The emission inventory of most industrial areas has shown that power plants, industry and vehicular emissions are the major contributors of NO₂ [43,44].

3.2. Diurnal Variations in the Concentrations of NO₂, SO₂, CO and O₃

The levels of the pollutants fluctuated over the days of the week, with NO₂, CO and O₃ showing similar temporal variation and the highest levels recorded on Sundays. In comparison, the level of SO₂ was highest on Mondays (Figure 4). The ambient concentrations of pollutants on weekdays (Monday to Friday) vs the weekend (Saturday to Sunday) showed higher levels of NO₂ (40.66 µg/m³ vs 37.26 µg/m³), SO₂ (19.73 µg/m³ vs 15.75 µg/m³) and CO (569.0 µg/m³ vs 515.0 µg/m³).

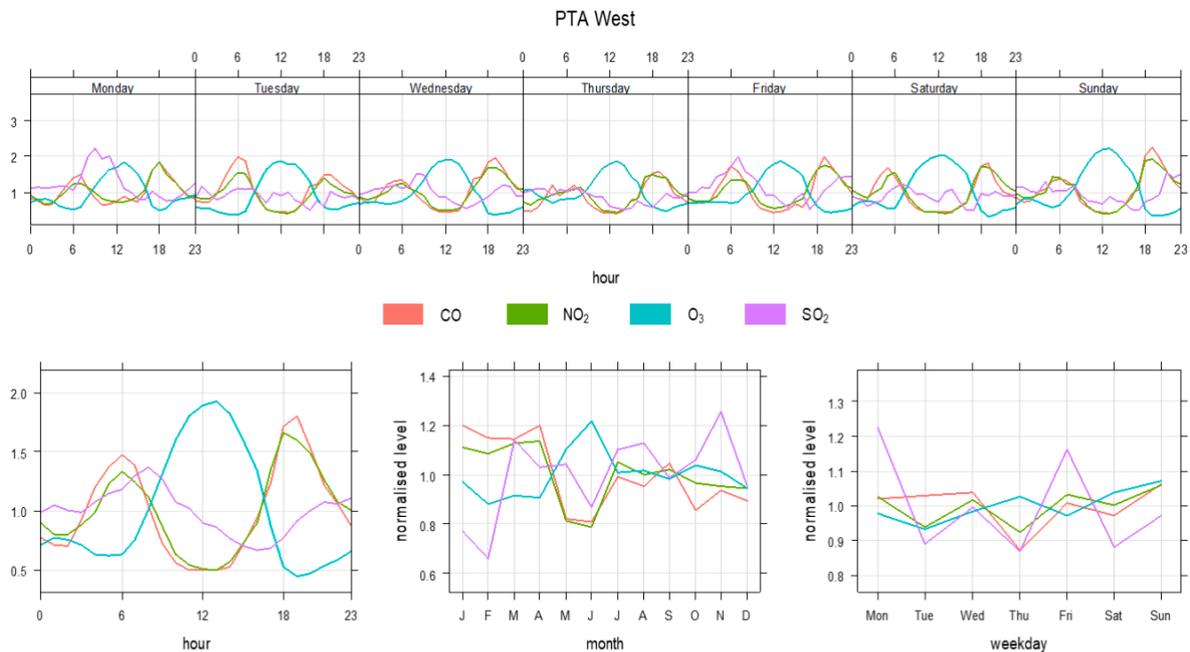


Figure 4. Trends in the concentrations of NO₂, SO₂, CO, and O₃. *PTA West – Pretoria West Industrial Area.

This finding is consistent with the results of a study conducted in Senegal in which higher levels of gaseous pollutants were recorded on weekdays than on weekends [37]. Other studies have presented similar patterns [38,45]. It is believed that the level of emissions of air pollutants from anthropogenic sources is lower on weekends than on weekdays in urban areas [45].

However, higher levels of O₃ were observed on weekends (50.09 µg/m³) than on weekdays (48.63 µg/m³). This corroborated findings from an earlier study conducted in Europe in the Veneto region of Italy [46]. In the current study, higher levels of 8-hour O₃ were recorded during the daytime (62.23 µg/m³) than during the nighttime (31.81 µg/m³). An obvious daily peak at mid-afternoon (Figure 4) that corresponded to hours with solar radiation was observed. Researchers have linked O₃ formation in the atmosphere with an extended period of sunshine (solar radiation) and high daytime temperatures [47,48].

Similar day and night variations were observed for NO₂ (36.95 µg/m³ vs 40.63 µg/m³), SO₂ (15.85 µg/m³ vs 18.58 µg/m³) and CO (528.0 µg/m³ vs 548.0 µg/m³), with more pollution recorded during the night hours than during the daytime hours. A similar trend was reported in Cairo by Hassan et al. [38]. Possible explanations for this trend are the build-up of pollutants in the atmosphere due to steady air, reduced vertical mixing within a low boundary layer [49] and nighttime conditions occasioned by reduced wind speeds and increased calm conditions.

Peak levels of NO₂ (5:00 p.m.–7:00 p.m.), SO₂ (6:00 a.m.–9:00 a.m.), CO (5:00 p.m.–7:00 p.m.), and O₃ (10:00 a.m.–4:00 p.m.) were observed at different hours of the day. Moreover, NO₂ and CO presented

two daily peaks in the morning (6:00 a.m.–8:00 a.m.) and evening (6:00 p.m.–8:00 p.m.) (Figure 4). Similar bimodal diurnal patterns are reported in the literature [37]. These periods correspond to hours with higher vehicular movement and industrial production. In between the two modes is the period with the lowest levels of NO₂ and CO (10:00 a.m.–2:00 p.m.) (Figure 4). This scenario could be due to reduced vehicular movement, improved atmospheric dispersion, higher levels of O₃ in the ambient air, the photolysis of NO_x, the oxidation of CO, and the elevated boundary layer [46]. In addition, the mean concentration of SO₂ increased at 6:00 a.m.–8:00 a.m. and 6:00 p.m.–8:00 p.m., probably due to changes in climatic conditions and the boundary layer.

3.3. Seasonal Distribution of NO₂, SO₂, CO and O₃

Elevated pollution levels for NO₂ ($70.196 \pm 52.77 \mu\text{g}/\text{m}^3$), SO₂ ($31.779 \pm 23.72 \mu\text{g}/\text{m}^3$) and CO ($1108.360 \pm 1053.40 \mu\text{g}/\text{m}^3$) were observed in winter compared with the summer levels of NO₂ ($18.760 \pm 11.70 \mu\text{g}/\text{m}^3$), SO₂ ($14.227 \pm 12.68 \mu\text{g}/\text{m}^3$) and CO ($352.889 \pm 201.13 \mu\text{g}/\text{m}^3$) (Table 4). The average concentrations of NO₂, SO₂ and CO were in the order of winter > autumn > spring > summer. These seasonal variations reflect the effects of meteorological conditions occasioned by dawdling winds and a greater percentage of wind calm hours [50,51]; lower mixing of boundary heights, limiting the diffusion capacity of the atmosphere and thus confining the emitted pollutants close to the ground [52]; less rainfall [53]; lower temperatures [53]; and reduced oxidation potential with a reduction in O₃ formation [46]. In contrast, a reduction of pollutants was seen in summer due to the increased duration of sunshine, resilient turbulent currents and precipitation that dilutes the concentration of pollutants emitted at the Earth's surface [54].

Table 4. Mean seasonal concentrations of NO₂, SO₂, CO and O₃.

Season	NO ₂ (μg/m ³)	SO ₂ (μg/m ³)	CO (μg/m ³)	O ₃ (μg/m ³)
	Mean	Mean	Mean	Mean
Summer	18.76	14.23	352.89	61.51
Autumn	39.51	18.83	592.42	44.04
Winter	70.20	31.80	1108.36	34.92
Spring	24.43	18.74	459.03	59.36

Nevertheless, O₃ showed a different seasonal variation pattern with the peak pollution levels observed in summer and the lowest in winter (Table 4). This pollutant displays the highest concentration in summer when solar radiation is higher and the atmospheric photochemistry is largely dynamic [46]. The formation of O₃ in the atmosphere is a function of photochemical reactions that are influenced by solar radiation and precursor emissions [55]. Also, the stratosphere–troposphere exchange process plays a critical role in the increase of the mean concentration of O₃ in summer and spring [56]. However, recent findings have reported higher O₃ concentrations in winter than in summer [57].

The pollution rise shows the wind directions that dominate the overall concentration of a pollutant. Figure 5a–d indicate that the south-westerly winds and the north-easterly winds are the most predominant winds controlling the overall concentrations of NO₂, SO₂, CO, and O₃. This clearly shows that the probability of these pollutants originating from the same source or direction is high. In Figure 5b, the concentration of SO₂ is highest when the winds are from the southwest, perhaps from the Vaal Triangle air pollution priority area, and also from the east, perhaps from the Highveld air pollution priority area where many Eskom power plants are sited.

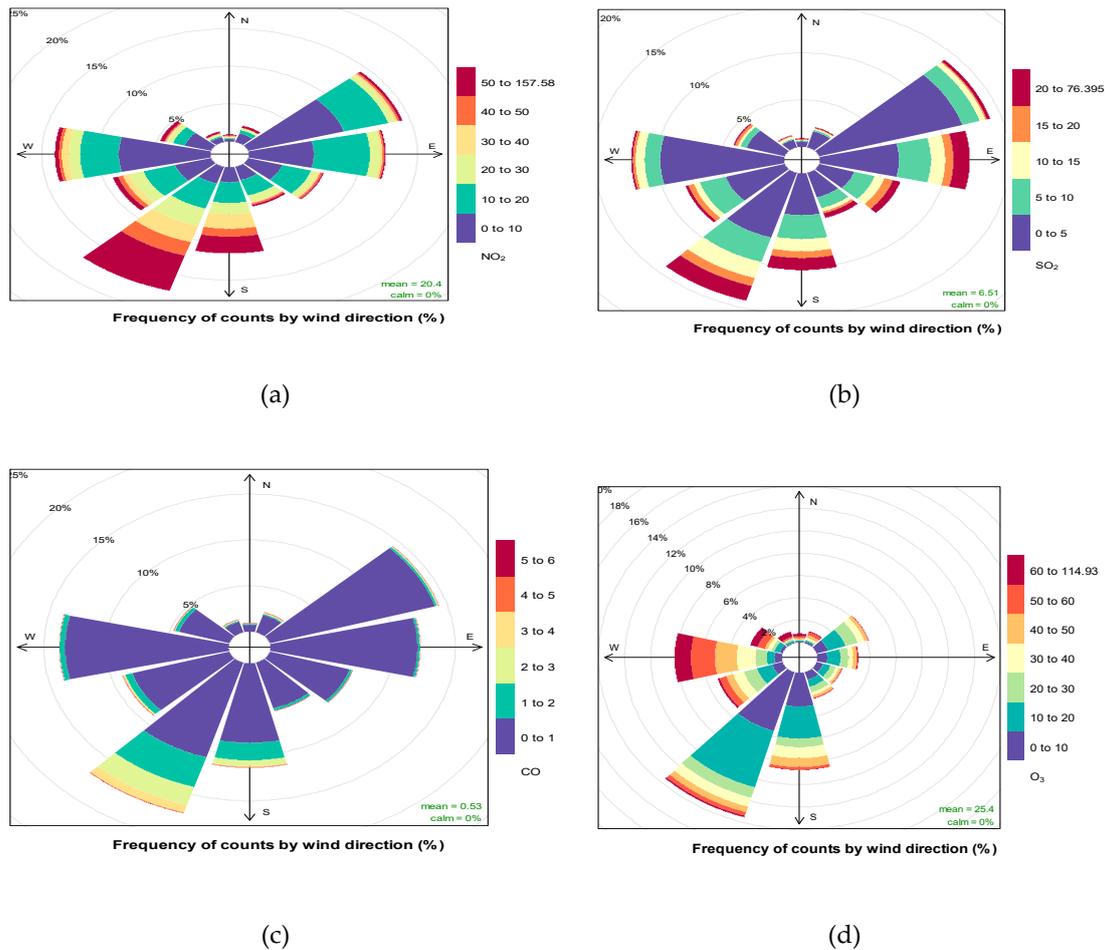


Figure 5. Pollution roses NO₂ (a), SO₂ (b), CO (c), and O₃ (d).

3.4. Non-Carcinogenic Health Risks of NO₂, SO₂, CO and O₃ via Inhalation Route

The results of the non-carcinogenic risks from exposure to an ADD of NO₂, SO₂, CO, and O₃ via the inhalation route are presented in Figure 6. It was assumed that the inhalation route is the major pathway for exposure to the pollutants. A similar pattern of health risk from exposure to NO₂, SO₂, CO, and O₃ was observed. The calculated HQ for each pollutant across exposed groups (except children) was less than 1 (HQ < 1). This indicates that the levels of NO₂, SO₂, CO, and O₃ recorded for Pretoria West are unlikely to pose a threat to public health (infants, toddlers and adults). However, the HQ of exposure to NO₂ (1.192), SO₂ (1.021) and O₃ (1.589) among children was greater than 1 (HQ > 1). This implies that children (2–5 years) have a higher potential for experiencing non-carcinogenic health effects through exposure to NO₂, SO₂ and O₃ than infants and adults.

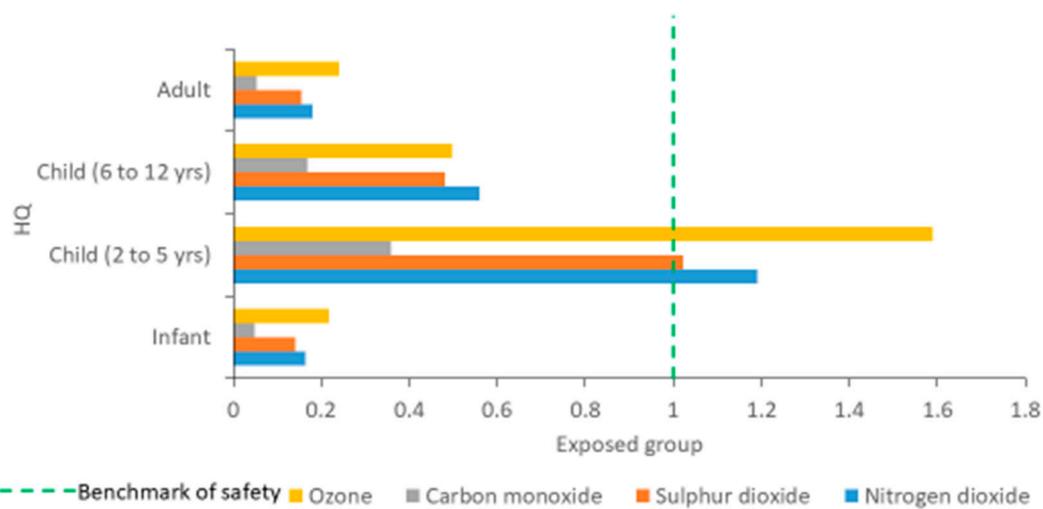


Figure 6. Non-carcinogenic risks of NO₂, SO₂, CO, and O₃.

The seasonal non-carcinogenic risks of NO₂, SO₂, CO, and O₃ through the inhalation pathway are presented in Figure 7. All pollutants induce greater non-carcinogenic effects during winter than during the other seasons. The order of HQ is winter > autumn > spring > summer. Similarly, higher non-carcinogenic risks from the ingestion of NO₂, SO₂, CO, and O₃ were observed among children than among the other age groups during the different seasons. This suggests that although the levels of NO₂, SO₂, CO, and O₃ in the study area are low, some non-cancer risks among vulnerable groups could be induced.

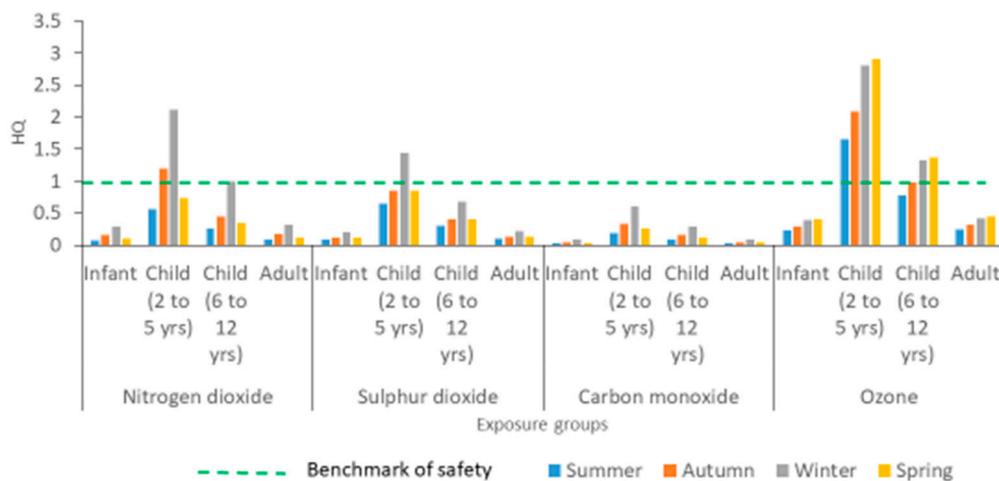


Figure 7. Seasonal non-carcinogenic risk assessment for NO₂, SO₂, CO, and O₃.

The possibility of adverse health outcomes occurring from exposure to levels of gaseous pollutants that are below the safe limits stipulated by regulatory agencies has been reported [58]. Human exposure to low concentrations of NO₂ may result in hospital admission for respiratory infections and acute and obstructive lung diseases [59,60]. In Europe, a significant association was found between exposure to a small amount of NO₂ and the occurrence of acute ischaemic stroke [61,62]. Owing to the ability of O₃ to impair lung tissues, exposure to O₃ can induce coughing, breathlessness and chest pain. An immune response to allergens in susceptible individuals could also be triggered [2].

4. Conclusions

This study provided information on the concentrations and trends of key gaseous pollutants in Pretoria West industrial area. Air quality in the study area was based on the monitored data of NO₂,

SO₂, CO, and O₃ from January to December 2016. The annual mean concentrations of the pollutants did not exceed the South African recommended standards. There was a daily diurnal variation in the concentration of the pollutants, with NO₂, SO₂ and CO having the highest and lowest levels during the night hours and the day hours respectively. Conversely, higher levels of O₃ were recorded during the daytime. Also, NO₂, SO₂, and CO presented the highest levels in winter and the lowest level in summer, while the O₃ concentration peaked in summer and was at its lowest in winter. Moreover, children are more likely to be susceptible to the non-cancer effects of exposure to the monitored gaseous pollutants. Although the annual concentration of the pollutants did not exceed the level recommended by the South African government, the recorded levels could pose some degree of non-cancer risk to susceptible individuals. Continuous monitoring of the ambient levels of the pollutant in the study area will ensure compliance with emission standards as instituted by government of South Africa.

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