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Research Article

Air Quality and Human Health Risk Assessment in the Residential Areas at the Proximity of the Nkolfoulou Landfill in Yaoundé Metropolis, Cameroon

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Landfill operations generate particulate matters (PM) and toxic gases that can jeopardize human health. This study was conducted in February 2016 to assess the air quality in the residential areas around the Nkolfoulou landfill in Yaoundé. The concentrations of $PM_{2.5}$ and PM_{10} were determined with Dust Sentry while those of CO, O_3, NO_2, CH_4, CO_2, CH_2O, H_2S, and SO_2 were measured using gas sensors. At the landfill neighborhood, 30% of the daily mean concentrations of $PM_{2.5}$ and PM_{10} crossed the daily safe limits. The concentrations of CO, O_3, NO_2, SO_2, and H_2S recorded at the propinquity of the landfill complied with the emission standards. Near the landfill, hourly mean concentrations of CH_2O and H_2S higher than their odour thresholds were recorded at each sampling site. The concentrations of CH_4 were less than its lower explosive limit while those of CO_2 were far below the safe limit for occupational health. The values of cancer risk (CR) due to the inhalation of CH_2O were $>10^{-6}$ while those of hazard index (HI) due to the inhalation of CH_2O, H_2S, and SO_2 were <1. Thus, there might be increased cancer risks at the Nkolfoulou landfill neighborhood, whereas the increased non-cancer risks were low. 96.76% of the daily average levels of air pollutants registered near the landfill surpassed those recorded at the remote control site. Hence, the landfill operations might be supplying air pollutants to the neighbouring residential areas.

1. Introduction

Landfilling is the most widely used method of solid waste disposal across the world [1–3]. Landfill operations generate air pollutants such as particulate matters (PM) and gases [4]. The landfill gases (LFG) emitted into the environment may originate from the waste or may be generated during its decomposition [2]. Pristine air is a prerequisite for good health [5, 6]. Outdoor air pollutants are carcinogen Group 1 to humans; they induce lung cancer [7]. Air pollutants may conduce to the pathogenesis of upper airway diseases, viz., sinusitis, rhinitis, mild otitis, sinonasal cancer, and olfactory impairment [8]. Breathing polluted air during pregnancy may cause foetus growth retardation and abortion [6, 9, 10].

A link between short- or long-term exposure to airborne PM and human mortality and morbidity has been substantiated by several epidemiological studies [11–14]. Chronic exposure to $PM_{2.5}$ and PM_{10} damages the respiratory and cardiovascular systems, while exposure to high concentrations of ozone (O_3) is a major factor in asthma morbidity and mortality [6]. High levels of sulfur dioxide (SO_2) reduce lung function and may provoke the irritation of the nose and the throat [15]. Hydrogen sulfide (H_2S) is the predominant landfill odour gas [16, 17]. Subjection to low and high concentrations of H_2S may induce the irritation of the throat and respiratory distress, respectively [18]. Formaldehyde (CH_2O) is not only a human carcinogen Group 1, causing cancer of the nasopharynx [19], but is also an irritant gas [20]. Many studies have been carried out

elsewhere on the impact of landfill on the ambient air quality [4, 11, 21–25]. But, in Cameroon, data related to this issue are scanty. Therefore, this study focuses on the influence of the Nkolfoulou landfill activities on the ambient air quality.

2. Materials and Methods

2.1. Study Site Description. The study area has tropical climate and is located at the apex of a hill called Nkolfoulou. The Nkolfoulou landfill is situated at about 16 km away from the Yaoundé center. It was established in 1989 and was still in operation during this study. It covers a total land area of about 45 ha [26] and receives about 1300 tons of waste generated daily in the town of Yaoundé [27]. Employing a geographical positioning system (GPS) Magellan Triton-300, the geographical coordinates of the selected study stations were recorded. ArcGIS 10 software was used to draw the map of the study area and to gauge the distances between the sampling sites and the landfill boundary. Table 1 represents the locations of the monitoring sites, while Figure 1 displays the map of the study area.

2.2. Data Collection and Health Risk Evaluation. In February 2016, towards the end of the long dry season, the measurements of air pollutants were performed first at ten sites coded RA_1, RA_2, RA_3, RA_4, RA_5, RA_6, RA_7, RA_8, RA_9, and RA_{10}, selected in the residential areas around the landfill, and finally at a background site RA_0 carefully chosen for control. The concentration of gases was measured using a handheld Aeroqual Gas Sensor model S-500L, battery-operated, possessing an interchangeable sensor head. For each site, the concentrations of gases were recorded continuously for every 1 hour at intervals of 30 minutes, each making 16 hours of measurement daily (24 hours). For each hour, gas concentrations were measured after every 5 minutes giving 12 readings per hour for each gas. Thus, 192 readings were recoded for each gaseous pollutant per site during a day (24 hours). The airborne particulates (PM_{10} and $PM_{2.5}$) measurements were carried out using a digital Aeroqual Dust Sentry (made by Aeroqual Limited, New Zealand) equipped with a laser. During measurements, the instrument was placed on a tripod of 1.5 m height. The measuring device was configured to record average concentrations of PM hourly at a flow rate of 2.0 L/min. Before measurements, all the instruments were calibrated according to the manufacturer's instructions.

The non-cancer risks induced by the inhalation of CH_2O, H_2S, and SO_2 were evaluated by calculating the hazard quotient (HQ) using equation (3) deduced from equation (1), whereas the cancer risk (CR) due to the inhalation of CH_2O was computed from equation (4) deduced from equation (3) [28]:

$$\mathrm{HQ} = \frac{\mathrm{EC}}{\mathrm{MRL}}, \tag{1}$$

where EC = exposure concentration ($\mu g/m^3$) and MRL = minimal risk level ($\mu g/m^3$).

Table 1: Specifications of the monitoring sites.

Site code	GPS coordinates		SL (m)	DLB (m)
	E	N		
RA_0	11°34′17.043″	3°56′25.866″	694	1000.00
RA_1	11°34′15.801″	3°55′27.96″	701	161.37
RA_2	11°34′36.123″	3°55′29.889″	720	34.40
RA_3	11°34′43.421″	3°55′29.084″	734	118.58
RA_4	11°34′26.945″	3°55′49.69″	730	239.06
RA_5	11°34′24.22″	3°56′0.289″	708	305.02
RA_6	11°34′12.123″	3°55′58.821″	661	58.25
RA_7	11°34′4.757″	3°55′54.325″	667	165.74
RA_8	11°34′0.786″	3°55′52.929″	693	255.33
RA_9	11°33′59.289″	3°55′46.615″	669	189.27
RA_{10}	11°33′51.403″	3°55′37.557″	673	279.40

SL = sea level; DLB = distance from the landfill boundary.

$$\mathrm{CR} = \mathrm{IUR} \times \mathrm{EC}, \tag{2}$$

where IUR = inhalation unit risk $(\mu g/m^3)^{-1}$. HQ and CR are unitless.

For acute exposures (exposure lasting 24 hours or less), EC = CA [28], where CA = contaminant concentration in air ($\mu g/m^3$). Hence, equations (1) and (2) become

$$\mathrm{HQ} = \frac{\mathrm{CA}}{\mathrm{MRL}}, \tag{3}$$

$$\mathrm{CR} = \mathrm{IUR} \times \mathrm{CA}. \tag{4}$$

For exposure to multiple non-carcinogenic substances, the resulting hazard index (HI) was calculated from the following equation [29, 30].

$$\mathrm{HI} = \sum_{i}^{n} \mathrm{HQ}_i. \tag{5}$$

The MRLs of CH_2O, H_2S, and SO_2 are 0.04 ppm (49.2 $\mu g/m^3$) [20], 0.07 ppm (98 $\mu g/m^3$) [18], and 0.01 ppm (26.2 $\mu g/m^3$) [15], respectively, for acute exposures while the IUR of CH_2O is 1.3×10^{-5} $(\mu g/m^3)^{-1}$ [31].

3. Results and Discussion

3.1. Particulate Matter. The concentrations of each air pollutant were averaged for each hour and then for 24 hours. The levels of outdoor $PM_{2.5}$ and PM_{10} measured at the monitoring sites are encapsulated in Table 2. The lowest hourly mean level of $PM_{2.5}$ was recorded at RA_{10} (9.53 $\mu g/m^3$), while the highest was registered at RA_3 (44.02 $\mu g/m^3$). The hourly mean levels of PM_{10} varied from 18.86 (RA_{10}) to 114.45 $\mu g/m^3$ (RA_3). The hourly high level of $PM_{2.5}$ and PM_{10} in the study area could be owing to landfill operations since they generate dust by a variety of mechanical and chemical processes [22].

The daily mean concentrations of $PM_{2.5}$ and PM_{10} varied from 18.59 $\mu g/m^3$ (RA_9) to 37.57 $\mu g/m^3$ (RA_3) and 28.84 $\mu g/m^3$ (RA_{10}) to 97.69 $\mu g/m^3$ (RA_3), respectively. The daily mean levels of $PM_{2.5}$ of 32.75 (RA_2), 37.57 (RA_3), and 31.39 $\mu g/m^3$ (RA_6) were higher than the daily safe limit of 25 $\mu g/m^3$ set by the WHO [6]. Likewise, the daily mean levels of PM_{10} of 91.34 (RA_2), 97.69 (RA_3), and 82.91 $\mu g/m^3$ (RA_6) surpassed the daily

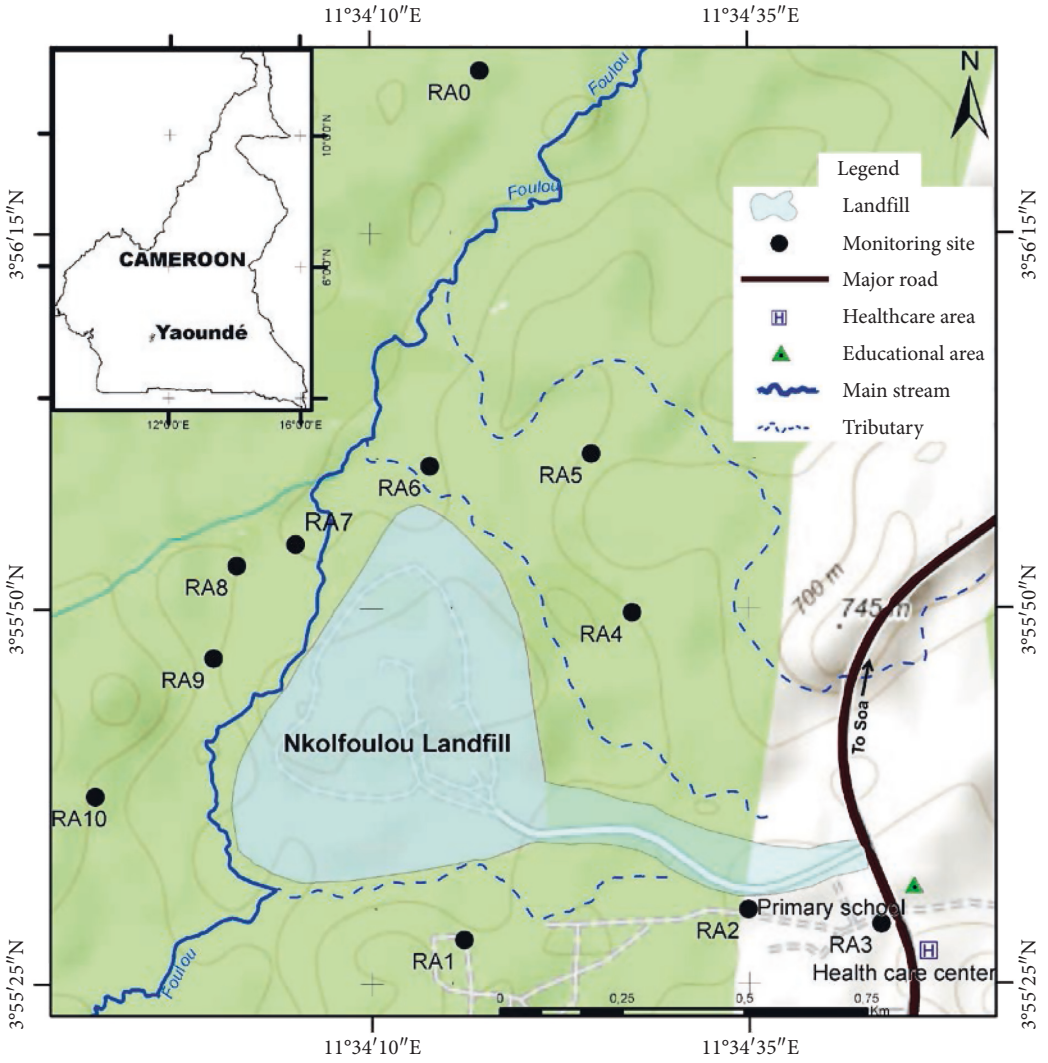

Figure 1: Map of the study area.

Table 2: Concentration of particulate matter at the monitoring sites ($n = 24$).

Site code	$PM_{2.5}$ ($\mu g/m^3$)			PM_{10} ($\mu g/m^3$)		
	Range of hourly mean		Daily mean	Range of hourly mean		Daily mean
	Min	Max		Min	Max	
RA_0	10.50	17.50	12.85	18.90	31.50	23.12
RA_1	12.09	22.34	19.19	25.39	46.91	40.29
RA_2	12.50	39.50	32.75	35.00	110.60	91.34
RA_3	18.20	44.02	37.57	47.32	114.45	97.69
RA_4	12.57	21.75	19.23	18.86	42.63	35.71
RA_5	13.40	22.58	20.49	28.14	47.42	43.04
RA_6	14.20	36.80	31.89	36.92	95.68	82.91
RA_7	13.91	21.56	19.56	29.21	45.28	41.07
RA_8	12.20	23.19	20.36	24.16	45.92	40.32
RA_9	9.53	21.35	18.59	20.34	40.65	37.84
RA_{10}	11.64	24.82	21.63	26.70	42.95	28.84

RA = residential area; ND = not detected; n = number of measurements per day (24 hours).

safe limit of 50 $\mu g/m^3$ laid down by the WHO [6]. Several studies have provided strong evidence that subjection to high concentration of PM may induce cardiopulmonary disease (CPD) and ischemic heart disease (IHD) mortality [32]. The hourly and daily average levels of $PM_{2.5}$ and PM_{10} recorded at the proximity of the landfill were lower than those registered at

the background site RA_0, implying that the landfill operations might be contributing to $PM_{2.5}$ and PM_{10} to the ambient air. The movement of vehicles and motorbikes on the unpaved and poorly maintained roads in the study area as well as the ongoing construction works may have constituted additional sources of PM.

3.2. Odourless Gases. Although O_3 has a shocking smell, humans get rapidly acclimated to it. Moreover, the frequently associated presence of nitrogen oxides suppresses its perception [33]. For these reasons, it was classified among odourless gases in this study. Table 3 lists the concentrations of odourless gases in the study area.

The hourly mean concentrations of CO and O_3 ranged from ND (not detected) to 6.44 mg/m^3 (RA_3) and ND to 137.42 μg/m^3 (RA_5), respectively, while their daily average levels varied from 0.04 (RA_{10}) to 1.48 mg/m^3 (RA_3) and 5.73 (RA_9) to 26.18 μg/m^3 (RA_5) in the same order. NO_2 was detected only at RA_2 and RA_3. Its hourly and daily mean levels ranged from ND to 94.07 μg/m^3 (RA_3) and 35.92 (RA_2) to 49.60 μg/m^3 (RA_3). During this study, none of the CO value exceeded the safe limit of 100, 60, 30, and 10 mg/m^3 for the averaging duration of 15 mn, 30 mn, 1 hr, and 8 hr, respectively, set by the WHO [5]. So also, all the concentrations of O_3 and NO_2 were far below their maximum emission limits laid down by the WHO in [5, 6], respectively. Relatively high levels of CO and NO_2 recorded at RA_2 and RA_3 compared with other sites may be attributable to their proximity to the highway.

The hourly mean value of 6.44 mg/m^3 for CO registered in this work was lower than the 8-hour mean level of 7.79 mg/m^3 recorded in a residential area around On-Nooch solid waste disposal site in Bangkok (Thailand) [21]. It was also less than 4 ppm (4.64 mg/m^3) obtained in a residential area at the vicinity of Eneka landfill in Port Harcourt (Nigeria) [25]. But, the higher hourly mean value of 94.07 μg/m^3 (0.947 mg/m^3) for NO_2 recorded in this work was greater than the hourly mean figure of 0.034 mg/m^3 found around On-Nooch dumpsite (Thailand) [21].

3.3. Odorous Gases. H_2S, CH_2O, and SO_2 are colorless and malodorous gases. H_2S has the characteristic odour of rotten eggs [18] while CH_2O has a pungent smell [20] as well as SO_2 [15]. Their concentrations are depicted in Table 4. In the residential areas adjacent to the landfill, the hourly mean levels of CH_2O, H_2S, and SO_2 ranged from ND to 206.76 μmg/m^3 (RA_6), ND to 236.40 μg/m^3 (RA_6), and ND to 28.56 μg/m^3 (RA_3), respectively, while their daily average varied from 14.49 (RA_5) to 32.25 μg/m^3 (RA_1), 8.74 (RA_5) to 28.06 μg/m^3 (RA_6), and 1.05 (RA_9) to 4.18 μg/m^3 (RA_3) in the same order. The maximum 30-minute mean limit of 100 μg/m^3 for CH_2O [5] (Table 5) was crossed at all the sampling points near the landfill, whereas the maximum daily mean safe limit of 20 μg/m^3 for SO_2 [6] (Table 5) was not violated at any site. Comparatively, all the daily mean values of SO_2 were much lower than the daily mean value of 8.91 mg/m^3 recorded at the vicinity of On-Nooch dumpsite [21]. High concentrations of CH_2O irritate the nose, the throat, and the eyes [5, 20]. Subjection to a high level of SO_2 exacerbates asthma and can cause lung dysfunction [6, 15, 34].

At the proximity of the landfill, all the maximum hourly and daily mean values of H_2S were higher than its odour threshold contained in the approximate range of 0.5–8 ppb (0.7–11.2 μg/m^3) [35, 36]. So also, all the maximum hourly and daily mean values of CH_2O at RA_1 and RA_6 exceeded its odour threshold which is in the range 30–600 μg/m^3 [5]. Besides, all the daily mean concentrations of H_2S crossed the safe limit of 7 μg/m^3, while all the maximum hourly mean concentrations of CH_2O violated the safe limit of 100 μg/m^3. These safe limits are prescribed by the WHO [5] for an averaging time of 30 min to prevent annoyance and sensory effects. Subjection to low levels of H_2S may induce headaches and breathing difficulties in some asthmatic patients [18]. These gases may worsen the poor health conditions of patients in the healthcare center or bring about discomfort and annoyance to pupils in the primary school since both areas are situated close to RA_3.

At the background site RA_0, CH_2O and H_2S were not detected while the values of SO_2 were less than those recorded at the vicinity of the landfill, suggesting that the landfill may be the main contributor of CH_2O and H_2S to its surroundings. CH_2O and H_2S may have originated, respectively, from the decomposition of carbohydrate and protein [37] in the landfill. Meanwhile, CH_2O could have another source since aldehydes can be generated either from photochemical oxidation of hydrocarbons (HC) in the atmosphere [38] or through the incomplete combustion of fuel [39]. High hourly and daily mean concentrations of SO_2 registered at RA_3 cause one to think that the traffic was also contributing to SO_2 by the combustion of sulfur-containing fuels. The nearness of RA_6 to the landfill, the closeness of RA_2 to the entrance of the landfill and to the highway, and the proximity of RA_3 to the highway and the motorbike park may explain the high levels of CH_2O, H_2S, and SO_2 recorded at these sites.

3.4. Potential Greenhouse Gases. CH_4 and CO_2 are the main constituents of landfill gases (LFG) [40]. They are generated during the putrefaction of waste. The CH_4 and CO_2 concentrations in the study area are depicted in Table 6. The hourly mean levels of CH_4 and CO_2 were found, respectively, between ND and 2.30 ppm (RA_6) and 401.60 (RA_9) and 649.27 ppm (RA_3) while their daily average ranged from 0.01 (RA_{10}) to 1.76 ppm (RA_6) and 459. 85 (RA_8) to 573.02 ppm (RA_3) in the same order. The higher hourly and daily mean concentrations of CH_4 recorded at RA_6 could be due to its proximity to the landfill, whereas the higher hourly and daily mean concentrations of CO_2 recorded at RA_3 could be attributable to its location very close to both the gate of the landfill and the highway. So, it is reasonable to think that some CO_2 at these stations may have originated from the combustion of fuel in motor vehicles.

All the concentrations of CH_4 were less than its lower explosive limit (LEL) which is 5% [40] while all the levels of CO_2 were far below 5000 ppm as the maximum

Table 3: Concentration of odourless gases at the monitoring sites ($n_1 = 12$; $n_2 = 192$).

Site code	CO (mg/m^3)			O_3 (μg/m^3)			NO_2 (μg/m^3)		
	Range of hourly mean		Daily mean	Range of hourly mean		Daily mean	Range of hourly mean		Daily mean
	Min	Max		Min	Max		Min	Max	
RA_0	ND	0.30	0.05	ND	10.51	1.32	ND	ND	NC
RA_1	ND	1.00	0.27	ND	40.01	5.73	ND	ND	NC
RA_2	ND	4.58	0.92	ND	58.90	10.63	ND	75.26	35.92
RA_3	ND	8.02	1.48	ND	39.41	6.54	ND	94.07	49.60
RA_4	ND	1.55	0.42	ND	58.90	6.54	ND	ND	NC
RA_5	ND	4.01	0.46	ND	137.42	26.18	ND	ND	NC
RA_6	ND	7.44	1.07	ND	38.94	5.73	ND	ND	NC
RA_7	ND	1.86	0.36	ND	39.26	8.18	ND	ND	NC
RA_8	ND	0.64	0.13	ND	78.53	6.54	ND	ND	NC
RA_9	ND	1.37	0.05	ND	19.63	5.89	ND	ND	NC
RA_{10}	ND	2.40	0.04	ND	58.90	19.63	ND	ND	NC

RA = residential area; ND = not detected; NC = not calculated because not detected; n_1 = number of measurements per hour; n_2 = number of measurements per day (24 hours).

Table 4: Concentration of odorous gases at the monitoring sites ($n_1 = 12$; $n_2 = 192$).

Site code	CH_2O (μg/m^3)			H_2S (μg/m^3)			SO_2 (μg/m^3)		
	Range of hourly mean		Daily mean	Range of hourly mean		Daily mean	Range of hourly mean		Daily mean
	Min	Max		Min	Max		Min	Max	
RA_0	ND	ND	NC	ND	ND	NC	ND	1.74	0.82
RA_1	ND	185.56	32.25	ND	152.97	20.45	ND	14.28	2.14
RA_2	ND	133.95	24.88	ND	139.06	19.60	ND	26.18	3.56
RA_3	ND	130.32	22.02	ND	122.49	11.02	ND	28.56	4.18
RA_4	ND	172.20	25.71	ND	166.87	22.45	ND	11.90	2.28
RA_5	ND	138.62	14.49	ND	62.97	8.74	ND	6.80	1.30
RA_6	ND	206.76	30.83	ND	236.40	28.06	ND	16.66	1.70
RA_7	ND	147.15	28.13	ND	194.68	25.13	ND	12.14	1.90
RA_8	ND	181.10	27.79	ND	180.78	24.02	ND	11.05	1.45
RA_9	ND	149.08	21.65	ND	139.06	20.25	ND	4.92	1.05
RA_{10}	ND	142.03	17.59	ND	125.15	17.53	ND	5.35	1.18

RA = residential area; ND = not detected; NC = not calculated because not detected; n_1 = number of measurements per hour; n_2 = number of measurements per day (24 hours).

Table 5: WHO ambient air quality standards.

Pollutant	Averaging duration	Maximum allowable limit	Reference
$PM_{2.5}$	24 hours	25 μg/m^3	[6]
	Annual	10 μg/m^3	[6]
PM_{10}	24 hours	50 μg/m^3	[6]
	Annual	20 μg/m^3	[6]
CO	15 minutes	100 mg/m^3	[5]
	30 minutes	60 mg/m^3	[5]
	1 hour	30 mg/m^3	[5]
	8 hours	10 mg/m^3	[5]
SO_2	10 minutes	500 μg/m^3	[6]
	24 hours	20 μg/m^3	[6]
CH_2O	30 minutes	0.1 mg/m^3	[5]
H_2S	24 hours	150 μg/m^3	[5]
O_3	8 hours	100 μg/m^3	[6]
NO_2	1 hour	200 μg/m^3	[5]
	Annual	40 μg/m^3	[5]

concentration level for occupational health [41]. Therefore, CH_4 and CO_2 are not a threat in the area under study for now.

Near the landfill, as far as the daily mean concentrations of gaseous pollutants were concerned, their abundance was in the following order: $CO_2 > CO > CH_4 > CH_2O > H_2S > O_3 > NO_2 > SO_2$.

3.5. Correlation Matrix. The correlation matrices for 9 measured air pollutants at the vicinity of the landfill are illustrated in Table 7. The significant positive correlation observed between $PM_{2.5}$ and CO ($r = 0.65$, $p \leq 0.05$), PM_{10} and CO_2 ($r = 0.69$, $p \leq 0.05$), and PM_{10} and CO ($r = 0.89$, $p \leq 0.01$) signifies that CO and CO_2 are the major contributors of PM in the study area. At the 0.05 P level, a significant positive correlation was observed between CO and CO_2 ($r = 0.70$) and between CO and SO_2 ($r = 0.70$)

Table 6: Level of potential greenhouse gases at the monitoring sites ($n_1 = 12$; $n_2 = 192$).

Site code	CH_4 (ppm)			CO_2 (ppm)		
	Range of hourly mean		Daily mean	Range of hourly mean		Daily mean
	Min	Max		Min	Max	
RA_0	ND	ND	NC	421.00	498.04	461.82
RA_1	ND	0.06	0.03	450.25	503.12	481.64
RA_2	ND	0.05	0.02	478.61	602.41	550.16
RA_3	ND	0.03	0.01	490.25	649.27	573.02
RA_4	ND	0.07	0.04	420.31	510.00	464.39
RA_5	ND	0.04	0.01	425.50	503.74	466.41
RA_6	ND	2.30	1.76	451.63	612.10	541.37
RA_7	ND	0.18	0.08	428.50	505.31	467.32
RA_8	ND	0.09	0.05	421.75	510.80	459.85
RA_9	ND	0.07	0.04	401.60	507.28	469.63
RA_{10}	ND	0.06	0.01	425.00	501.37	460.11

RA = residential area, ND = not detected, NC = not calculated because ND, n_1 = number of measurements per hour, n_2 = number of measurements per day (24 hours).

Table 7: Correlation matrix.

	$PM_{2.5}$	PM_{10}	CH_4	H_2S	CH_2O	CO_2	SO_2	CO	O_3
$PM_{2.5}$	1								
PM_{10}	0.564	1							
CH_4	−0.320	0.042	1						
H_2S	−0.309	−0.139	**0.927****	1					
CH_2O	−0.212	−0.091	**0.709***	**0.818****	1				
CO_2	0.420	**0.685***	0.018	−0.127	0.188	1			
SO_2	0.410	0.600	−0.030	0.018	0.382	0.576	1		
CO	**0.648***	**0.891****	0.042	−0.067	0.127	**0.697***	**0.697***	1	
O_3	0.350	−0.043	−0.615	−0.572	**−0.689***	−0.332	−0.117	−0.049	1

*Correlation is significant at the 0.05 level; **Correlation is significant at the 0.01 level; bold values are statistically significant.

implying that these pair variables have almost the same sources that could be either the combustion of fuel, fire wood, kerosene, or cooking gas in the study area. A significant high positive correlation was observed between CH_4 and H_2S ($r = 0.93$, $p \leq 0.01$), CH_4 and CH_2O ($r = 0.71$, $p \leq 0.05$) and between CH_2O and H_2S ($r = 0.89$, $p \leq 0.01$) indicating that these pair variables have the same source which could be the landfill through the degradation of refuse. The negative significant correlation observed between O_3 and CH_2O ($r = -0.69$, $p \leq 0.05$) signifies that when one of the variable rises, the other decreases. This is because O_3 is formed from CH_2O by photochemical reactions.

3.6. Non-cancer and Cancer Risk Assessment. The non-carcinogenic risks associated with the exposure to CH_2O, H_2S, and SO_2 via inhalation were evaluated by calculating the hazard quotient (HQ) and the hazard index (HI), whereas the carcinogenic risks due to CH_2O through inhalation was estimated by computing the cancer risk (CR). HQ or HI values below 1.0 indicate that the pollutant under investigation is not likely to cause health impairment, whereas HQ or HI values above 1.0 indicate risk levels that are likely to damage health [42, 43]. The CR values $> 10^{-6}$ indicate that potential carcinogenic effects may occur, whereas CR values $\leq 10^{-6}$ represent an admissible level [43]. The data for HQ and HI are depicted in Figure 2 while those for CR are displayed in Figure 3. In the residential areas bordering the landfill, the values of HQ_{CH_2O}, HQ_{H_2S}, and HQ_{SO_2} varied from $2.95E-01$ (RA_5) to $6.55E-01$ (RA_1) (mean $4.99E-01$), $8.92E-02$ (RA_5) to $2.86E-01$ (RA_3 and RA_6) (mean $2.24E-01$), and $4.01E-02$ (RA_9) to $1.36E-01$ (RA_2 and RA_3) (mean $7.66E-02$), respectively. In this same area, the HI values ranged from $4.33E-01$ (RA_5) to $9.76E-01$ (RA_6) (mean $8.00E-01$), while those of CR due to CH_2O was found between $1.88E-04$ (RA_5) and $4.19E-04$ (RA_1) (mean $3.19E-04$). None of the HQ and HI values exceeded the threshold value, set at the unity, implying that CH_2O, H_2S, and SO_2 are not likely to induce adverse health effects in the area under study for now. All the CR values were higher than 10^{-6} indicating that the nearby residents to the landfill are at risk of developing cancer in future owing to the inhalation of CH_2O. Comparatively, all the CR values due to CH_2O registered in this study were higher than 2.9×10^{-5} recorded near a plant treating organic waste in Catalonia (Spain) [44].

The risk levels in this study might have been overestimated as the chemical concentrations were measured solely for 24 hours instead of one year. Contrastingly, risks might have been underestimated because only the concentrations of CH_2O, H_2S, and SO_2 among a multitude of volatile toxic compounds that might be present were considered for the assessment of health risk. Furthermore, only exposure via inhalation was considered although exposure

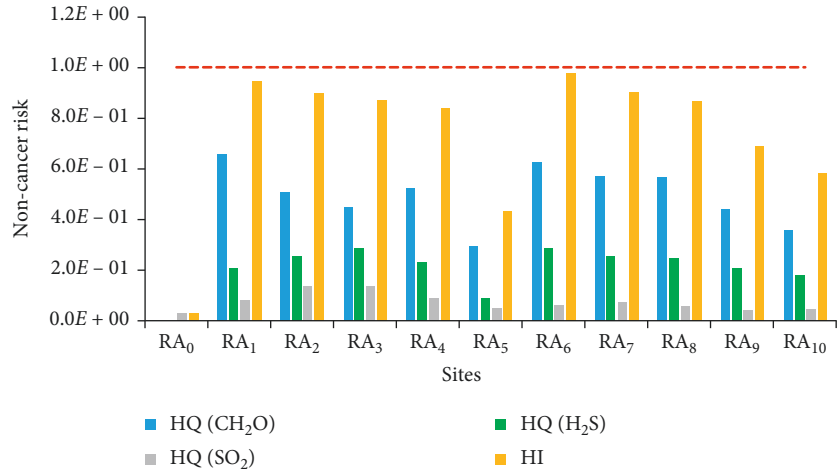

Figure 2: Non-cancer risks at the monitoring sites (the non-cancer risks of CH_2O and H_2S at RA0 were not calculated because they were not detected at that site; the horizontal line represents the admissible level of non-cancer risk [42, 43]).

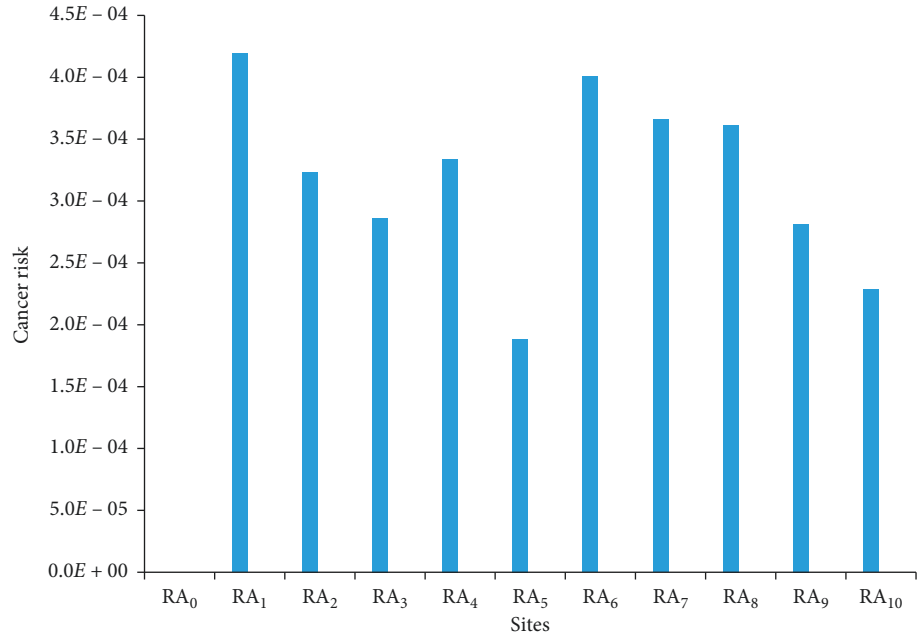

Figure 3: Cancer risks (CR) at the monitoring sites (CR at RA0 was not calculated because CH_2O was not detected at that site).

through ingestion and skin absorption may occur even if it is most often much lower [43].

4. Conclusion and Recommendations

According to the results of the present study, at the vicinity of the landfill, 30% of the daily mean concentrations of $PM_{2.5}$ and PM_{10} and all the detected levels of CH_2O crossed the daily maximum safe limit, while the concentrations of CO, O_3, NO_2, SO_2, and H_2S were within the emission standards. However, noxious gases, viz., CH_2O and H_2S, were detected at the concentrations higher than their odour thresholds. Continuous dispatch of these gases into the ambient air may significantly reduce air quality and imperil public health and welfare. The values of cancer risk (CR) and hazard index (HI), respectively, were higher than 10^{-6} and less than the unity. Thus, the nearby residents to the Nkolfoulou landfill may experience an increase in risks of developing cancer while there was no significant increase of non-cancer risks. 96.76% of the daily average levels of air pollutants recorded in the neighborhood of the Nkolfoulou landfill exceeded those found at the remote control site, implying that the landfill operations might be contributing to air pollutants to the ambient air.

By this study, the following mitigation strategies can be recommended:

(a) Daily cover of odorous wastes or odour treatment at the landfill site.

(b) The road linking the highway to the landfill should be paved or thoroughly watered daily to keep the concentrations of PM at bay.

(c) Planting trees around the landfill to absorb air pollutants.

Data Availability

All the data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest concerning the publication of this article.

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