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Particulate matter and carbon dioxide gas concentrations and their effects on meteorology: a case study using Benghazi City, Libya

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ABSTRACT:

The main aim of this work is to assess the spatiotemporal variation of particulate matter (PM1, PM2.5 and PM10) during the monitoring period from February 2023 to December 2023 and to determine the level concentration of CO2 in the atmosphere. The station that was used in this work named AirVisual Outdoor monitor; this station recorded the parameters every five minutes. The data obtained from these stations are air quality index (AQI), temperature, humidity, wind speed and wind direction. The results showed the air quality index (AQI) in February, May, October and November periods is classified as unhealthy for sensitive groups (level 3), People with heart or lung disease, older adults, and children are considered sensitive and therefore at greater risk, the rest of periods are classified as moderate air quality (level 2). The highest values of PM1 and PM2.5 were recorded in the February period while the highest value of PM10 was observed in the May period. According to the classification and source of air pollution, the atmosphere contained mixed particles (fine and coarse particles) during all periods. The February period was affected by anthropogenic pollution and the rest of the periods were affected by mixed to natural pollution (dust source). In general, Benghazi city is more affected by natural pollution than anthropogenic pollution. Most of the meteorological parameters were positively correlated with PMs, which reflect that an increase in meteorology is associated with an increase in PMs. The May period recorded the highest value of CO2 424 ppm, May period is usually the period in which each year the highest CO2 levels are recorded because the plants will close their stomata to prevent water evaporation and reduce photosynthesis efficiency. At this time, human activities become more and more frequent, which eventually leads to an increase in the concentration of CO2 in the atmosphere. Globally the CO2 concentration in May 2022 was recorded 421 ppm by the Mauna Loa Observatory in Hawaii. In May 2023 was recorded 424 ppm, an increase of about 3 ppm degrees from last year, this increase caused the new rise in global warming caused by human activities.

Keywords:

Air quality, Particulate matters, Carbon dioxide, Meteorology, Benghazi city, Libya.

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Abbreviations

AQI	Air Quality Index
PM	Particulate Matter
T	Temperature
H	Humidity
WS	Wind Speed
WD	Wind Direction
P	Pressure
US EPA	U.S. Environmental Protection Agency
WHO	World Health Organization
IPCC	Intergovernmental Panel on Climate Change
FEPA	Federal Environmental Protection Agency

1 Introduction

Libya is an Arab country located in North Africa, bordered by the Mediterranean Sea to the north, Egypt to the east, Sudan to the southeast, Chad and Niger to the south, and Algeria and Tunisia to the west. The capital of Libya is Tripoli, which is also the largest city in the country. It is located in western Libya and is inhabited by more than two million people out of the total population of the country, which exceeds seven million. The second largest city is Benghazi, located in eastern Libya with a population exceeding one million people (Fig. 1). During recent years, Benghazi city is experiencing unprecedented economic growth rate and rapid urbanization. This resulted in expansion of this city, increase in urban population, vehicular population, a backlog of vehicles and construction activity. The principal causes of air pollution in Benghazi city, are natural sources (sandstorms and dust that come from desert) and human activity (combustion of garbage, fuel oil combustion, car exhaust and oil refining companies). In addition, the citizens suffered from windblown dust that came from desert and suffered greenhouse gas emissions that emitted from burning garbage, vehicle exhaust and from various industries and factories (Fares et al. 2023).

2 Aims of the work

1) To evaluate the spatiotemporal fluctuation of PM_1, $PM_{2.5}$, and PM_{10} particulate matter throughout the February 2023-December 2023 monitoring period.
2) To assess the correlations between pollutants and the impact of meteorological factors.
3) To determine the level concentration of CO_2 in Libya and correlate it with globally atmospheric CO_2 concentration.
4) To aware, the local people risk of air pollution in Benghazi city.

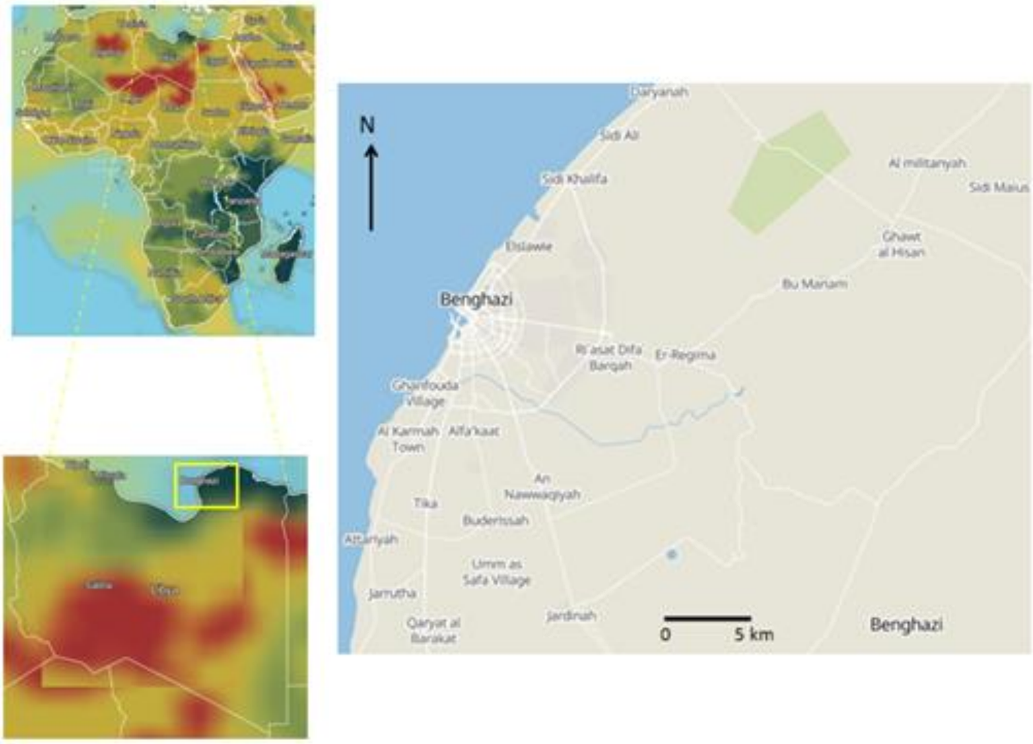


Fig. 1 - Composite map showing the location of Benghazi city (modified from IQAir 2023a).

3 Pervious works

The authors believe that this paper is the first survey of particle pollution (PM_1, $PM_{2.5}$ and PM_{10}) and CO_2 in the central area of Benghazi city. The following is a brief survey on the published work especially that dealing with aerosol metals pollutants and other subjects in Benghazi city and other cities. Nassar et al. (2018) studied the sources of air pollution in Libya. They found that the largest pollutants were CO_2 (96.76%) with lesser values of CO (2.13%), PM (0.55%), SO_2 (0.21%), NO_x (0.18%), CH_4 (0.089%), VOC (0.061%) and N_2O (0.028%). Busheina et al. (2017) evaluated the atmospheric pollution around Zawiya city, NW Libya. They reported the maximum of total suspended particulates were observed in May 2008, which is characterized by high wind speed (7.8 knots) compared to other months of the year. Abogrean et al. (2017) measured the O_3 concentrations in Tripoli city, NW Libya. They reported low concentration of O_3 was recorded in winter and spring seasons while recorded high concentration in summer and fall seasons. Almabrok et al. (2020) studied the levels of aerosol metals contamination in falling dust at different roadsides in Benghazi city. They found that the concentrations of aerosols metals were increased with increased the movement of traffic in those particular areas, density of population and industrial activities. Najar et al. (2023) measured VOCs in twelve refueling stations from different regions of Benghazi City. They reported the pollutant concentrations were within the range of the FEPA air quality standard in most stations.

4. Methodology

Stationary Monitoring Stations (AirVisual Outdoor Monitor)

Automatic monitoring machines stationed at fixed locations, air quality regulations vary from country to country, but all of these stations measure key pollutants harmful to human health according to World Health Organization (WHO 2006) guidelines. Advantages of stationary measuring stations are it is very accurate, the data obtained and presented are very reliable and it operates 24 hours a day. In this work, a station named AirVisual Outdoor was used that designed in Switzerland and made it in Germany, this station is an excellent air quality monitor and needs a constant power source and can synchronize data over WiFi. The AirVisual Outdoor supports WiFi, Ethernet, 4G, and power over Ethernet. The AirVisual Outdoor contains sensors for ultra-fine (PM_1), fine particles ($PM_{2.5}$), coarse particles (PM_{10}), atmospheric pressure temperature and humidity. Five AirVisual Outdoor monitor stations have been installed in Libya after agreement between IQAir Company (Air Quality Technology Company) and the Libyan Center for Climate Change Research. The devices were installed in several cities, including Benghazi, Tripoli, Zliten, Awjilah and Al Bayda (Fig. 2). The AirVisual Outdoors are characterized by high quality sensing elements to provide reliable and accurate readouts. Table (1) shows the specification monitoring station of AirVisual Outdoor). The monitoring station in Benghazi city measures every five minutes for each parameter (AQI Air Quality Index, PM_1, $PM_{2.5}$, PM_{10}, CO_2, T, H, WS, and WD). Authors in this paper recorded daily reads from February to December except CO_2 authors recorded from March to December 2023.

Fig. 2 - Composite photos showing (a) Tripoli station; (b) Zliten station; (c) Awjilah station; (d) Benghazi station; and (e) Al Bayda station.

Table 1- Description of AirVisual Outdoor (monitoring station).

Paramters	Functions
PM_1	0-1,000 μg/m^3 ±10 μg/m^3 / or ±10%
$PM_{2.5}$	0-1,000 μg/m^3 ±10 μg/m^3 / or ±10%
PM_{10}	0-1,000 μg/m^3
CO_2	requires optional module
T	-40 to 90 °C / -40 °F to 194 °F ±2 degrees C or F
Humidity	0 - 100% RH ±1%
Data Display	AirVisual app (iOS and Android)
Usage	Web dashboard

5 Results and discussion

5.1 Air Quality Index (AQI)

The air quality index (AQI) is an index for reporting daily air quality. It tells you how clean or unhealthy your air is, and what associated health effects might be a concern. The AQI focuses on health affects you may experience within a few hours or days after breathing unhealthy air. According to the US EPA (2014), the AQI is divided into six levels of health concern. Each level is marked with color code and determines the health concern. The AQI focuses on health effects you may experience in the hours or days after breathing unhealthy air. The AirVisual Outdoor Monitor covered an area about 132 km^2 of Benghazi city. The air pollution level 1 is indicated good air quality, level 2 air pollution is moderate health concern for some people, level 3 is termed unhealthy for sensitive groups, level 4 with red color code is unhealthy, level 5 is called very unhealthy, and levels 6 is hazardous level of health concern (Table 2).

5.2 Winter Season (February Period)

The calculated value of AQI was reported in (Table 3) that obtained from AirVisual Outdoor monitor revealed that the AQI ranged from 37 to 299 µg/m^3, with the main average (160, µg/m^3). The main average of PM_1, $PM_{2.5}$ and PM_{10} were 39.1, 73.4 and 198.2 µg/m^3, respectively (Table 3), which indicates that the February period was considered unhealthy; some members of the general public may experience some adverse health effect with this kind of pollution, while sensitive groups may experience more serious health issues (US EPA 2014). However, the AQI, PM_1, $PM_{2.5}$ and PM_{10} are unstable and fluctuating as a result of the daily change in weather and the influence of some pollutants, whether natural or anthropogenic (Figs. 3,4 and 5) .

5.2.1 Source of Air Pollution

Three types of air pollution were established Huang et al. (2014): (1) Dust type (type I), the $PM_{2.5}/PM_{10}$ ratio is about 0.41; (2) Mixed type (type II), the $PM_{2.5}/PM_{10}$ ratio ranges from 0.4 to 0.6; and (3) Anthropogenic type (type III), the $PM_{2.5}/PM_{10}$ ratio is greater than 0.6. According to Wu et al. (2015), Kong et al. (2016), and Tian et al. (2018) the particles are classified into three types: (1) Coarse particulates ($PM_{2.5}/PM_{10}<0.2$); (2) Mixed particulates ($PM_{2.5}/PM_{10}$ ranges from 0.2 to 0.8); and (3) Fine particulates ($PM_{2.5}/PM_{10}$,>0.8). Based on the $PM_{2.5}/PM_{10}$ ratio, the February period in Benghazi city was influenced by mixed pollutions (Fig. 6) and different types of particulates (Fig. 7). The values of anthropogenic type, dust type, and mixed type are 61%, 27%, and 11% from the total pollution, respectively (Fig. 8). The anthropogenic type includes fuel oil combustion, car exhaust, combustion of garbage, unpaved roads, industrial factories, and thermal power generating plants, while the dust type includes dust and sand storms.

Meteorological parameters are mainly responsible for atmospheric pollution whenever PM emission in an area is constant (Li et al. 2015), such as removal (dry and wet deposition) and transport dispersion of PM from the atmosphere is influenced by meteorological factors, such as wind speed, wind direction and temperature.

The correlation coefficient of AQI with T and WS were passivity correlated (r = 0.2 and 0.17), which reflects the wind speed play a major importance in the distribution of pollutants in the atmosphere (Fig. 9).

As the pollutants move towards the prevailing winds, so the areas located in the winds, there are pollutant reception areas, which are more polluted (Milad 2018). Wind direction changed from NE to SE on the 20th and continued to the end of the February with the increased in wind speed, the dust storm transported from the Sahara over Benghazi city, which caused dust load and greatly affected visibility of air quality (Fig. 10). This result confirmed SE wind direction is a statistically significant factor for natural sources of particulates pollution (Fig. 11) revealed the percentage of the wind directions in Benghazi city, NE and SE directions are the major trend of wind in February period.

Table 2 - AQI values, PM1, $PM_{2.5}$ and PM_{10} concentration color codes, and air pollutant level of health concern (US EPA 2014).

AQI Value of Index	Level of Health Concern	PM_1 and $PM_{2.5}$ Con. $\mu g/m^3$	PM_{10} Con. $\mu g/m^3$	Daily AQI Color	Air Pollution Level
0 - 50	Good	0 - 12	0 - 54	Green	Level 1
51 - 100	Moderate	12.1 - 35.4	55 - 154	Yellow	Level 2
101 - 150	Unhealty for sensitive groups	35.5 - 55.4	155 - 254	Orange	Level 3
151 - 200	Unhealty	55.5 - 150.4	255 - 354	Red	Level 4
201 - 300	Very unhealty	150.5 - 250.4	355 - 424	Purple	Level 5
301 - 500	Hazardous	250.5 - Higher	425 - Higher	Maroon	Level 6

Table 3 - Daily average concentration of PM_1, $PM_{2.5}$, PM_{10}, AQI (concentrations in $\mu g/m^3$), temperature (C°), humidity (%), wind direction and wind speed (km/h).

Date	AQI	$PM_{2.5}$	PM_{10}	PM_1	T	WD	WS	$PM_{2.5}/PM_{10}$
3	46	18.5	27	14.5	17	_	30	0.69
4	49	11.8	17.4	9.1	12.1	_	50	0.68
5	59	15.8	24	12.6	12.2	_	30	0.66
6	37	8.9	13.6	7.1	9.8	_	24	0.65
7	58	15.3	32.1	12.2	10.8	SE	18	0.48
8	98	34.3	51.8	27.5	11.8	SE	13	0.66
9	475	463	695	370	10.6	SE	21	0.67
10	123	44.6	67.1	35.7	9.6	SE	23	0.66
11	59	15.8	24	17.2	10.9	ESE	19	0.66
12	116	41	62.9	33.4	11.5	NE	17	0.65
13	108	38.5	58	30.9	11.3	NE	12	0.66
14	80	26	39.3	20.8	10.7	NE	12	0.66
15	79	25.4	38.3	20.3	12.6	NE	14	0.66
16	133	48.4	72.9	38.7	12.5	NE	16	0.66
17	145	53.5	80.5	42.9	12.2	NE	18	0.66
18	149	55.1	82.8	44	13.9	ESE	16	0.67
19	153	58.4	87.8	46.7	14.2	ESE	12	0.67
20	75	23.5	54.8	10	14.9	SSE	12	0.43
21	158	68.3	255	18.7	14.5	SSE	14	0.27
22	85	28.3	64.1	12.7	15.7	S	16	0.44
23	139	51.7	137	22	15.3	SSW	12	0.38
24	119	42	120	17	15.9	SE	16	0.35
25	123	44.3	173	9.8	17	SE	25	0.26
26	286	236.5	1155	35	17.7	SE	41	0.20
27	299	249.4	1233	37.3	17.5	SE	32	0.20
28	170	100	335.8	25	19.8	SE	32	0.30
Average	138	50.4	198.2	39.1	13.3	_	_	0.54

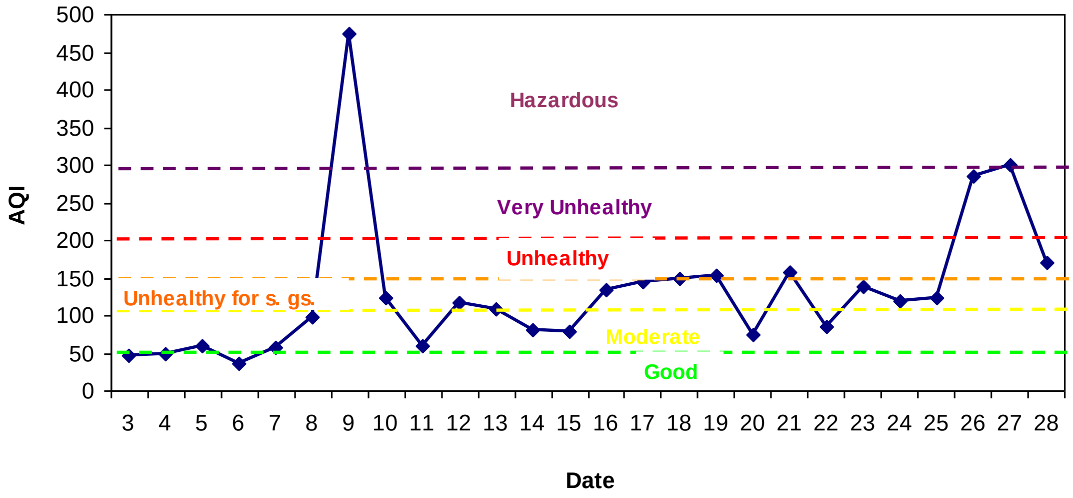


Fig. 3: The level of air pollution in Benghazi city during the February period (US EPA 2014).

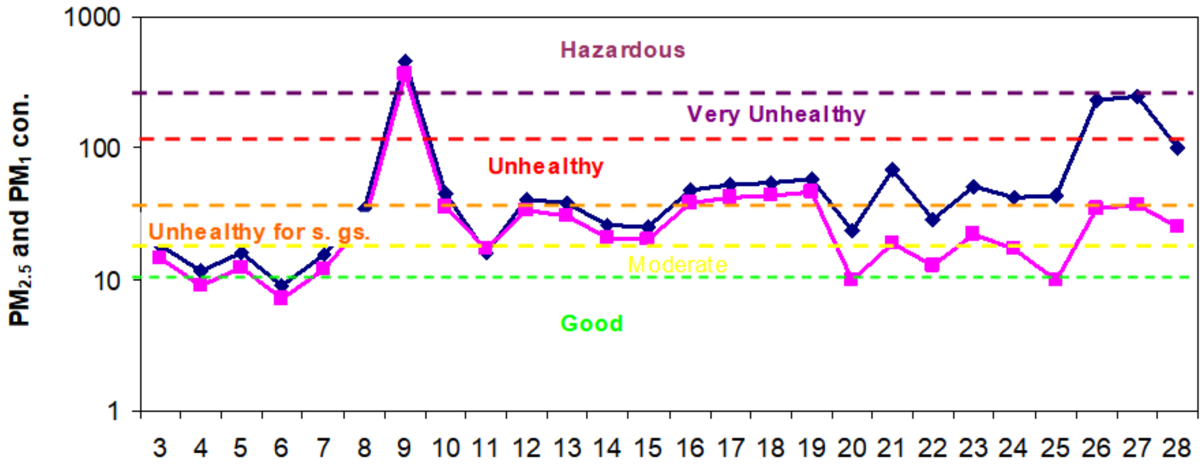


Fig. 4 - The daily concentration of $PM_{2.5}$ and PM_1 during the February period (US EPA 2014).

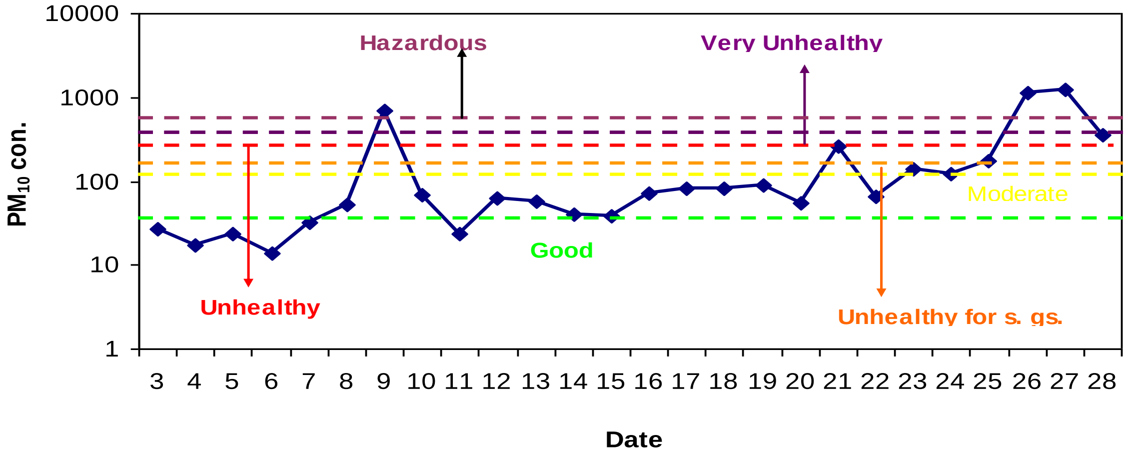


Fig. 5 - The daily concentration of PM_{10} during the February period (US EPA 2014).

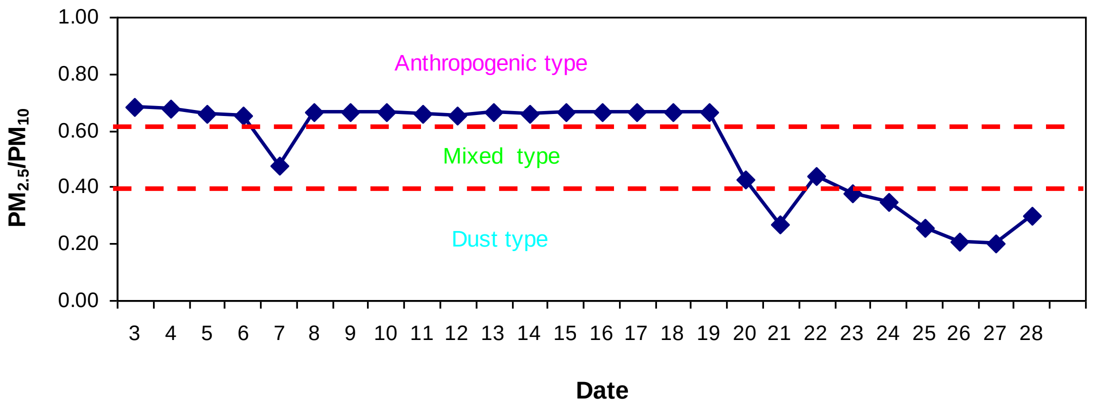


Fig. 6 - Source of air pollution based on the $PM_{2.5}/PM_{10}$ ratios during February period (fields after Huang et al. 2014).

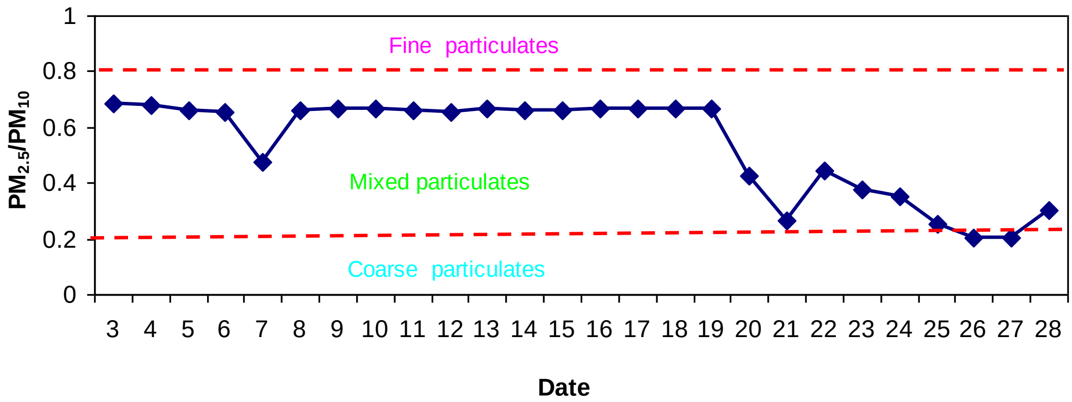


Fig. 7 - Classification of particles based on the $PM_{2.5}/PM_{10}$ ratio during February period (fields after Wu et al. 2015).

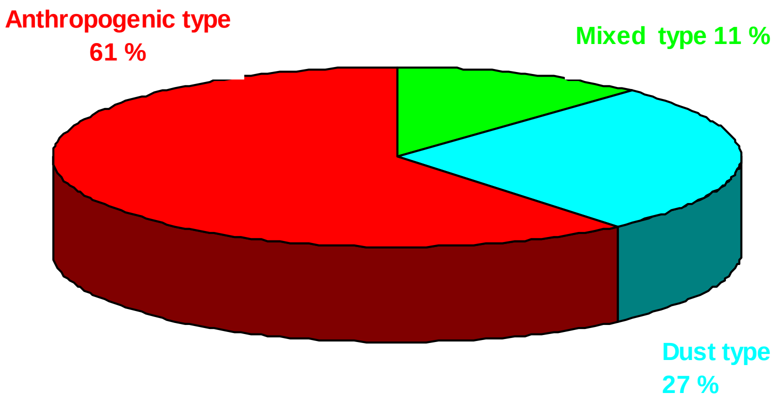


Fig. 8 - The proportions of pollution types in February period.

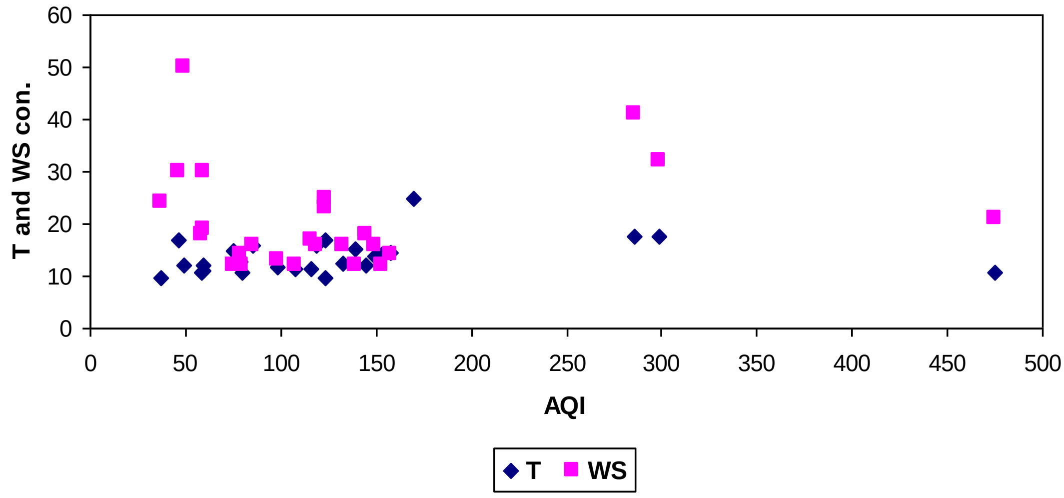


Fig. 9 - Relationship between AQI with T and WS during February period.

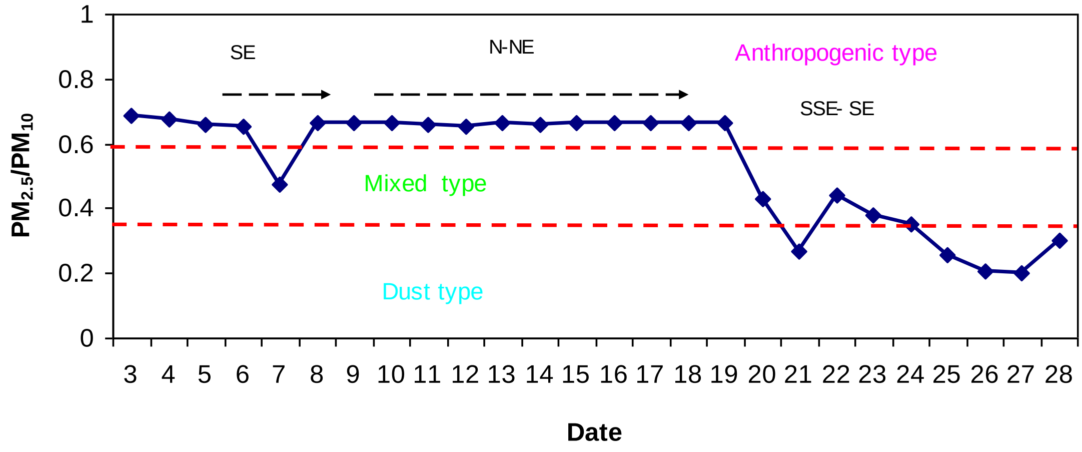


Fig. 10 - Relationship between pollution type and wind direction during February period (fields after Wu et al. 2015).

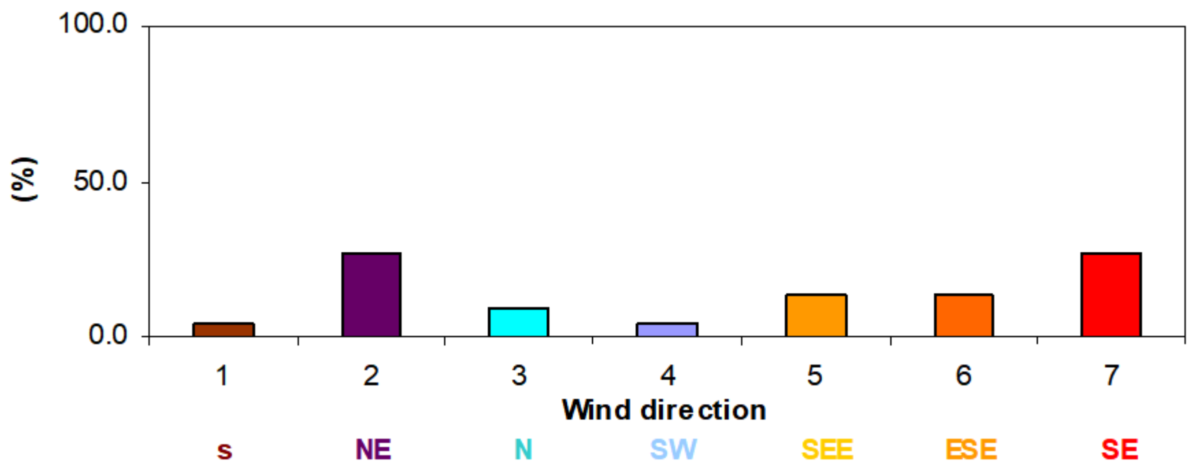
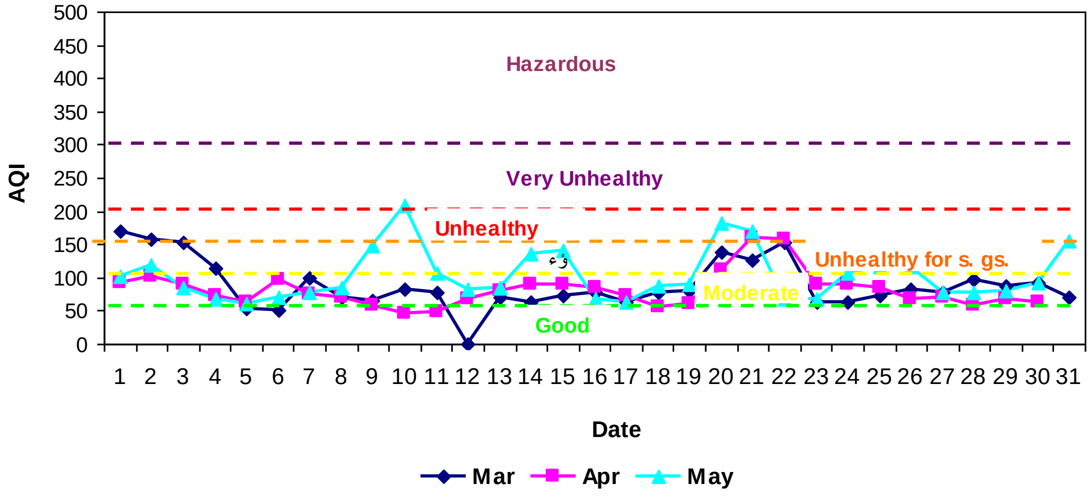


Fig. 11 - The percentage of wind direction during February period.



5.3 Spring Season (March, April and May)

The AQI in March and April period had a similar distribution (Fig. 12), the monthly average (89, 84 µg/m^3) is classified as moderate air quality, this may pose a moderate health concern for a very small number of individuals. Respiratory symptoms may occur in people with an unusually high exposure to ozone or particulate matter (US EPA 2014). In May, the main average (104 µg/m^3) was exceeding the safe limit and falling to an unhealthy level for sensitive groups (Fig. 13). The daily average concentrations of PM_1, $PM_{2.5}$ and PM_{10} in March, April and May period are shown in (Figs. 14, 15 and 16).

Based on the monitoring, the highest average monthly concentration of particulate pollutants in spring season was observed in May period, PM_1 (12.7 µg/m^3) is classified as moderate air quality whereas $PM_{2.5}$ and PM_{10} (36.5 and 252.4 µg/m^3, respectively) is above the permissible limit of (US EPA 2014) and classified as unhealthy for sensitive groups (Tables 4, 5 and 6).

Strong correlations occur between mortality and fine particles (usually measured as $PM_{2.5}$) and other endpoints like hospitalization for cardio-pulmonary illness. A lesser body of research indicates that coarse mass (particles with a size between 2.5 and 10 µg/m^3) may also have some negative health impacts (WHO 2003).

PM_{10} was largest values appeared in all periods of spring season (Fig. 17), which suggests that the PM_{10} is more from natural sources (such as dust and sandstorms) and also may emitted from anthropogenic sources after reaction of gases (Chen et al. 2017; Yuan et al. 2019). Based on the air pollution source and particle sizes, the periods of March and April were mainly affected by pollutants resulting from natural factors such as dust and sand storms, while mixed pollution has a significant influence throughout the period of May (Fig. 18). On the other hand, the March and April periods were characterized by mixed particle pollution while the May period contains mixed and coarse particulate pollutants in the atmosphere. The IQAir map indicated pollutants resulting from natural factors coming from the state of Nigeria and passing through Chad with southerly winds heading to Libya. Most of the cities in southeastern Libya were affected by this pollution, and then it moved to Europe, clearly visible in satellite imagery (Fig. 19). SE directions of wind have a major impact on increasing PM and natural pollution and associated with coarse particles.

Fig. 12 - The daily concentration of AQI (μg/m^3) during spring season (US EPA 2014).

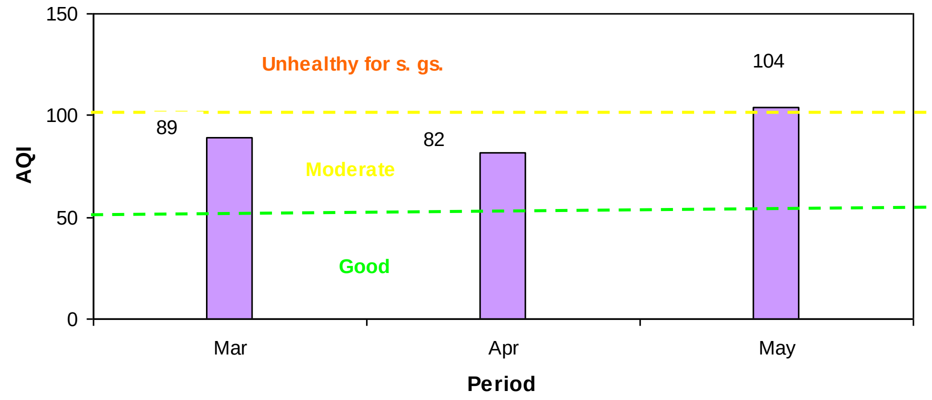


Fig. 13 - The monthly average concentration of AQI (μg/m^3) during spring season (US EPA 2014).

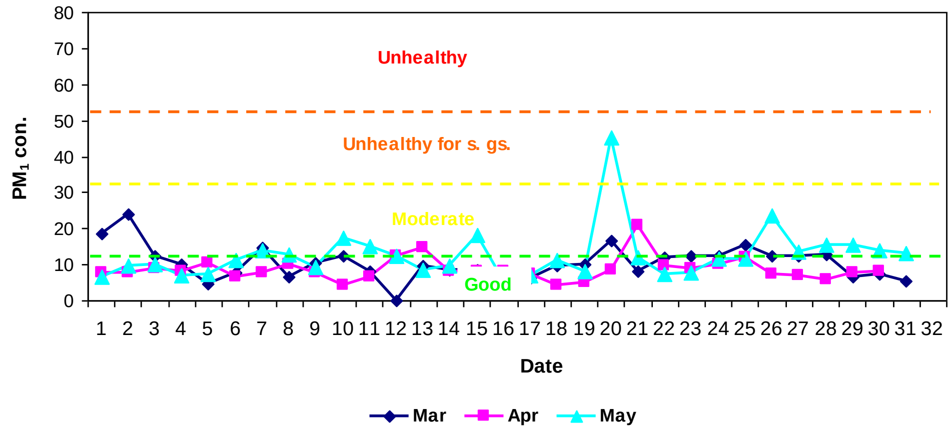


Fig. 14 - The daily average concentration of PM_1 during spring season (US EPA 2014).

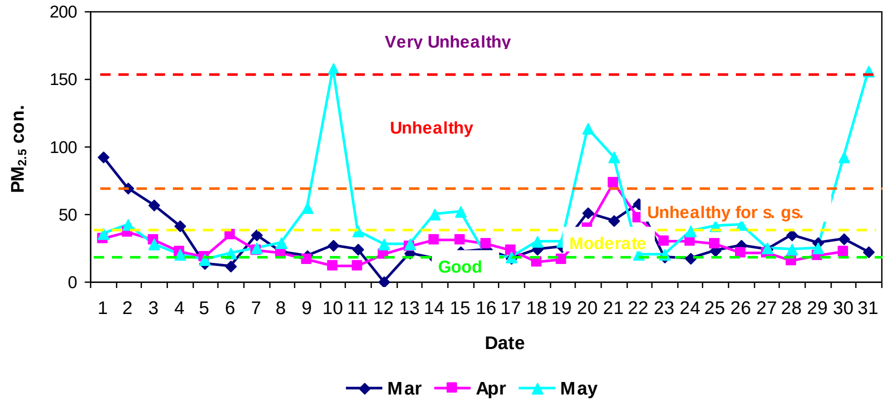


Fig. 15 - The daily average concentration of $PM_{2.5}$ during spring season (US EPA 2014).

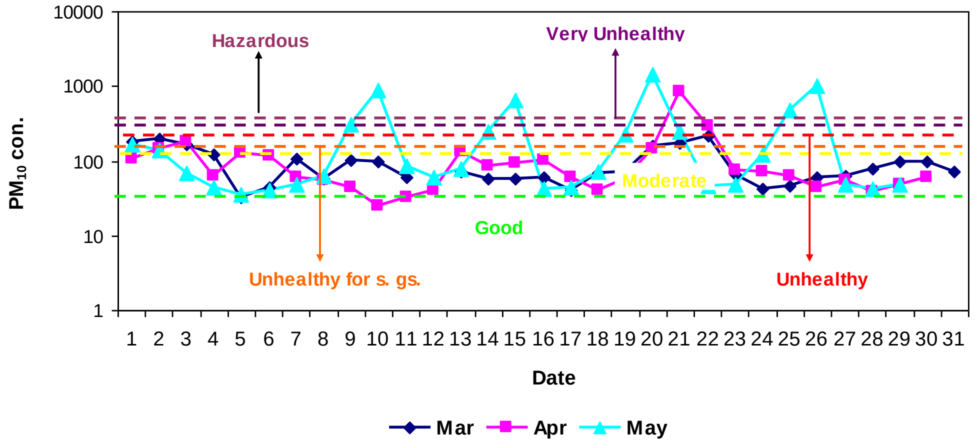


Table 4 - Daily average concentration of PM_1, $PM_{2.5}$, PM_{10}, AQI (concentrations in $\mu g/m^3$), CO_2 (ppm), temperature (C°), humidity (%), wind direction and wind speed (km/h) for March period.

Date	AQI	$PM_{2.5}$	PM_{10}	CO_2	PM_1	T	WD	WS	$PM_{2.5}/PM_{10}$
1	170	91.9	184	_	18.7	18.5	NE	19	0.50
2	158	69.5	197.5	_	24.1	17.1	NE	18	0.35
3	152	56.8	169.5	_	12.5	19.3	SE	18	0.34
4	114	40.9	120.9	_	10.2	17.5	NE	40	0.34
5	54	13.6	32.4	_	4.7	15	NW	22	0.42
6	50	12	44.3	_	7.6	15.5	W	25	0.27
7	99	34.9	108	_	14.8	16.8	W	25	0.32
8	71	21.8	57.9	_	6.5	16.2	NW	22	0.38
9	66	19.2	104.5	_	10.5	16.9	NW	20	0.18
10	82	26.7	99.7	_	12.3	19.4	SE	22	0.27
11	77	24	59	_	8.2	18.1	SE	25	0.41
12					No data recorded				
13	70	21.1	72.1	_	9.5	15.7	NW	25	0.29
14	62	17.3	57	_	8.5	15.3	NE	32	0.30
15	72	22.2	58.3	_	8.4	15.6	S	22	0.38
16	77	24.3	61.2	_	7.6	15.5	NW	33	0.40
17	62	17.5	39.7	414	6.3	13.9	N	32	0.44
18	77	24.5	68.2	415	9.7	15.1	N	32	0.36
19	80	25.9	71.2	415	9.9	15.2	E	32	0.36
20	139	50.9	160.6	419	16.5	15.1	E	22	0.32
21	126	45.5	173.8	412	8	19.6	SE	50	0.26
22	152	57.4	220	408	11.9	19.9	E	50	0.26
23	64	18.4	66.8	411	12.5	16.4	N	32	0.28
24	62	17.5	42.7	414	12.2	15	N	40	0.41
25	74	23.2	46.5	418	15.6	16.5	NW	36	0.50
26	83	27.4	61.5	416	12.5	16.4	NW	29	0.45
27	77	24.5	61.6	424	12.5	16.8	SW	26	0.40
28	98	34.4	79.8	414	12.9	19	NW	29	0.43
29	87	29.2	97.5	419	6.7	15.1	NW	32	0.30
30	93	32.2	99.8	421	7.3	14.4	N	18	0.32
31	70	20.6	64.9	420	5.7	15.7	N	22	0.32
Monthly avg.	89	30	94.7	415	10.7	16.5	_	_	0.32

Table 5 - Daily average concentration of PM_1, $PM_{2.5}$, PM_{10}, AQI (concentrations in µg/m^3), CO_2 (ppm), temperature (C°), humidity (%), wind direction and wind speed (km/h) for April period.

Date	AQI	$PM_{2.5}$	PM_{10}	PM_1	T	WD	WS	$PM_{2.5}/PM_{10}$	CO_2	H
1	93	32.1	105	7.7	19.3	SE	50	0.31	420	36.3
2	102	36.4	147.5	7.6	32.8	S	50	0.25	410	24.6
3	89	30.4	180.6	8.8	17.8	NW	40	0.17	401	61.2
4	72	22	62.5	8	16.7	W	47	0.35	407	66.5
5	64	18.4	129.9	10.3	14.1	W	18	0.14	419	75.4
6	98	34.7	115	6.4	16.7	NE	40	0.30	412	59.4
7	75	23.3	60.8	7.8	14.8	NE	61	0.38	416	60.5
8	71	21.4	55.7	9.9	15	NE	28	0.38	417	72.6
9	59	16	44	7.8	16.4	NW	30	0.36	417	76.4
10	47	11.3	25	4.4	15.9	NW	15	0.45	415	65.5
11	49	11.9	31.9	6.4	13.8	N	7	0.37	412	71.3
12	69	20.6	40.7	12.4	15.8	W	40	0.51	418	69
13	79	25.6	131.6	14.8	19.3	SW	22	0.19	429	50.9
14	91	31.2	84.3	8.1	21.8	S	43	0.37	414	44.2
15	89	30.4	93.8	8.1	17.5	N	36	0.32	413	70
16	85	28.2	101.6	8.3	18.9	SW	32	0.28	420	60
17	73	22.8	61.2	7.3	17.5	N	36	0.37	412	69.3
18	56	14.7	40	4.3	17.6	N	38	0.37	414	64.3
19	60	16.3	57.4	5.1	17.5	NE	38	0.28	417	68
20	112	39.8	147.3	8.5	21.3	NE	40	0.27	420	43.2
21	160	73	844	20.8	24	NE	47	0.09	410	28.3
22	158	46.9	300	9.8	25.1	NE	48	0.16	408	30.5
23	89	30.1	75	8.7	21.8	N	43	0.40	410	61.9
24	89	30	71.9	10.2	20	N	25	0.42	415	72.1
25	84	27.6	62.5	11.9	19	N	36	0.44	419	70.3
26	69	20.7	44.4	7.3	21	SW	36	0.47	419	54.7
27	70	21.3	55.9	6.8	18.5	N	43	0.38	414	67.4
28	58	15.6	38.9	5.7	17.6	N	43	0.40	414	53
29	67	19.7	48	7.6	18	N	35	0.41	416	60
30	64	22.4	59.1	8	19.9	W	25	0.38	417	48.5
Monthly avg.	82	26.8	110.2	8.6	18.6	_	_	0.24	416	58.8

Table 6 - Daily average concentration of PM_1, $PM_{2.5}$, PM_{10}, AQI (concentrations in μg/m^3), CO_2 (ppm), temperature (C°), humidity (%), wind direction and wind speed (km/h) for May period.

Date	AQI	$PM_{2.5}$	PM_{10}	PM_1	T	WD	WS	$PM_{2.5}/PM_{10}$	CO_2	H
1	102	35.5	167.9	6.4	24.5	SE	20	0.21	413	28.2
2	118	42.4	140.5	9.6	22.4	N	15	0.30	408	52.8
3	85	28.2	68.7	10.1	18.8	NE	20	0.41	415	76
4	68	20.2	43.4	7	18.6	NW	23	0.47	416	75.7
5	61	16.8	35	7.2	17.9	NW	29	0.48	413	97.5
6	70	21	40	11.1	19.2	NW	21	0.53	417	74
7	78	24.8	47.9	14	19.8	N	21	0.52	419	72.8
8	86	28.9	64	12.9	21	NE	25	0.45	418	56.5
9	149	55.2	312	9.3	24.8	E	18	0.18	411	33.7
10	209	158	877	17.3	23.9	N	23	0.18	407	42.5
11	106	37.5	85	15.1	21.5	W	22	0.44	413	71.1
12	83	27.5	59.5	12.2	21.4	NW	24	0.46	421	60.9
13	85	28.1	77.9	8.6	25.5	NW	22	0.36	423	38
14	137	50	244	9.6	29	SE	30	0.20	419	26.3
15	140	51.5	657	18.2	27.8	SE	35	0.08	418	35.4
16	67	19.5	42.8	5.5	20	SW	15	0.46	423	70.3
17	64	18.3	44.8	6.9	20.5	NW	17	0.41	430	66.8
18	88	29.7	72.5	11.1	23.5	NW	18	0.41	435	41.2
19	89	30.1	225	8.1	28.3	SW	19	0.13	429	26.1
20	181	113.8	1408	45.2	24.8	SE	14	0.08	438	46
21	170	92.7	250	12.1	20.9	NW	26	0.37	449	75.3
22	68	20.4	47	7.3	20,2	NW	23	0.43	453	76.7
23	69	20.6	47.6	7.7	20.7	NW	23	0.43	435	74.2
24	106	37.5	123.8	11.5	23.9	NE	26	0.30	439	54.8
25	116	41.5	471	11.6	26.4	NW	26	0.09	432	42.8
26	117	42	1008	23.4	23.7	NW	24	0.04	429	66
27	78	25	47.6	13.6	19.5	NW	21	0.53	430	80.5
28	77	24.3	42.5	15.3	20.9	N	22	0.57	433	78
29	79	25.4	47.6	15.3	22.4	NE	23.0	0.53	424	70
30	92	31.8	123	8.8	22	N	21	0.26	414	38
31	156	64.4	886.7	27.1	27.3	W	43	0.07	406	50.5
Monthly avg.	104	36.5	252.4	12.7	22.7	_	_	0.14	424	57.6

Fig. 16 - The daily average concentration of PM_{10} during spring season (US EPA 2014).

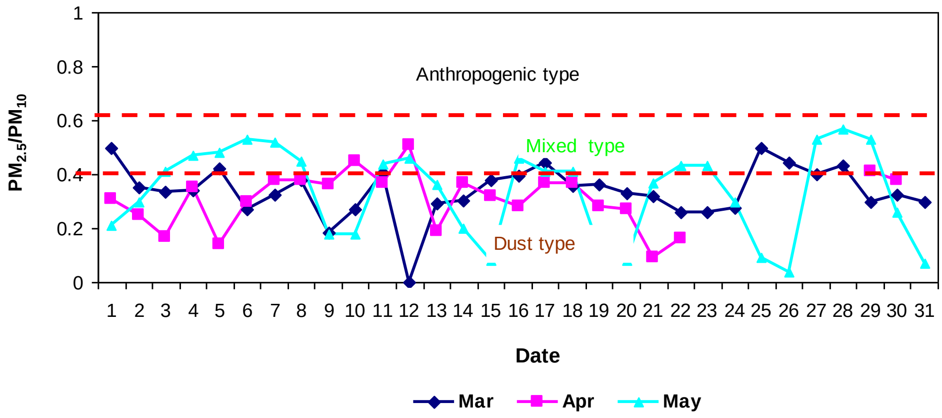
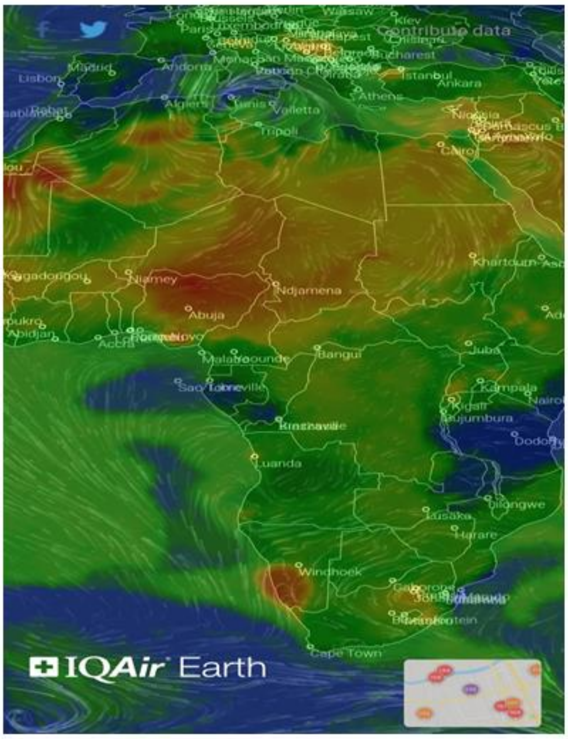


Fig. 17 - Source of air pollution based on $PM_{2.5}/PM_{10}$ ratios during spring season (fields after Huang et al. 2014).

Fig. 18 - Classification of particles based on the $PM_{2.5}/PM_{10}$ ratio during spring season (fields after Wu et al. 2015).



Meteorological parameters are basically responsible for air contamination at whatever point PM emission in an region is constant (Li et al. 2015), such as removal (dry and wet deposition) and transport dispersion of PM from the atmosphere is influenced by meteorological factors, such as temperature, humidity and wind speed. In March period, the authors recorded temperature and wind speed while in April and May period they recorded temperature, humidity and wind speed.

Relationship between monthly variations of the mass concentrations of PMs with temperature, humidity and wind speed was determined by using spearman correlation analysis. The relationship between AQI and T and WS in all periods were positively correlated ($r = 0.6$ and 0.2, respectively, in March, $r = 0.64$ and 0.4, respectively, in April and $r = 0.45$ and 0.3, respectively, in May), while there was a negative correlation with humidity ($r = -0.4$, in April and May) (Figs. 20, 21 and 22).

As the temperature and humidity gradually increase from the period of March to the period of May, and the highest average was recorded in the May period, as a result of the entry of the summer season (Fig. 23).

Fig. 19: The move of pollution from Nigeria state to Libya in the May, 2023 (from IQAir 2023b).

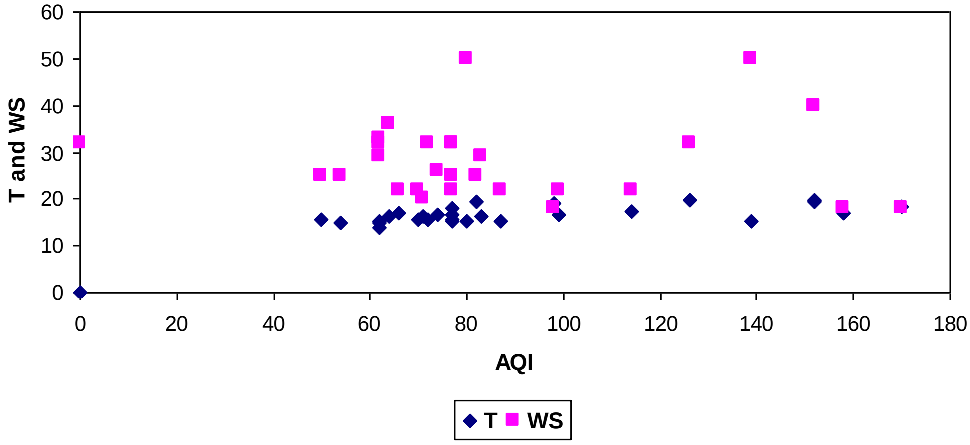


Fig. 20 - Relationship between AQI with T and WS during March period.

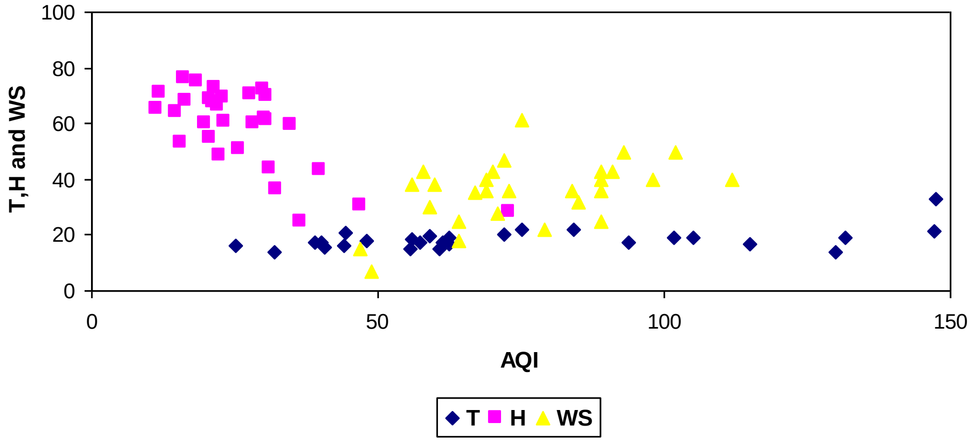


Fig. 21 - Relationship between AQI with T, H and WS during April period.

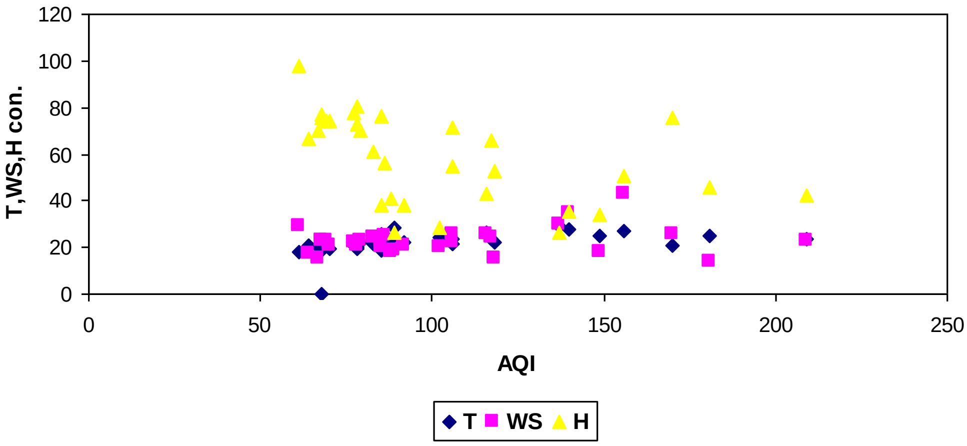
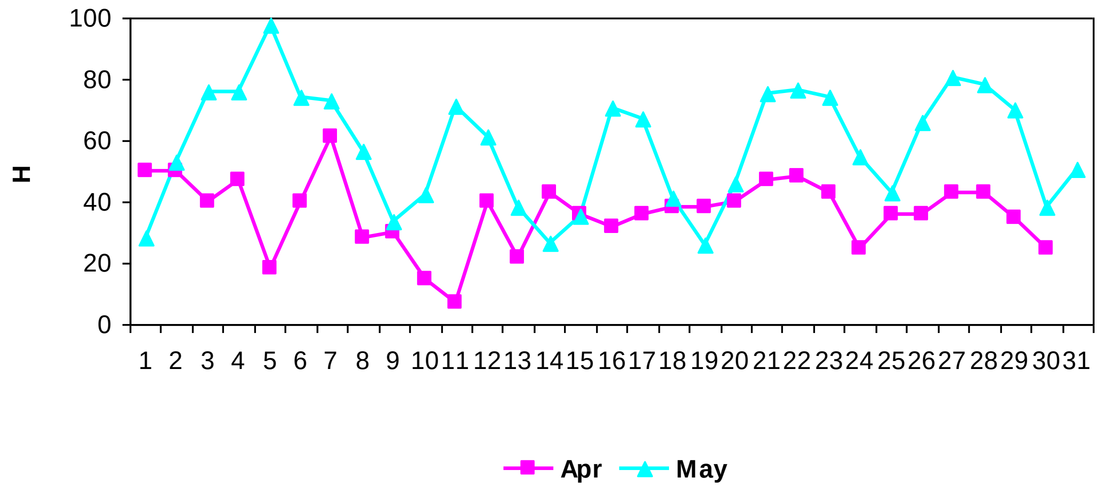


Fig. 22 - Relationship between AQI with T, H and WS during May period.



5.3.1 Carbon Dioxide (CO2) in Spring Season

One of the most significant issues facing humanity today is climate change, which has an impact on both human society and natural ecosystems worldwide (Song et al. 2023). The sixth report of the Intergovernmental Panel on Climate Change predicted that the global temperature will rise by 1.5 C^o over the next two decades due to the emissions of greenhouse gases, particularly carbon dioxide and methane (IPCC 2014; Fang et al. 2015).

One of the major human-caused reasons for CO_2 emissions is energy consumption, which results from various human activities like burning fossil fuels, industrial operations, and the destruction of forest vegetation (Shan et al. 2018). It should be noted that the extravagant use of fuel, cutting down forests or reducing green spaces contributed to the increase in the proportion of second gas CO_2 in the atmosphere, which may lead to a rise in the Earth's temperature, which is known as global warming (IPCC 1995; Joos et al. 1999).

Currently, there is one station in Libya to measure CO_2 located in Benghazi city, and it effectively started recording on March 17th, 2023.

Generally, the emission sources of CO_2 in Libya are mainly from oil, gas, flaring and cement but in Benghazi is mainly from car exhaust, combustion of garbage, power plants and industrial factories.

AirVisual Outdoor monitor was used to measure the atmospheric CO_2 over Benghazi city. In general, the CO_2 concentration in March ranged from 408 to 424 ppm (Fig. 24), the CO_2 concentration was positively correlated with wind speed (r = 0.4) which indicated that the wind speed play a major importance in the distribution of CO_2 in the atmosphere (Milad 2018, Fig. 25), whereas there is no relationship with temperature and AQI.

The CO_2 concentration in April ranged from 407 to 420 ppm (Fig. 26). There was weak correlations with temperature, wind speed, AQI, and relative humidity (r = -0.2, -0.1, -0.3, and 0.2, respectively), which suggests that humidity was affected on CO_2 led to move (Fig. 27). The CO_2 concentration has similar distribution in March and April period. The CO_2 level some day's increases in the morning because of an increase in traffic congestion and some human activities resulting from factories. On the other hand, the CO_2 level some day's increases at night due to plants respiring at night in a process opposite to the photosynthesis they do during the day, as plant cells take in oxygen from the air and release carbon dioxide and moisture (Magita et al. 2022).

The concentration of CO_2 was reported in the May period from 406 to 453 ppm (Fig. 28) and was weakly correlated with AQI, humidity, temperature and wind speed (r = 0.2, 0.2, -0.16 and -0.1), which suggests that the increase in CO_2, led to increase in AQI and RH trend (Fig. 29). The period of May recorded the highest value of CO_2 (Fig. 30). This is because May is a warm period and the temperature increases, which means that the plants will close their stomata to prevent water evaporation and reduce photosynthesis efficiency, this case in the north part of globe (Sharma et al. 2019).

In the same time at the southern part of the globe, it is the autumn season, meaning that most of leaves are falling off, and this leads to a decrease in the photosynthesis process, as human activities increase in frequency at this time, carbon dioxide reaches the highest concentration in the year (Fig. 31).

May period is usually the period in which each year the highest CO_2 levels are recorded. Globally, the concentration of CO_2 in May 2022 was recorded 421 ppm, in May 2021 was reported 419 ppm, in May 2020 was recorded 417 ppm and in May 2019 was reported 414 ppm, the Mauna Loa Observatory in Hawaii takes these measurements.

According to the AirVisual Outdoor monitor that was installed in Benghazi city recorded, the mean average of CO_2 in May 2023 is about 424 ppm, that is, it increased three degrees in the last year (Fig. 32). May 2023 recorded the highest level of CO_2 in 4 million years, this increase caused the new rise in global climate temperature caused by human activities, the most important of which are transportation, cement production, flaring, deforestation, and electricity production using fossil fuels.

Fig. 23 - Daily average concentration of humidity during April and May period.

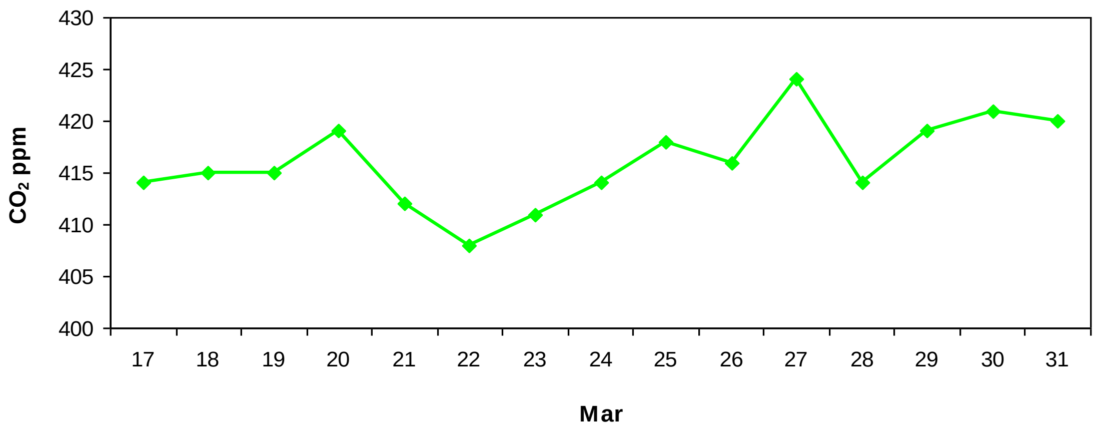


Fig. 24 - The daily average distribution of CO_2 during the March period.

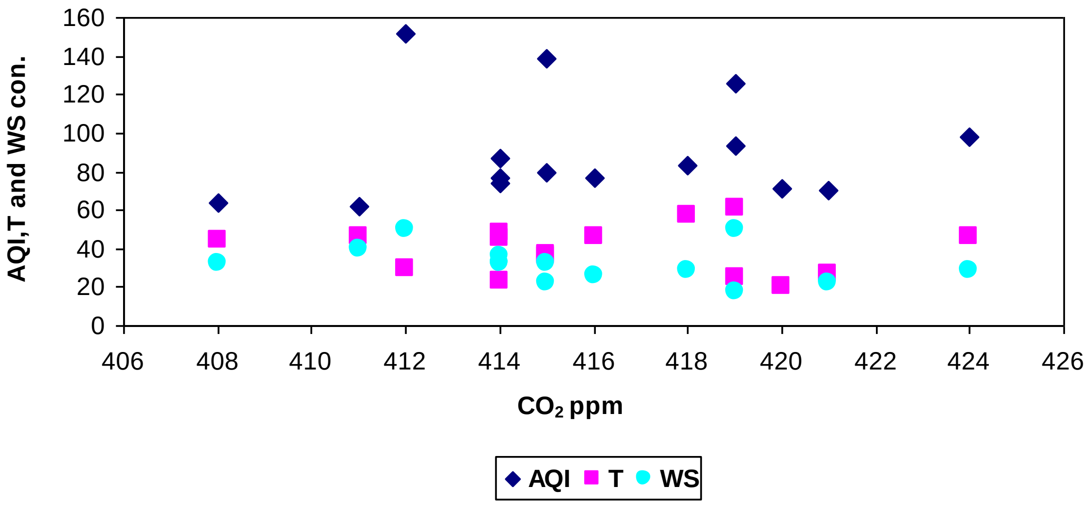


Fig. 25 - Relationship between CO_2 with AQI, T and WS.

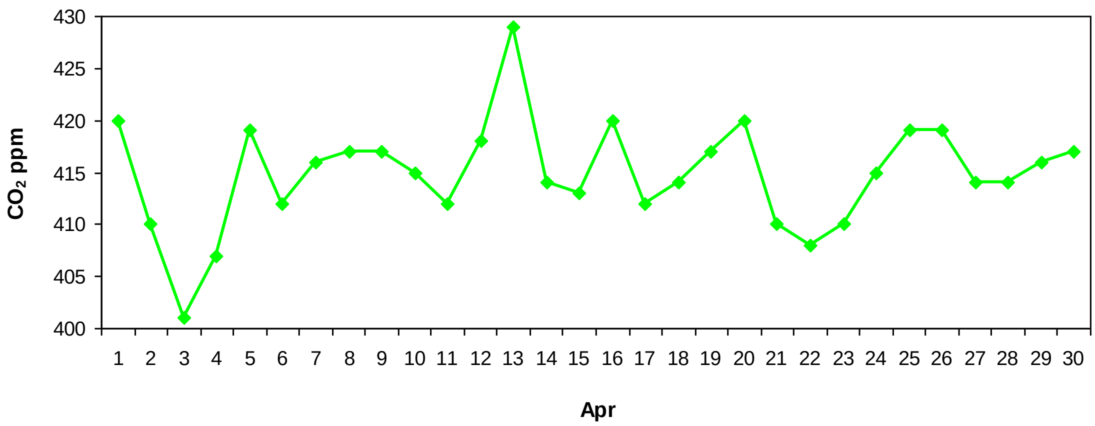


Fig. 26 - The daily average distribution of CO_2 during the April period.

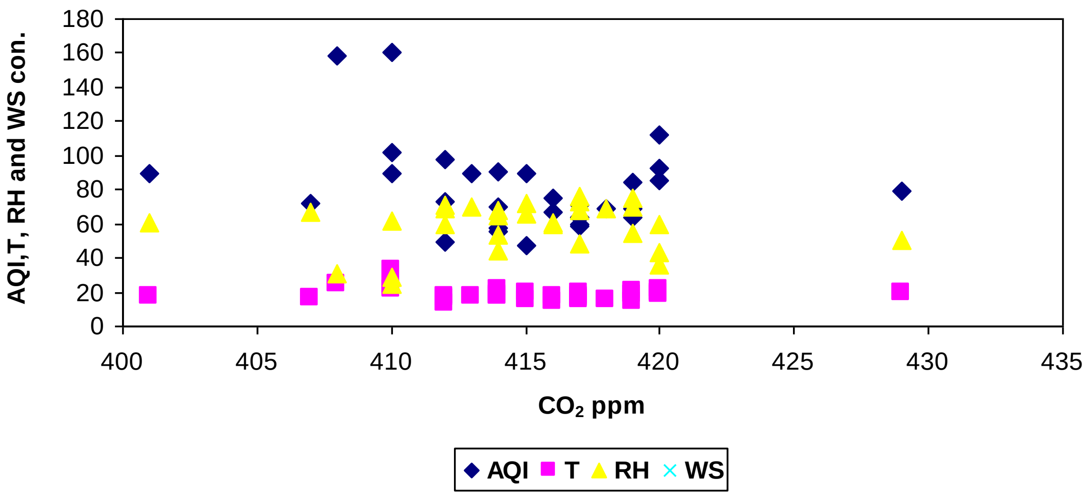


Fig. 27 - Relationship between CO_2 with AQI, T, RH and WS.

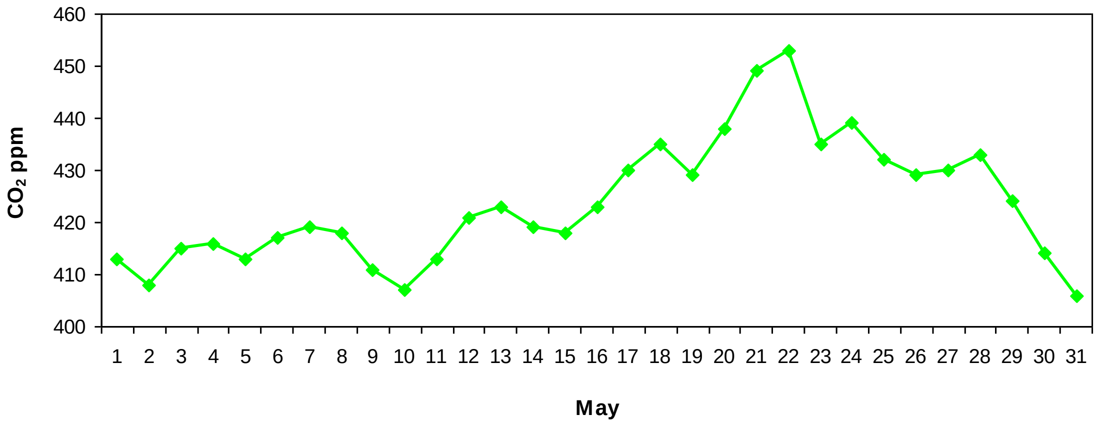


Fig. 28 - The daily average distribution of CO_2 during the May period.

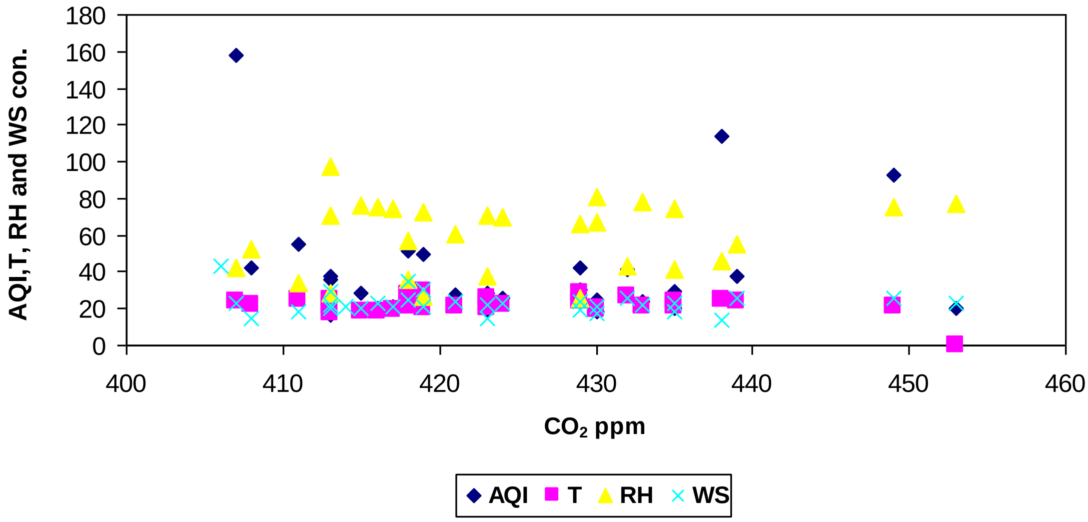


Fig. 29 - Relationship between CO_2 with AQI, T, RH and WS.

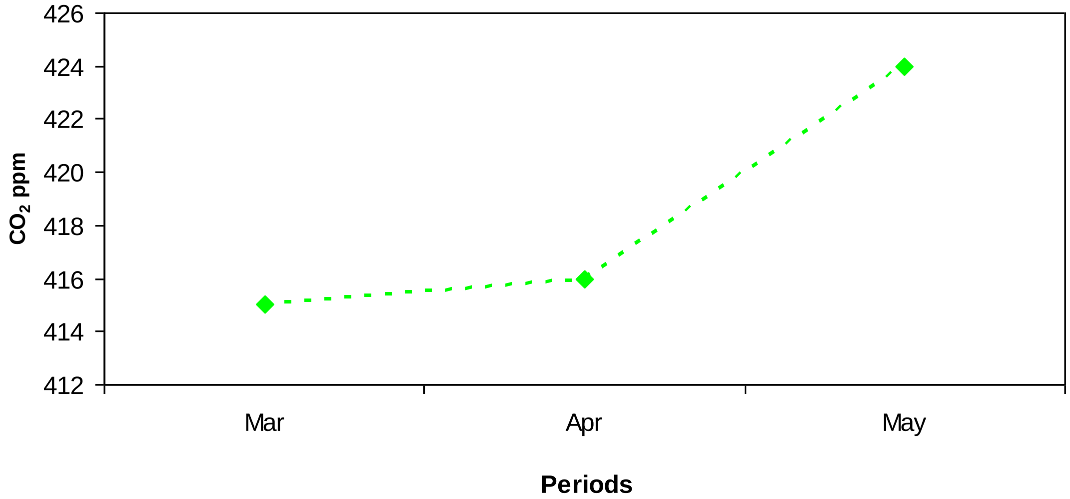


Fig. 30 - The average monthly concentration of CO_2 during all periods in Benghazi city.

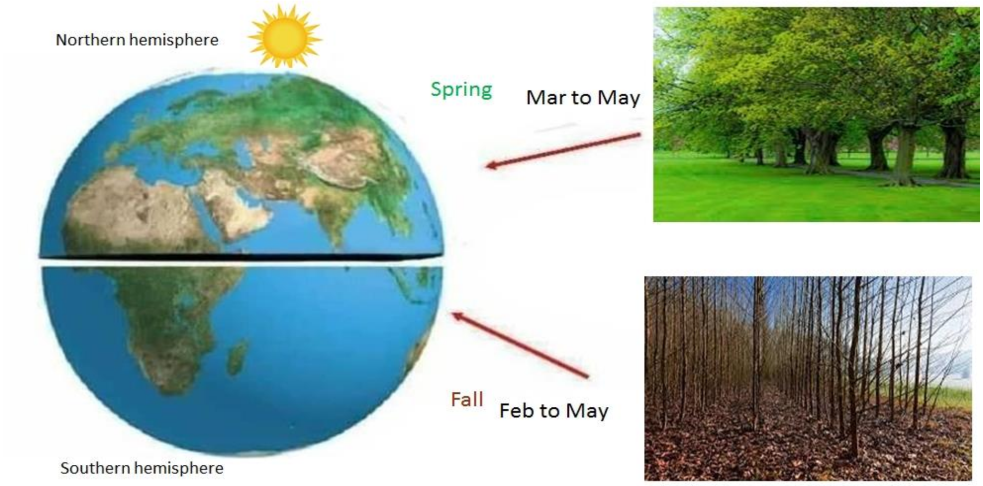


Fig. 31 - The northern and southern part of the hemisphere in the May period.

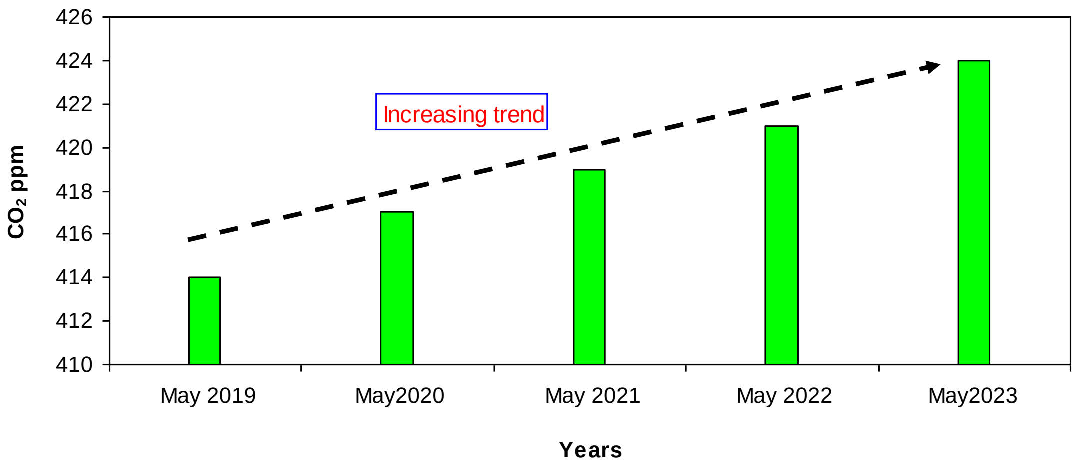


Fig. 32 - The main globally average of CO_2 concentration during May 2019 to May 2023

5.4 Summer Season (June, July and August)

Particulate matter (PM) is a major pollutant in the environment that can penetrate the respiratory system and create health concerns and problems due to its size (Hoek and Raaschou 2014; Choi, et al. 2022). Depending on the climatologic parameters, PM with a diameter of less than 10 m is classified as repairable-suspended-particulate-matter. It can change its physicochemical properties and can float in the air for a short to longer period (Vautard et al. 2007; Kong et al. 2021).

Tables 7, 8 and 9 showed the daily average concentration of particulate matter pollution during the summer season in Benghazi city. In summer season, the highest values of $PM_{2.5}$ (72.3 µg /m^3), PM_{10} (500 µg /m^3) were recorded in June, while PM_1 (32.6 µg /m^3) represents the highest concentration in August. The concentrations of PM $_{2.5}$, PM_{10} and PM_1 were in level 2 which reflected that moderate air quality (Figs. 33, 34 and 35).

$PM_{2.5}$ concentrations in Benghazi city in some days (the first, fifth, and fifteen days in June period, the first day of the twenty-fifth and twenty - sixth in July and on the twenty-seventh day of August period) were higher than the permissible limit. PM_{10} concentrations (the first day in June and on the twenty-sixth day of July) are higher than the permissible of US EPA (2014), while PM_1 concentrations were in the safe limit. Moreover, these days were affected on the general health of people such as exposure to skin, eye irritation, asthma and coughing.

Table 7 - Daily average concentration of $PM_{2.5}$, PM_{10}, AQI for June period (concentrations in μg/m^3), CO_2 (ppm), temperature (C°), humidity (%), wind direction and wind speed (km/h).

Date	AQI	$PM_{2.5}$	PM_{10}	PM_1	T	WD	WS	$PM_{2.5}/PM_{10}$	CO_2	H
1	160	72.3	246.2	15.7	22.2	N	39.6	0.29	410	77.6
2	95	33.1	60.8	16.5	22.1	NE	25	0.54	416	75.2
3	83	27.4	59.7	12.5	23.4	NE	28.8	0.46	419	63.3
4	87	29.5	74.9	10.6	25.4	NE	32	0.39	419	53.1
5	119	42.7	123	11.4	26.9	NE	25.5	0.35	422	41.8
6	98	34.7	94.9	10.6	27	NE	26.5	0.37	415	42
7	91	31.2	69.3	13.5	24.6	E	28.8	0.45	414	63.7
8	87	29.3	58.8	14.9	22.3	NE	28	0.50	416	78.8
9	73	22.7	41	13.8	22.3	N	21.6	0.55	421	79.4
10	81	26.6	51.9	14.5	23.1	NW	18	0.51	423	76.7
11	81	26.5	52.7	13.1	20.8	NE	21	0.50	424	81.7
12	85	28.2	60.6	12.9	23.1	N	28	0.47	419	79.4
13	75	23.5	48.3	12.9	23.3	NW	18	0.49	419	81.4
14	95	33.3	95.9	12.2	26.8	SE	21	0.35	421	59
15	120	43.3	500	16.5	27.1	SE	43	0.09	413	60
16	73	22.7	46.9	9.4	23.6	NW	25	0.48	419	80
17	78	24.8	51.2	11.2	23.3	NW	21	0.48	419	81
18	73	22.5	44.4	11.5	23.6	N	29	0.51	415	78.2
19	69	20.6	42	10.5	23.8	N	25	0.49	411	75.7
20	71	21.7	45.9	10.8	24	N	28	0.47	411	76.2
21	74	23.2	52.3	11.1	24.4	N	32	0.44	412	73.9
22	78	25	50.4	13.8	25.1	N	33	0.50	414	78.4
23	68	20.4	45.4	13.9	26.3	N	21	0.45	414	73
24	78	24.9	51.9	13	27	N	25	0.48	415	71.5
25	78	24.9	52.4	12.5	26.9	W	18	0.48	415	74.2
26	88	29.6	63.5	12.9	25.4	N	21	0.47	417	79.8
27	88	29.7	61.9	13.6	25.5	NW	18	0.48	418	80
28	87	29.3	58.3	20	26.1	NW	18	0.50	420	77.2
29	74	22.9	42.1	12.8	26.4	NW	21.0	0.54	419	71.9
30	70	22	24	13	26.4	N	21	0.92	419	72
Average	84	28	79.4	13.1	24.6	_	25.36	0.35	417	72

Table 8 - Daily average concentration of $PM_{2.5}$, PM_{10}, AQI for July period (concentrations in µg/m^3) CO_2 (ppm), temperature (C°), humidity (%), wind direction and wind speed (km/h).

Date	AQI	$PM_{2.5}$	PM_{10}	PM_1	T	WD	WS	$PM_{2.5}/PM_{10}$	CO_2	H
1	119	43	91.8	22.5	28.3	NW	28.8	0.47	419	63.2
2	100	35.3	43.3	8.3	26.6	NW	36	0.82	407	71
3	68	20.2	41.4	8.3	26.8	N	32.4	0.49	408	71.5
4	67	19.8	33	6.5	26.5	NE	32.4	0.60	408	70.8
5	58	15.5	42.6	9.6	26.6	NE	36	0.36	408	75.4
6	68	20.1	54.5	10.7	26.8	NE	32.4	0.37	410	74.2
7	78	24.8	57.6	11	27.3	NE	32.4	0.43	414	72
8	80	26	56.3	12.2	27.4	NE	27.5	0.46	410	72
9	74	23	76	11.9	26.7	NW	28.8	0.30	411	70
10	No data recorded									
11	88	29.6	95.3	10.9	27	NE	36	0.31	407	67
12	74	22.9	52.5	12.2	27.3	NE	36	0.44	407	68
13	70	21.3	43.2	12.2	27	NE	28.8	0.49	407	74.6
14	73	22.8	41.3	10.5	27.3	NE	39.6	0.55	409	76.4
15	88	29.6	59.2	15.5	27.4	NE	25.2	0.50	414	80
16	96	33.4	69.4	16	27.3	NW	25.2	0.48	418	80
17	80	26	51.4	12.3	28.1	NW	28.8	0.51	419	74
18	90	30.7	60.7	15.5	29	N	28.8	0.51	420	73.7
19	86	28.7	93.9	15.8	30.1	NW	28.8	0.31	418	70.6
20	87	29.7	50.4	18.6	29.2	NW	32.4	0.59	418	74.1
21	84	27.9	52.8	16	29.9	N	25.2	0.53	419	68.3
22	88	29.7	66.2	12.6	30.2	NE	28.8	0.45	419	60.3
23	101	35.5	87.3	12.4	30.7	NW	25.2	0.41	425	65.9
24	104	36.5	87	12.9	31.7	NW	25.2	0.42	415	65
25	106	37.747	91.2	13.7	30.6	NW	25.2	0.41	415	72
26	129	37.8	182	14.8	32.5	NW	25.2	0.21	421	47
27	70	21	77	11.9	30.5	NE	25.2	0.27	405	73
28	63	17.6	49.9	7.9	28.7	NW	21.6	0.35	405	66.2
29	60	18	38	6.8	29.2	SE	25.2	0.47	405	65.6
30	63	17	41	6.8	28.4	SE	25.2	0.41	403	72.6
31	56	17.4	36.4	7.9	28.1	SE	25.2	0.48	401	68.4
Average	82	27.1	64.6	12.2	28.4	_	26	0.42	412	70

Table 9 - Daily average concentration of $PM_{2.5}$, PM_{10}, AQI, for August period (concentrations in µg/m^3), CO_2 (ppm), temperature (C°), humidity (%), wind direction and wind speed (km/h).

Date	AQI	$PM_{2.5}$	PM_{10}	PM_1	T	WD	WS	$PM_{2.5}/PM_{10}$	CO_2	H
1	60	16.6	36	6.7	28.1	NW	25.2	0.46	401	73.4
2	62	17.4	49.4	8	30.7	NE	25.2	0.35	407	68.4
3	66	19.1	44	8.5	28.5	NW	21.6	0.43	410	69.7
4	60	16.2	36.1	7	29.5	NE	18	0.45	411	66.4
5	71	21.7	50	9.5	30.9	NW	25.2	0.43	409	64.5
6	65	18.8	43	5.7	28.8	NW	28.8	0.44	411	61.5
7	63	17.6	39.6	6	28.6	NW	15	0.44	407	61.8
8	72	22	55.7	6.7	28	NE	25.2	0.39	405	60.7
9	70	21	52	6.8	26.8	NE	32.2	0.40	405	61.5
10	57	15	36	5.1	27.8	NE	28.2	0.42	414	65.7
11	56	14.7	35	4.9	27.8	N	28.2	0.42	411	60.3
12	65	19	38	9.9	27.2	NW	25.2	0.50	410	62.3
13	64	19	35	10	26.8	NW	21.6	0.54	411	64.4
14	65	19	37	10.2	27.3	NW	21.6	0.51	411	65.5
15	66	20	39	10.7	27.7	NW	25.2	0.51	410	65.5
16	71	22	44.6	11.2	27.3	NW	25.2	0.49	412	67.4
17	71	22	39.4	12.7	27.3	NW	25.3	0.56	412	70
18	71	22	35.8	13.7	28.1	NW	21.6	0.61	413	73.7
19	74	23	40.3	14.7	28.2	NW	21.6	0.57	414	72
20	90	31	51	21.2	27.9	NW	25	0.61	413	73.5
21	101	36	70	20.3	28.8	NW	21	0.51	419	67.8
22	94	33	70	15.2	29.6	NW	18	0.47	418	60.3
23	83	28	57	13.5	29.4	NW	18	0.49	416	63.3
24	82	27	46.1	17.7	27.7	NW	18	0.59	416	77.1
25	92	31.8	51.8	18.7	28.5	NW	21.6	0.61	416	70.8
26	102	35.8	61.8	25	27.9	NW	21.6	0.58	415	74.7
27	108	38.5	59.2	27.9	28.2	NW	25.2	0.65	419	75.3
28	139	50.9	97.4	32.2	29.3	NW	21.2	0.52	410	68.8
29	96	33.4	65.8	14.2	27.3	NW	18	0.51	411	56
30	55	13.9	34.7	4.4	28.6	NW	21.6	0.40	411	62
31	60	15	36	6.2	28.6	NW	21.6	0.42	411	65
Average	77	24.2	49.2	12.7	28.4	_	23.1	0.49	412	66.4

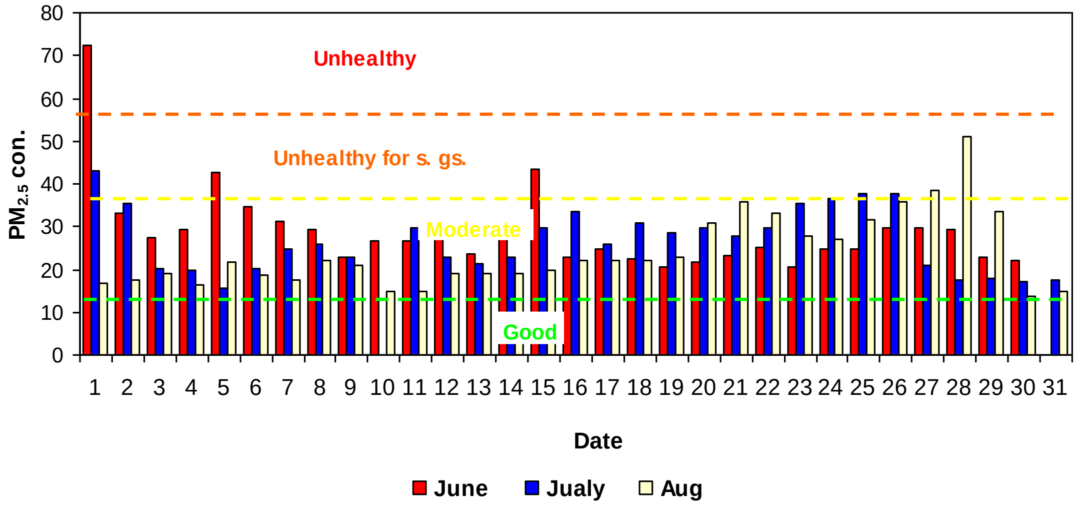


Fig. 33 - The daily concentrations of $PM_{2.5}$ during the summer season in Benghazi city (US EPA 2014).

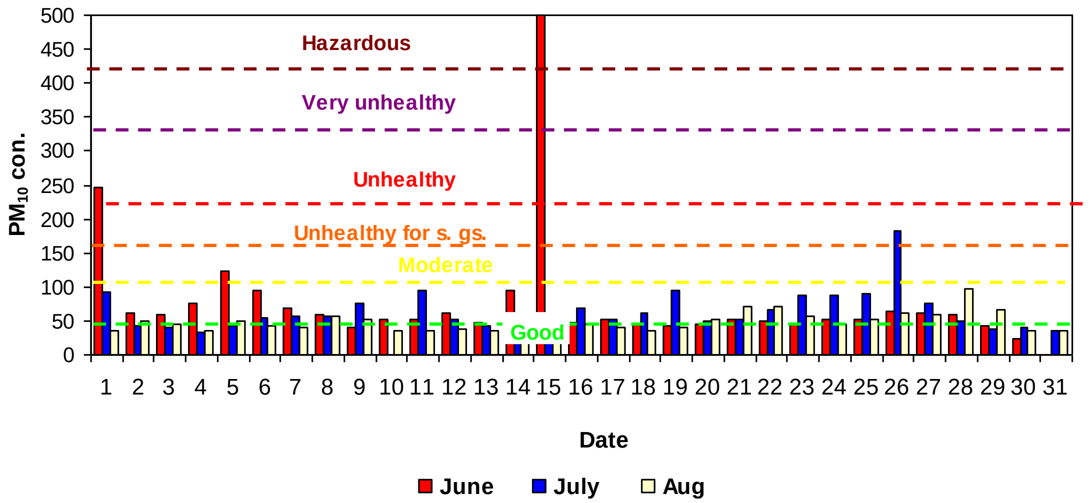


Fig. 34 - The daily concentrations of PM_{10} during the summer season in Benghazi city (US EPA 2014).

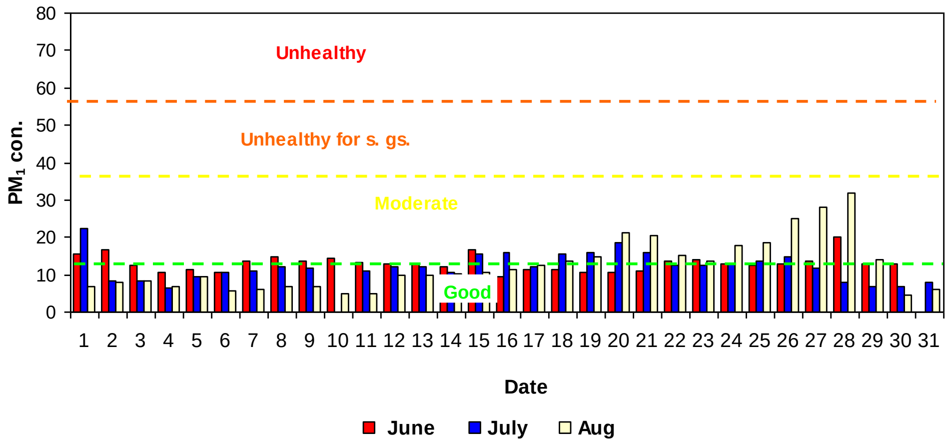


Fig. 35 - The daily concentrations of PM_1 during the summer season in Benghazi city (US EPA 2014).

5.4.1 Correlations of Air Pollutants with Meteorological Variables

The correlation coefficient was calculated to evaluate the relationship between atmospheric pollutants ($PM_{2.5}$ and PM_{10}) and meteorological variables for Benghazi city. $PM_{2.5}$ showed positive correlation with PM_{10} (r = 0.66, in June, r = 0.70, in July and r = 0.9 in August), this significant correlation is an indication of these two pollutants originate from similar sources (Fig. 36).

$PM_{2.5}$ and PM 10 in the studied areas were weakly positive correlated with temperature, humidity and wind speed (r = 0.23, 0.2 and 0.3, and r = 0.1,0.13 and 0.2 in June, r = 0.34, 0.22 and 0.37, and r = 0.5, 0.4 and 0.63 in July, and r = 0.2,0.22 and 0.19, and r = 0.3 and 0.21 in August), which indicated there was no relationship between particles meteorological parameters during summer season. The highest daily average of temperature was observed in August whereas the highest daily of humidity was recorded in June.

The pollution roses in Fig. 37 shows how monthly wind flows affect PMs levels in the studied areas. The mostly the wind directions in the studied areas were north, northeast and northwest. Therefore, the emitted anthropogenic pollutants from southern Europe areas were carried by north winds especially the fine particles ($PM_{2.5}$) into the Libyan coast (Fig. 38).

The summer becomes the season with the highest concentrations of $PM_{2.5}$, this seems to indicate the decisive contribution of anthropogenic, both local and remote. The PM_{10} has very low concentrations during the summer season due to low frequent of dust and sand storms (dust event) (Erel et al. 2007; Asaf et al. 2008; Dayan et al. 2017).

The $PM_{2.5}/PM_{10}$ ratio was used to determine the particle sizes and source of pollutions in atmosphere in the studied areas and the atmosphere is in mixed zone of particles and in mixed pollution sources (Figs. 39 and 40).

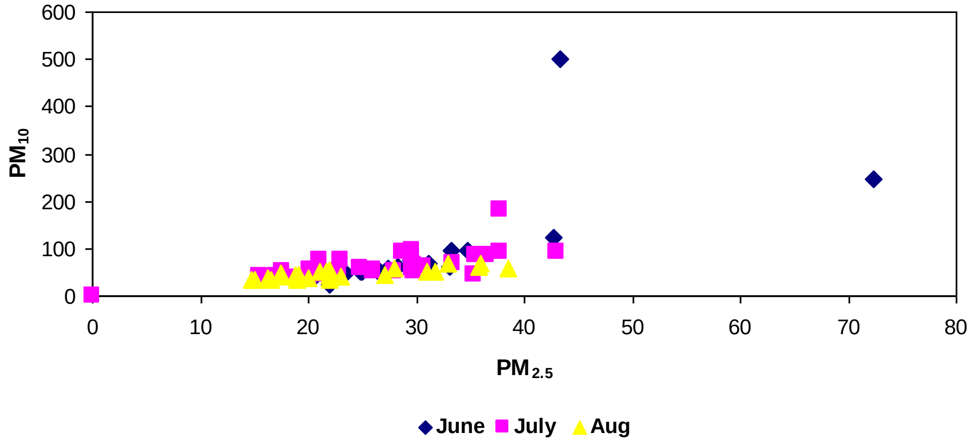


Fig. 36 - Relationship between $PM_{2.5}$ and PM_{10} in Benghazi city.

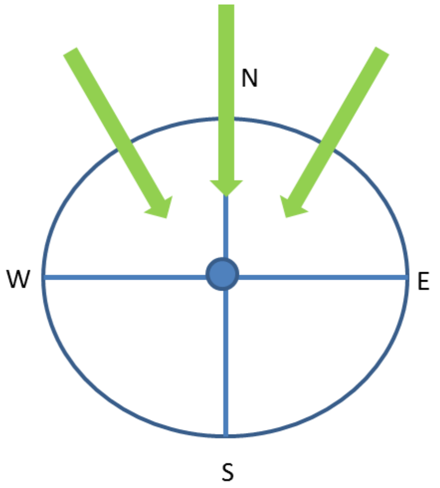


Fig. 37 - Major trend of wind directions carried by pollution from south Europe areas.

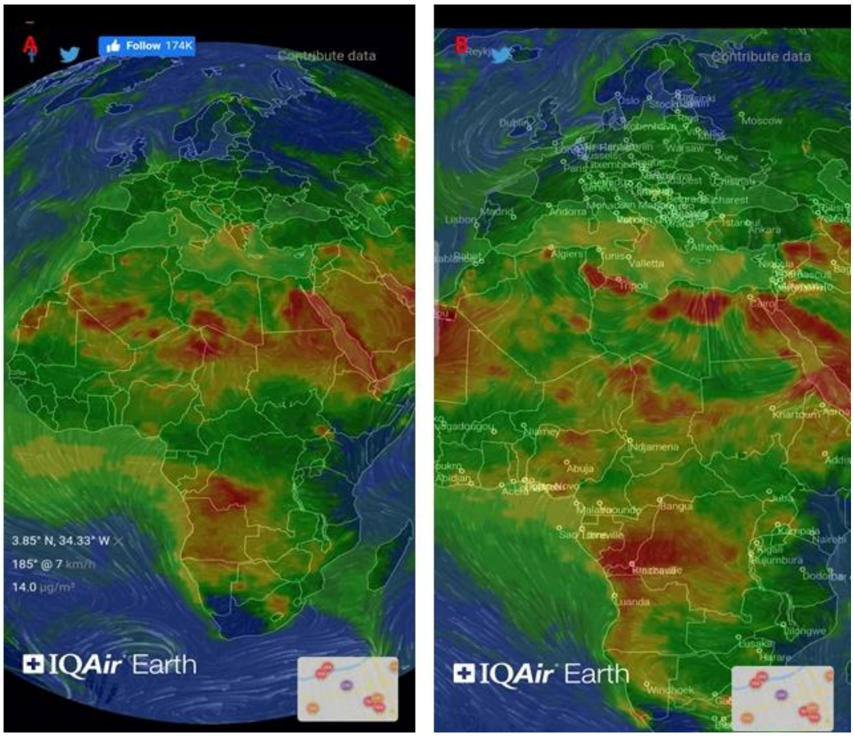


Fig. 38 - The north winds carried pollutants from southern Europe areas (modified from IQAir 2023b).

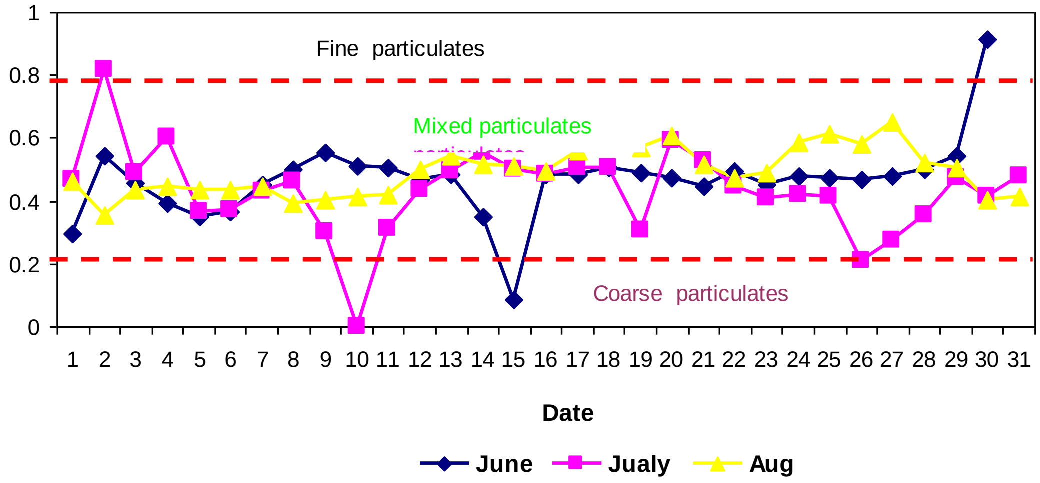


Fig. 39 - Classification of particles based on $PM_{2.5}/PM_{10}$ ratios during summer season in Benghazi city (fields after Wu et al. 2015).

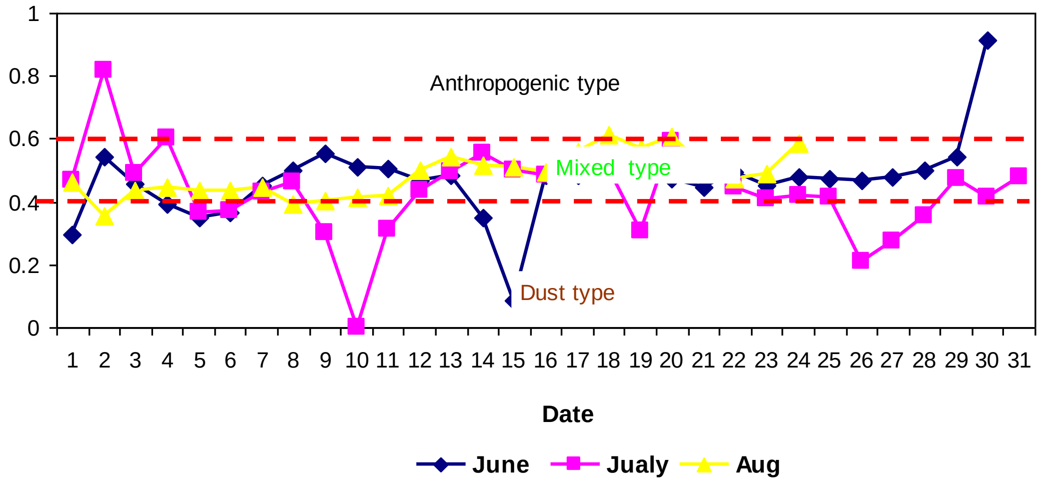


Fig. 40 - Source of particles based on PM2.5/PM10 ratios during summer season in Benghazi city (fields after Huang et al. 2014).

5.4.2 Risk Assessment

The daily average of AQI during summer season in Benghazi city varied from 56 μg/m^3 to 160 μg /m^3 (Fig. 41), which reflects that the air quality in the studied area was as level 2 (moderate air quality), air pollution is acceptable, however, there may be risk or moderate health concern for a few people (very small number) especially those who are usually sensitive to air pollution. The monthly average of AQI was shown in (Fig. 42).

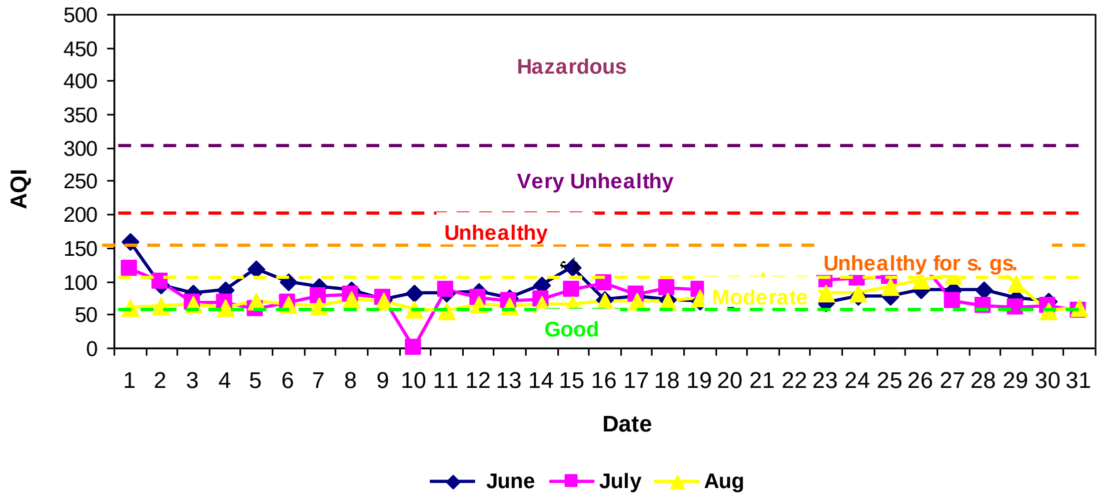


Fig. 41 - Daily average concentrations of AQI in studied area (US EPA 2014).

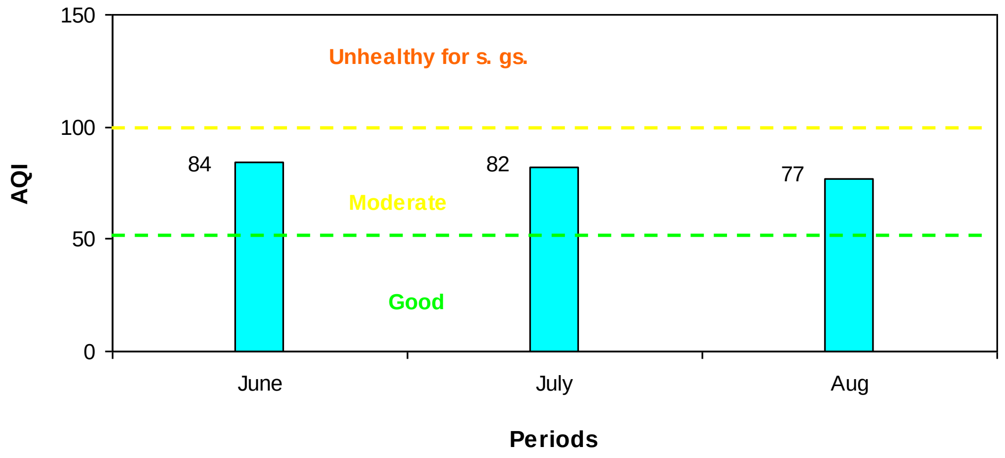


Fig. 42 - Monthly average concentrations of AQI in the studied area (US EPA 2014).

5.4.3 Carbon Dioxides in Summer Season

The level of CO_2 in the summer season was lower than the level in the spring, because the southern part of the Earth begins the winter season, leaf growth also begins with a slight increase in the process of photosynthesis, which leads to a reduction in CO_2. However, the increase or decrease in CO_2 is related to human activities, tree leaves and the movement of the universe. The concentrations of CO_2 in June (417 ppm, in average) was reported the highest concentration in summer season, whereas July (412 ppm, in average) and August (412 ppm, in average) have similar distribution (Figs. 43 and 44).

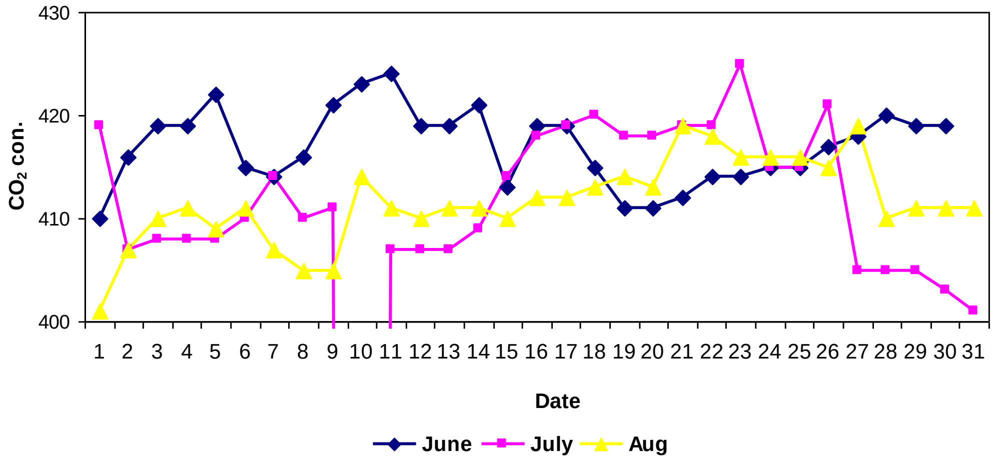


Fig. 43 - Daily average of CO_2 during summer season.

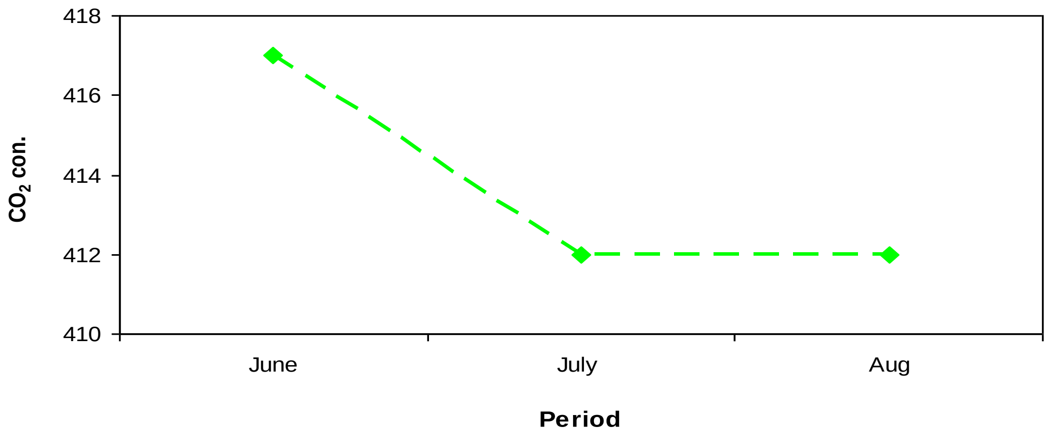


Fig. 44 - Monthly average of CO_2 during summer season.

5.5 Storm Daniel

Storm Daniel is considered to be the largest natural disaster that faced the State of Libya in terms of the number of victims, which reached thousands of victims. This phenomenon is considered rare in terms of the amount of rain falling within 24 hours, and this storm was carrying with it very heavy rain that exceeded 400 millimeters, an amount that had not been recorded for last 40 years in Libya. The storm began to approach on 9th of September at night at 10:00 PM after wind speeds increased to 46.7 km/h with the rain rate 80%, and a drop in atmospheric pressure that reached 1004.5 mbar, the average wind speed reached 25.2 km/h at 9:00, in Benghazi city (Fig. 45).

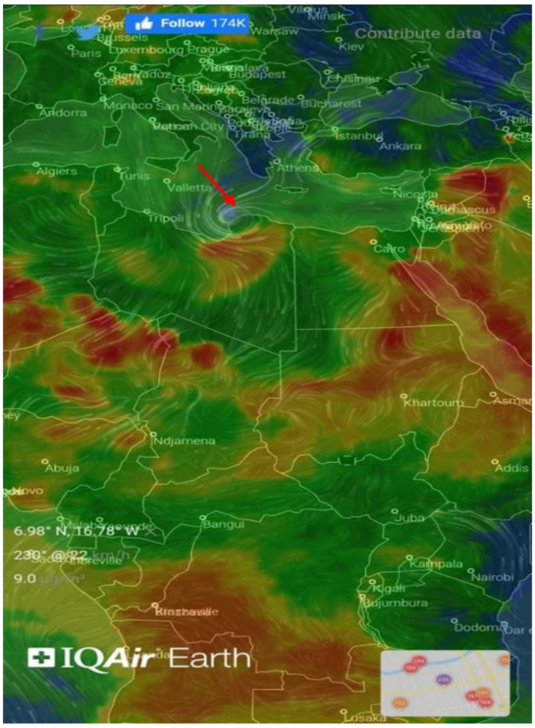


Fig. 45 - The arrival of Storm Daniel on Benghazi on 9th of September (from IQAir 2023b).

On the 10th day of September, the wind speed increased in Benghazi city, and the peak of the storm (Daniel) began to affect the city, reaching 75.6 km/h at exactly 1:00 pm with a 100% rain rate. The atmospheric pressure recorded the lowest concentration of 1004.3 m bar over the year (Fig. 46). This storm caused the seawater to rise more than 3 m above mean sea level, it led to the destruction of some buildings in the city. After that, Storm Daniel moved east towards the Al Jabal Al Akhdar because of a difference in atmospheric pressure, which was 1003.7 millibars (Fig. 47) and swept away many cities and villages in eastern Libya, such as Al-Marj, Takenis, Al-Bayda, and Shahat. All of these areas were exposed to strong winds and rain. Torrents and floods led to the drowning of most of them, as these cities were located in depressions and valleys, and left many human casualties and the destruction of some residential buildings and infrastructures (Fig. 48).

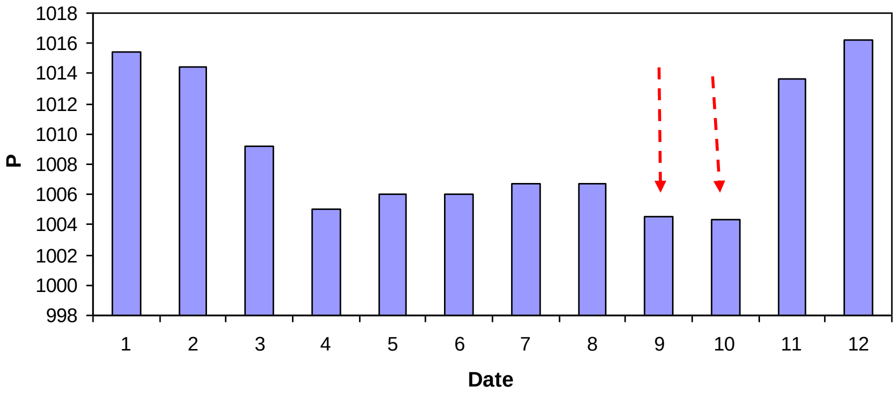


Fig. 46 - The decrease in pressure (%) on 9th and 10th of September in Benghazi city.

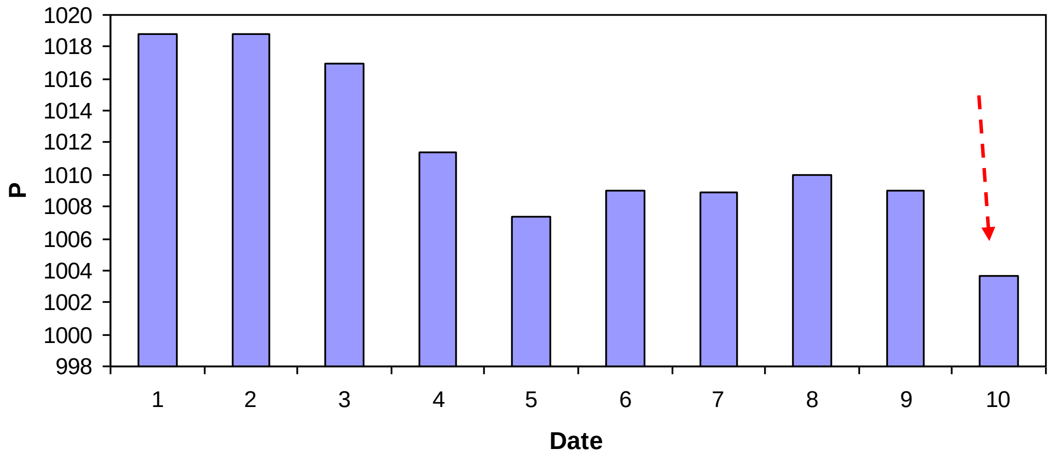


Fig. 47 - The decrease in pressure (%) on 10th of September in Al Jabal Al Akhdar .

Fig. 48 - Some natural disasters in some areas in the Al Jabal Al Akhdar, NE Libya.

However, the real disaster was in Derna city, where a valley called Wadi Derna passes through the center of the city (Fig. 49), which divides the city into two parts.

In the valley, there are two dams, the large Mansoura dam, which is about 70 meters high, the water storage capacity about 22.5 million cubic meters, while the second dam, meaning the lower one, was slightly smaller and called is Derna dam, which is about 45 meter high, the water storage capacity about 1.5 million cubic meters (Fig. 50). The dams suffer from cracks and a lack of regular maintenance since 1999.

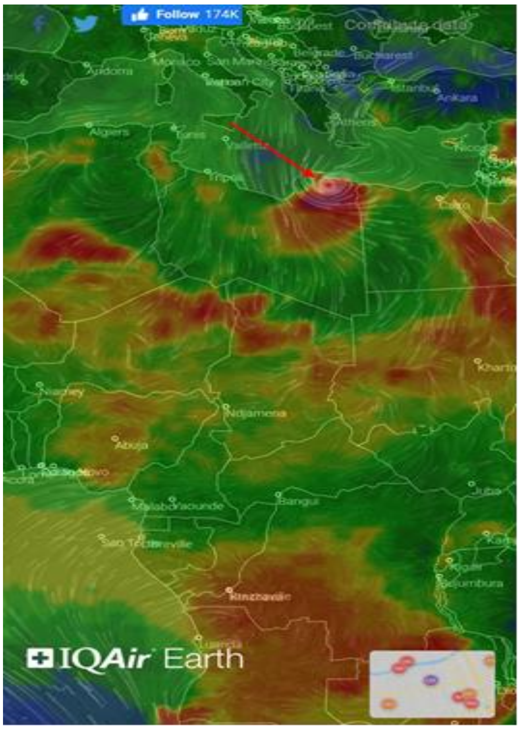


Fig. 49 - The strength of Daniel storm on the Al Jabal Al Akhdar, especially the city of Derna, on 10th September (from IQAir 2023b).

Fig. 50 - Map of Derna city and the two main dams were highlighted.

After heavy rains, tremendous water pressure, and technical reasons for the dam, it led to the collapse of the first dam, and the second dam quickly followed, and huge quantities of water flowed loaded with mud mixed with gravel with different sizes, and this doubled its destructive capacity, which led to the destruction of the earthen barriers. The infrastructure was also subjected to widespread destruction, including bridges, roads, and buildings that were swept away by the torrents. That is, entire neighborhoods with an area of 700,000 square meters disappeared, equivalent to approximately a quarter of the population of the city of Derna (Fig. 51).

Fig. 51 - Shows Derna flooding, northeastern Libya.

After 10th September, the storm headed to the Libyan-Egyptian border with a decrease in wind speed of less than 50 km/h, and then it headed to the city of Cairo with a wind speed of less than 30 km/h. On the 13th of September, and the storm ended at that point after, it covered a distance of more than 2220 km (Fig. 52).

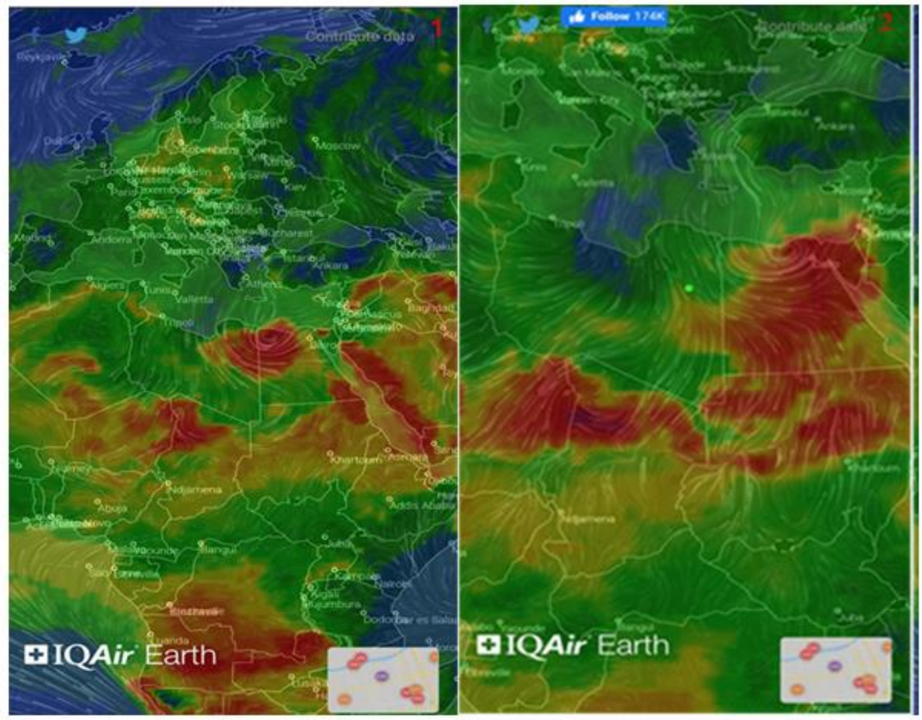


Fig. 52 - The strength of the Storm Daniel on the Libyan-Egyptian border on September11th and how it disappeared on September 13th in Cairo (from IQAir 2023b).

5.6 Fall Season (September, October and November)

5.6.1 Assessment of AQI, PM1, PM2.5 and PM10

Based on the AirVisual Outdoor monitoring in fall season, the monthly average concentration of the air quality index in September (80 μg/m^3) and November (85 μg/m^3) periods were classified as moderate air quality whereas the October (107 μg/m^3) period was classified as unhealthy for sensitive groups (Fig. 53).

$PM_{2.5}$, PM_{10} and PM_1 daily concentrations during fall season shown in (Figs. 54, 55 and 56) $PM_{2.5}$ concentration were exceeded more than save limit on the twenty fifth day in October and the fifth day in November periods. PM_{10} concentrations were not meet with permissible limit on the days twenty fourth, twenty fifth and twenty sixth in October period while the days in November period such as the first, second, third, fourth, fifth, twenty fourth, twenty nine and thirty. PM_1 concentrations on the eleven, twelve and thirteen days in October period were above the safe limit. The meteorological parameters in studied area including temperature T, humidity and wind speed WS. In general, the meteorological parameters were moderate positively correlated with the $PM_{2.5}$ and PM_{10} during fall season,(r= 0.6, 0.7and 0.62 and r= 0.75,0.77 and 0.71 in September period), (r= 0.53, 0.56 and 0.55 and 0.52,0.54 and 0.59 in October period) and (r= 0.4, 0.4 and 0.39 and 0.45, 0.44 and 0.47 in November), which influenced that an increase in pollutants is associated with an increase in meteorological parameters (Giri et al. 2008; Lin et al. 2009; Munir et al. 2013) .The relationship between $PM_{2.5}$ with PM_{10} are moderate positive correlated r= 0.64 in September, r= 0.65 in October and r= 0.63 in November, indicated that $PM_{2.5}$ and PM_{10} were originated from similar source.

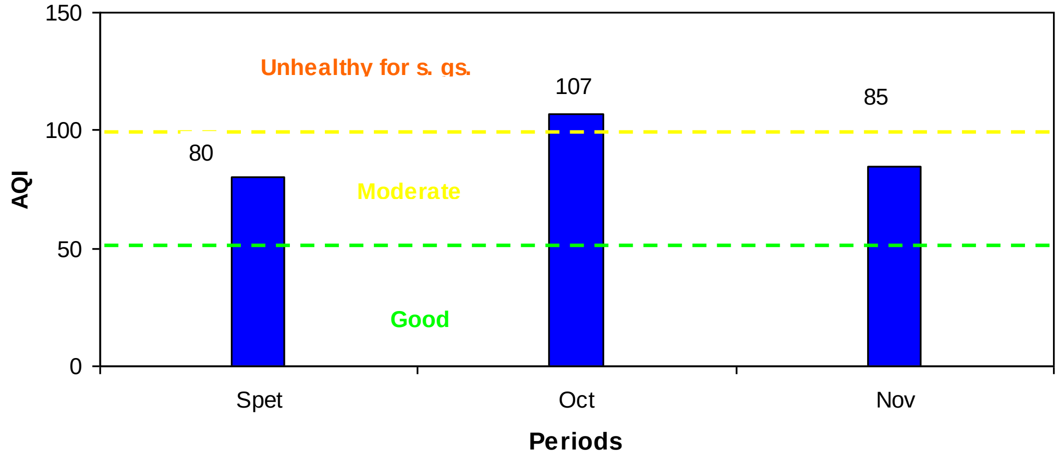


Fig. 53 - Monthly average of AQI during fall season (US EPA 2014).

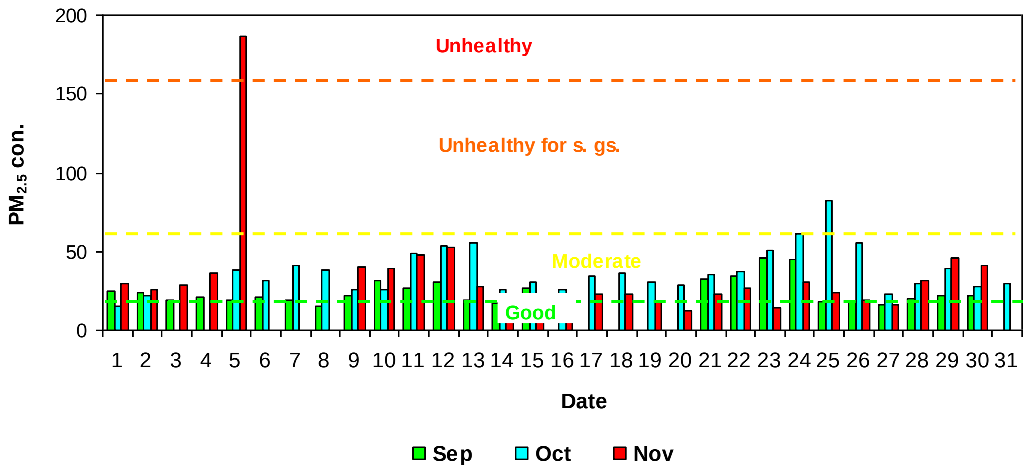


Fig. 54 - The daily concentrations of $PM_{2.5}$ during the fall season in Benghazi city (US EPA 2014).

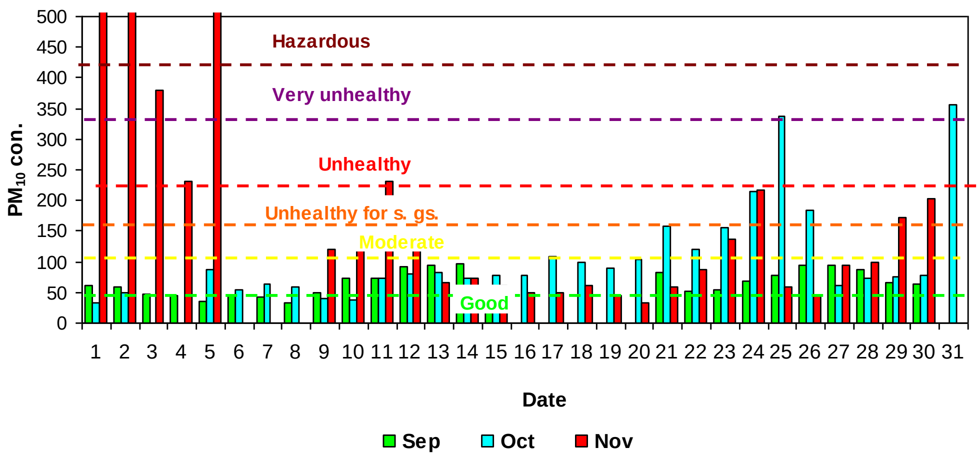


Fig. 55 - The daily concentrations of PM_{10} during the fall season in Benghazi city (US EPA 2014).

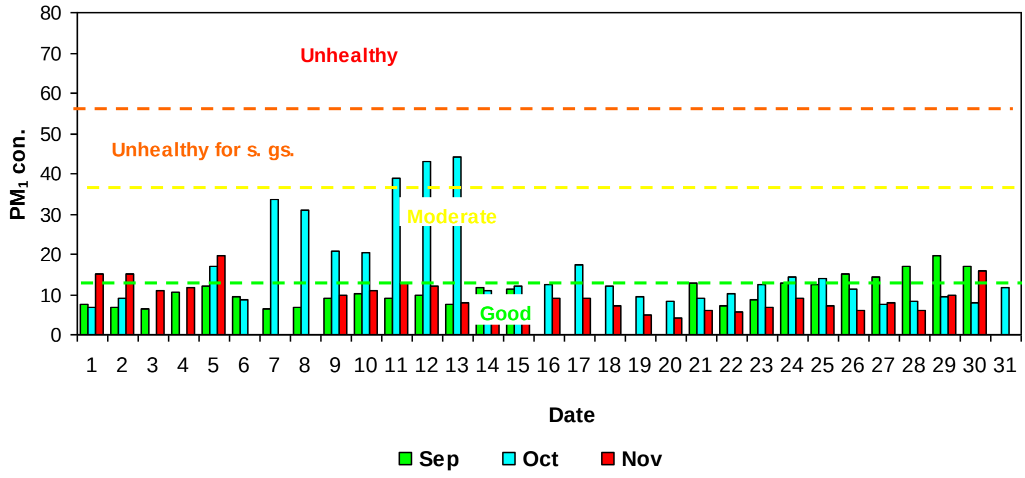


Fig. 56 - The daily concentrations of PM_1 during the fall season in Benghazi city (US EPA 2014).

5.6.2 Classification and Source of Air Pollution

$PM_{2.5}$/ PM_{10} is very useful to determine the particle sizes and the source of air pollution in the atmosphere, Based on the $PM_{2.5}$/ PM_{10}, the atmosphere in the September and October periods were characterized by mixed particles and in the November period contained coarse and mixed particles (Fig. 57).

The studied area was affected on mixed and dust sources in September and November whereas in October period was affected on mixed to anthropogenic sources such as local and external dust, car exhaust, transportation, industrial and factories processes (Fig. 58). The concentration of pollution in fall season is more polluted than summer season (Azad and Kitada 1998 and Salam et al. 2003). The major particle wind direction in the September period was NE direction while in October and November periods were SE direction (Fig. 59).

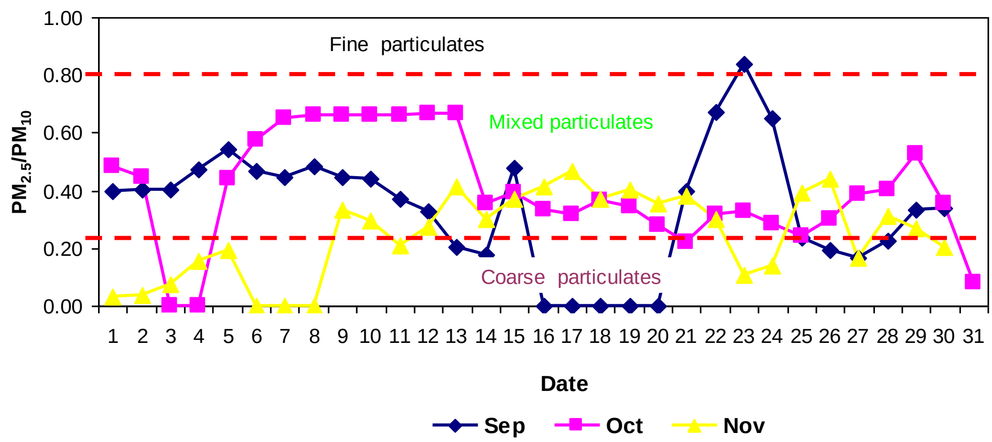


Fig. 57 - Classification of particles based on $PM_{2.5}/PM_{10}$ ratios during fall season in Benghazi city (fields after Wu et al. 2015).

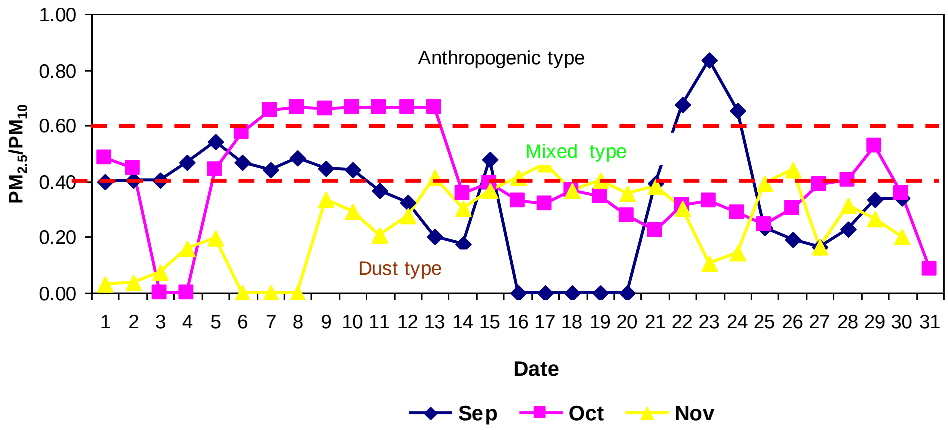


Fig. 58 - Source of particles based on PM2.5/PM10 ratios during fall season in Benghazi city (fields after Huang et al. 2014).

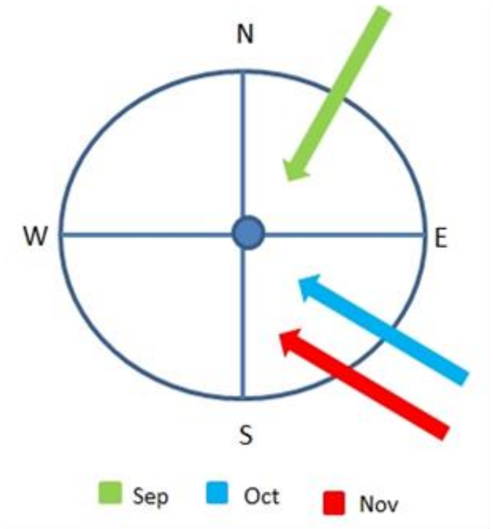


Fig. 59 - Major trend of particle wind directions during fall season.

5.6.3 Carbon Dioxides in Fall Season

The carbon dioxide in September period was ranged from 401 ppm to 419 ppm, with the monthly average 414 ppm, in the October period was starched from 409 to 421 ppm, with the monthly average 414 ppm and in the November period was ranged from 396 ppm to 433 ppm (Tables 10-12), with the average monthly 414 ppm. The CO_2 in fall season are the same level in all periods (Fig. 60).

Table 10 - Daily average concentration of $PM_{2.5}$, PM_{10}, AQI for September period (concentrations in μg/m^3), CO_2 (ppm), temperature (C°), humidity (%), wind direction and wind speed (km/h).

Date	AQI	$PM_{2.5}$	PM_{10}	PM_1	T	WD	WS	$PM_{2.5}/PM_{10}$	CO_2	H
1	77	24.7	62	7.7	29.7	21.6	NE	0.40	416	53.9
2	75	23.5	58.5	6.7	27.5	25.2	NE	0.40	412	66
3	66	19.2	47.7	6.5	27	28.8	N	0.40	413	65.6
4	71	21.5	45.7	10.5	27.3	28.8	NW	0.47	411	70
5	66	19.2	35.5	12	22.8	32.4	NE	0.54	412	81.2
6	70	21.3	45.5	9.5	24.5	18	SE	0.47	418	75.2
7	66	19.3	43.5	6.4	26	18	W	0.44	413	73.2
8	58	15.5	31.9	6.8	27	29	SW	0.49	412	72.5
9	73	22.4	50	8.9	25	26	SW	0.45	409	80.4
10	93	32	72.3	10.3	22.3	55	NE	0.44	408	88.6
11	82	27	73.1	9.2	24.2	44	NE	0.37	415	70.5
12	89	30.3	92.9	9.8	24.5	32	NE	0.33	417	70
13	65	18.8	93.2	7.7	23.4	32	NE	0.20	417	70.2
14	61	17	96.3	11.7	22.4	29	NE	0.18	418	80.8
15	84	27	56.6	11.2	25	21.6	NE	0.48	415	74.8
16										
17										
18					No data recorded					
19										
20										
21	95	33	83.4	12.8	25.8	14.4	NW	0.40	416	76.5
22	99	34.9	51.8	7.2	24.5	18	NE	0.67	418	69
23	127	46	55	8.8	24.7	18	SE	0.84	419	69.7
24	125	45	69	12.8	24.4	18	NW	0.65	421	69.1
25	64	18.3	77.8	12.5	23.8	18	NW	0.24	420	69.9
26	64	18.4	94.8	15	24	21.6	SW	0.19	420	66.3
27	59	15.8	95.4	14.4	23.4	21.6	SW	0.17	418	67.6
28	68	20	87.7	16.8	23.6	21.6	NW	0.23	419	67.7
29	72	22.3	66.8	19.7	23.5	18	SE	0.33	412	68.6
30	71	21.8	64	17.1	22.8	18	SE	0.34	410	73.1
Average	80	25.8	66	9.9	25.5	18.72	_	0.39	414	70.8

Table 11 - Daily average concentration of $PM_{2.5}$, PM_{10}, AQI for October period (concentrations in µg/m^3), CO_2 (ppm), temperature (C°), humidity (%), wind direction and wind speed (km/h).

Date	AQI	$PM_{2.5}$	PM_{10}	PM_1	T	WD	WS	$PM_{2.5}/PM_{10}$	CO_2	H
1	58	15.5	31.9	6.8	27	18	NW	0.49	412	72.5
2	73	22.4	50	8.9	25	18	NW	0.45	409	80.4
3					No data recorded					
4										
5	109	38.6	87.7	16.8	23.6	21.6	NW	0.44	419	67.4
6	92	31.9	55.4	8.6	22.8	25.2	N	0.58	410	67
7	116	41	62.9	33.4	24.7	25.2	N	0.65	416	70
8	108	38.5	58	30.9	24.4	18	NW	0.66	418	81.2
9	80	26	39.3	20.8	23.8	21.6	NW	0.66	419	75.2
10	79	25.4	38.3	20.3	24	21.6	NE	0.66	421	73.2
11	133	48.4	72.9	38.7	23.4	28.8	NE	0.66	415	72.5
12	145	53.5	80.5	42.9	23.6	18	NW	0.66	420	77.2
13	149	55.1	82.8	44	23.5	18	NW	0.67	412	88.6
14	79	25.7	72.2	10.8	23	18	NW	0.36	409	70.5
15	90	30.6	78.1	12.1	23	18	NW	0.39	409	68
16	80	26	78.6	12.6	23.2	18	NW	0.33	409	74.8
17	98	34.4	108.6	17.4	23.4	14.4	SW	0.32	417	79.4
18	103	36.5	99.9	12.2	23.4	25.2	SW	0.37	413	54.3
19	91	31	90.2	9.5	25.4	36	SE	0.34	409	38.5
20	86	29	104	8.4	26.4	28.8	SW	0.28	407	30.8
21	99	35.1	158	9.2	26.8	32.4	SW	0.22	404	29.7
22	106	37.6	119.5	10.2	26.5	28.8	SE	0.31	406	42.7
23	139	50.9	155.4	12.4	24.1	18	NW	0.33	411	68
24	154	61.7	215	14.2	24	18	NE	0.29	418	62.4
25	165	82	337	14.1	24.4	18	SW	0.24	422	55
26	151	55.8	185	11.4	24.8	10.8	NW	0.30	413	61
27	75	23.4	60.3	7.6	23.4	18	NW	0.39	417	73.5
28	87	29.3	72.2	8.4	24.1	10.8	SW	0.41	420	65.5
29	110	39.3	74.3	9.3	23.5	21.6	SW	0.53	414	66.5
30	84	27.7	78	7.9	25.4	21.6	NW	0.36	412	48
31	87	29.5	355	11.7	24.5	18	NW	0.08	407	60
Average	107	38.1	107.3	12.7	23.5	21.2	_	0.36	414	64.7

Table 12 - Daily average concentration of $PM_{2.5}$, PM_{10}, AQI for November period (concentrations in $\mu g/m^3$), CO_2 (ppm), temperature (C°), humidity (%), wind direction and wind speed (km/h).

Date	AQI	$PM_{2.5}$	PM_{10}	PM_1	T	WD	WS	$PM_{2.5}/PM_{10}$	CO_2	H
1	153	29.4	953	15	25.4	SE	14.4	0.03	412	68
2	152	26.3	700	15	24.5	SW	25.2	0.04	407	75.3
3	136	29	380	11	23.4	SW	26	0.08	419	73.9
4	138	36.6	231	11.7	21.9	SW	33	0.16	417	72.9
5	237	186.2	953.4	19.5	23.4	NE	12	0.20	419	68
6										
7					No data recorded					
8										
9	113	40.3	121	10	20.9	NW	26	0.33	419	72.8
10	111	39.7	135.3	11	20.9	SE	21	0.29	416	75.5
11	131	47.9	231	13	21.1	SE	21	0.21	417	68
12	144	52.9	191.2	12	21.3	NW	18	0.28	419	68.3
13	83	27.5	66.3	8	21	NW	28	0.41	419	75.3
14	72	22.3	73.6	7	21.1	NW	21	0.30	419	65.3
15	72	22.3	60.5	7	21.5	NW	18	0.37	416	74.4
16	68	20.1	48.7	9	22.1	NW	18	0.41	415	77
17	73	22.7	48.8	9	21.7	NW	21	0.47	418	75
18	74	22.9	62.1	7	20.8	NW	39	0.37	410	71
19	63	17.8	44.1	5	18.4	NW	39	0.40	412	56.5
20	50	12	33.9	4	19.6	NW	28	0.35	415	61.7
21	73	22.5	58.9	6	18.5	SW	21	0.38	411	69
22	82	26.5	88	5.5	18.2	SE	32	0.30	405	55.3
23	56	14.6	135.8	6.8	19.6	SE	32	0.11	407	41.7
24	90	30.6	216	9	19.6	SE	36	0.14	399	47.9
25	75	23.5	59.9	7	18	W	50	0.39	396	69
26	66	19.4	44	6	16.2	W	46	0.44	400	60.5
27	59	15.8	95	8	16.4	SE	21	0.17	411	57.4
28	91	31.3	100	6	16	SW	36	0.31	415	51.9
29	127	46	172	10	16.8	NW	18	0.27	421	67.6
30	114	41	202	16	18.3	NW	10	0.20	433	77
Average	85	28.4	171.2	9.2	20.4	_	27.27	0.17	414	65.5

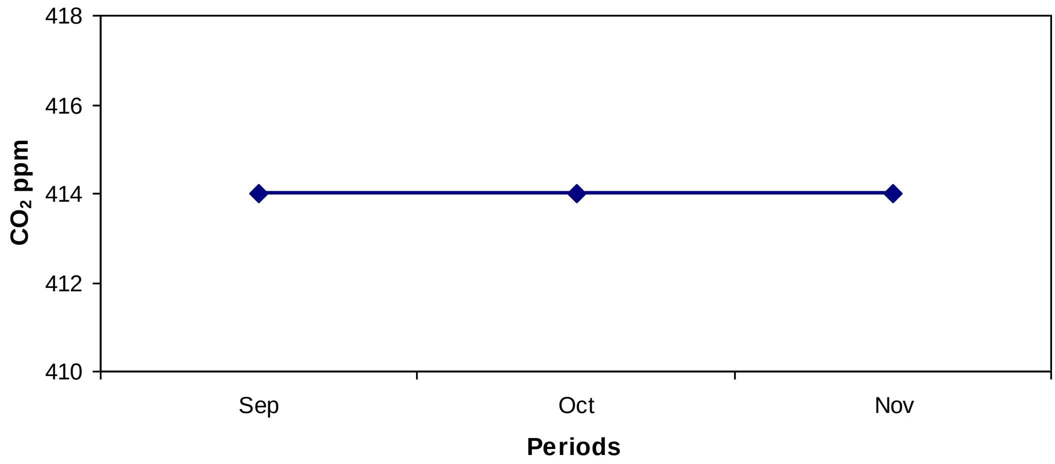


Fig. 60- Monthly average of CO_2 during fall season.

5.7 Winter Season (December)

The monthly average concentration of the air quality index (90 μg/m^3) is classified as moderate air quality, the $PM_{2.5}$ and PM_{10} are classified as moderate air quality while PM1 is classified as good air quality. The CO_2 concentration in December ranged between 415 ppm to 430 ppm, with the main average 419 ppm (Table 13).

5.8 The Monthly Average Concentrations of All Parameters During All Periods

The most polluted period in Benghazi city was in February AQI 160 μg/m^3 and the cleanest period was in the August AQI 77 μg/m^3 (Fig. 61). The highest concentrations of $PM_{2.5}$ and PM_1 were observed in February period and the lowest value of PM $_{2.5}$ was in September period 25.8 μg/m^3 while the lowest concentration of PM_1 was in April 8.7 μg/m^3 (Fig. 62).

The highest level of PM_{10} was recorded in May period 252 μg/m^3 and the lowest level of PM_{10} was seen in August period 49.2 μg/m^3 (Fig. 63).

The carbon dioxide CO_2 was reported highest concentration in May period 424 ppm and lowest concentration was in July and August periods 412 ppm (Fig. 64).

The temperature recorded the highest level in July and August periods 28.4 C° and the lowest level in February 13.3 C° (Fig. 65). The humidity was observed the highest level in June 72 % and lowest level in April 58.7% (Fig. 66).

Table 13 - Daily average concentration of $PM_{2.5}$, PM_{10}, AQI for December period (concentrations in µg/m^3), CO_2 (ppm), temperature (C°), humidity (%), wind direction and wind speed (km/h).

Date	AQI	$PM_{2.5}$	PM_{10}	PM_1	T	WD	WS	$PM_{2.5}/PM_{10}$	CO_2	H
1	139	50.5	172	16.1	18	NW	12	0.29	426	71
2	103	36.5	202	12.9	17.3	NW	18	0.18	420	47.3
3	95	33.3	112	9.1	17.8	NW	25	0.30	416	54
4	78	25	62.5	9	16.9	N	25	0.40	415	69.5
5	68	20	50	8.3	16.9	SE	20	0.40	420	71.1
6	79	25.7	71	6.9	19	SE	20	0.36	420	64.9
7	79	25.3	67	7.1	18.4	NE	23	0.38	417	55.8
8	70	24.3	65	7.1	18	N	22	0.37	417	55

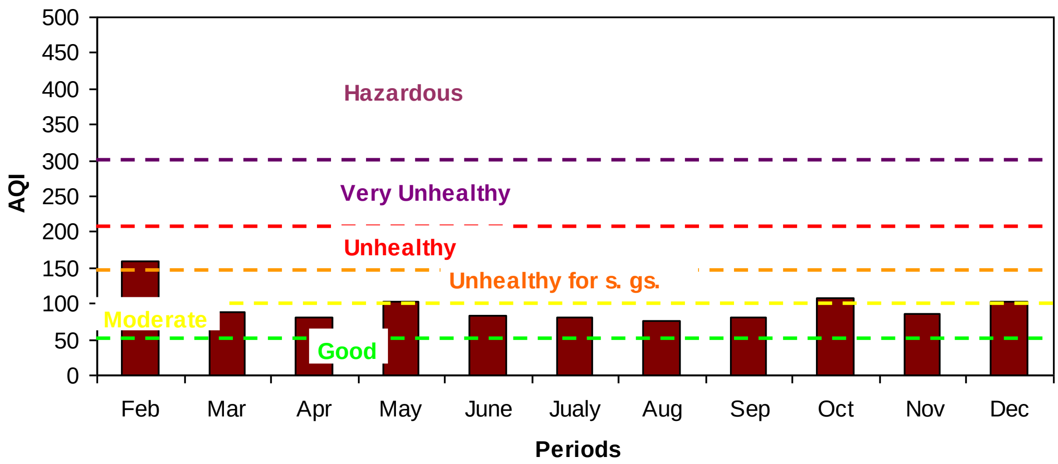


Fig. 61 - The monthly average concentration of AQI (µg/m3) for all periods (US EPA 2014).

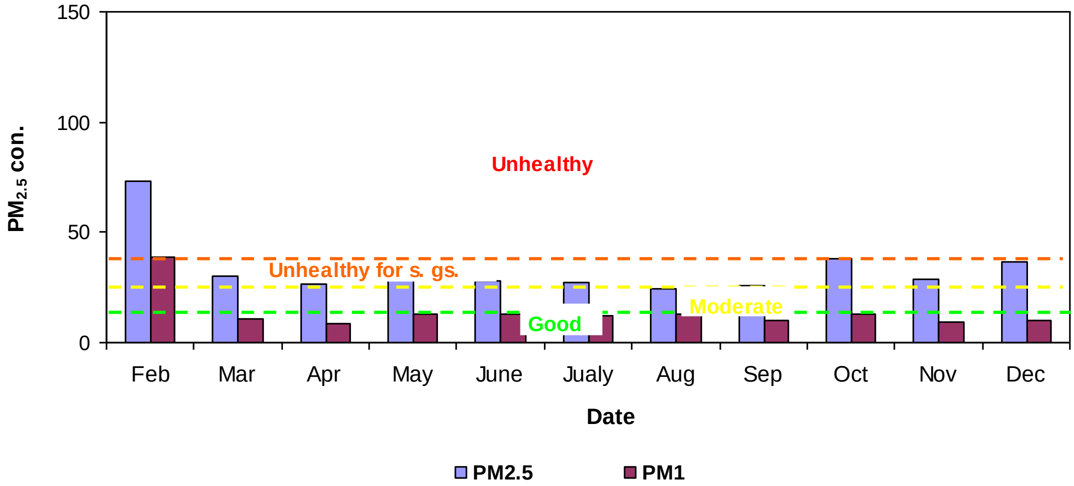


Fig. 62 - The monthly average concentration of $PM_{2.5}$ and PM_1 for all periods (US EPA 2014).

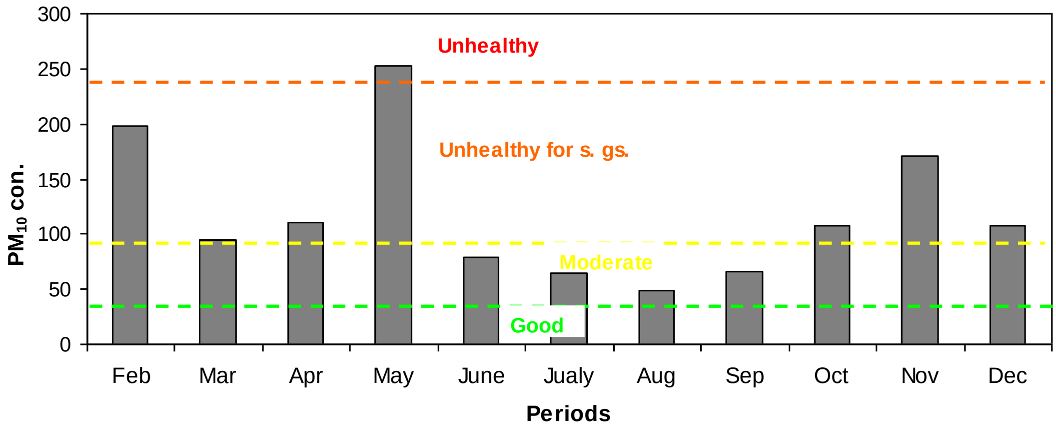


Fig. 63 - The monthly average concentration of PM_{10} for all periods (US EPA 2014).

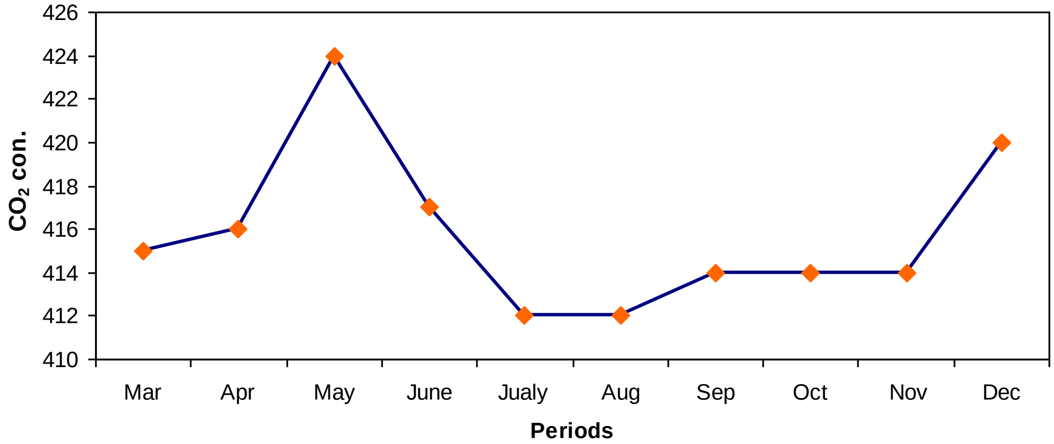


Fig. 64 - The monthly average concentration of CO_2 ppm for all periods.

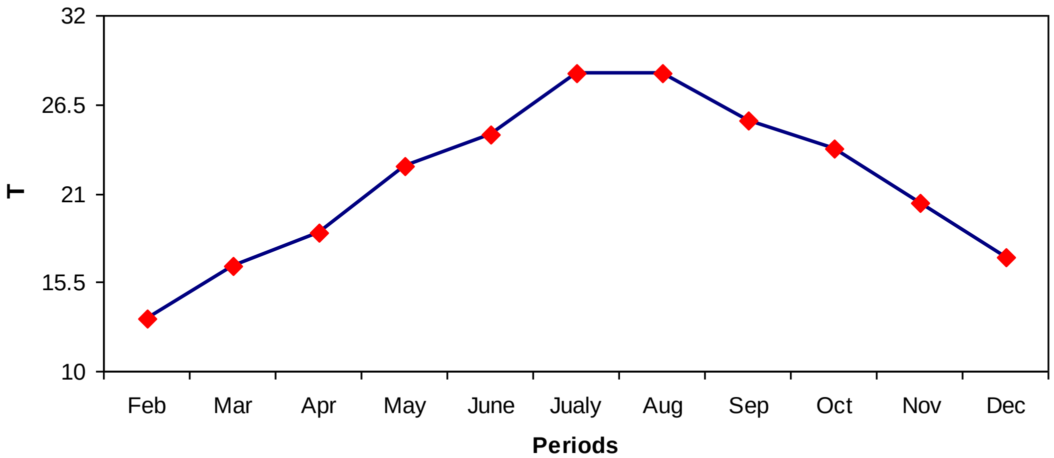


Fig. 65 - The monthly average of temperature C° for all periods.

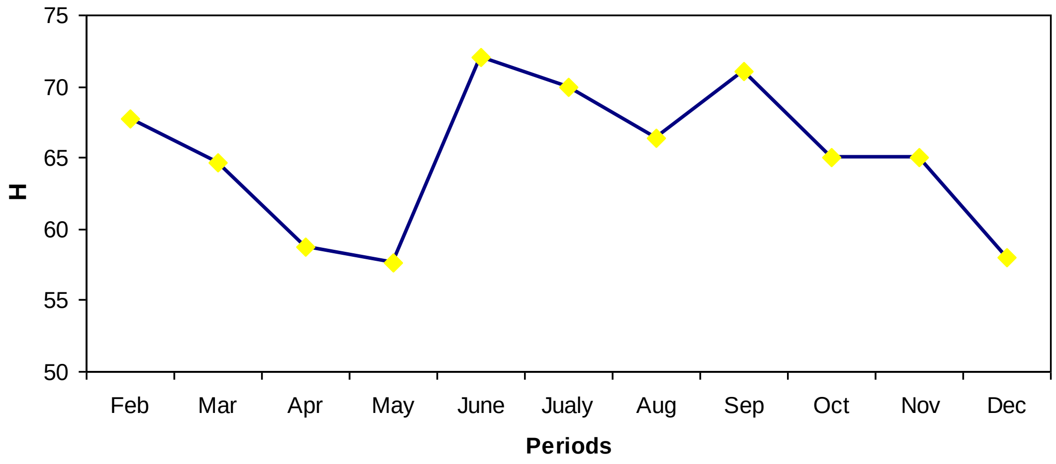


Fig. 66 - The monthly average of humidity (%) for all periods.

6. Conclusion

Winter and spring season

- The AirVisual Outdoor monitor measures PM_1, $PM_{2.5}$, PM_{10}, AQI, CO_2, temperature, humidity, wind direction and wind speed.
- Five stations have been installed in Libya (Benghazi, Tripoli, Zliten, Awjilah and Al Bayada cities).
- Benghazi station was the first station installed in Libya, and record began on February 3rd, 2023.
- There is only one CO_2 sensor module in Libya installed in Benghazi city record which began on March 17th, 2023.
- The main average concentration of AQI in was 160 µg /m^3, classified as unhealthy in February period.
- In the spring season, the March and April periods, the main average of the AQI is classified as moderate air quality (89 and 84 µg /m^3) while in May was classified as unhealthy for sensitive groups.
- Based on the $PM_{2.5}$ / PM_{10} ratio, in February period, it contained a mixed size of particulate pollution and was affected by anthropogenic, natural and mixed pollution. In the spring season, the March and April periods contained mixed size of particulate pollution while in May period was characterized by mixed and coarse size pollution in the atmosphere; generally, the spring season was affected by mainly natural pollution.
- February and May periods were an unhealthy atmosphere in Benghazi due to increased concentrations of $PM_{2.5}$ and PM_{10} which will lead to an increase in respiratory/cardiovascular diseases and cancer in people.

- The PM_{10} was the highest value in all periods, which suggests that the PM_{10} is more from natural sources such as dust and sandstorms, most of these pollutants (PMs), especially in the May period came from Nigeria state by southerly winds.
- AQI concentration increases with decrease in humidity and increase with increase in temperature and wind speed in spring season.
- The May period recorded the highest value of CO_2 in Benghazi, an increase of about 7 to 8 ppm degrees from April and March. May period is usually the period in which each year the highest CO_2 levels are recorded because the plants will close their stomata to prevent water evaporation and reduce photosynthesis efficiency. At this time, human activities become more and more frequent, which eventually leads to an increase in the concentration of CO_2 in the atmosphere.
- Globally, the CO_2 concentration in the May 2022 was recorded 421 ppm by the Mauna Loa Observatory in Hawaii. In the May 2023 was recorded 424 ppm, an increase of about 3 ppm degrees from last year, this increase caused the new rise in global climate temperature caused by human activities.

Summer season

- According to AQI classification, the study area in summer season is classified as level 2 and considered as moderate air quality.
- The summer season reported the low concentrations of PMs in all seasons.
- The atmosphere in the study area contained mixed particles and mixed pollution types, which indicated that they originated from similar sources.
- Local and external pollutants coming with monsoon (north winds) from southern Europe areas affect the study area.
- $PM_{2.5}$ is higher than PM_{10} during summer season due to the lack of dust events.
- The summer season was the less polluted than spring season.
- There was no relationship between the meteorological parameters with $PM_{2.5}$ and PM_{10} during summer season.
- The concentrations of CO_2 in summer season is lower than spring season. In addition CO_2 level in July was recorded the highest level in summer season.

Fall and winter season

- Lack of systems and devices to monitor the rise in water levels in dam.
- The lack of sufficient stations to monitor climate changes, as well as early warning stations for climate change.
- Random construction in the depressions and sides of the valley led to the loss of thousands of lives due to torrents and floods.
- Lack of awareness and culture among people about the potential danger of this storm, as all citizens were informed of the necessity of evacuating homes by the Libyan

Army and Red Crescent forces since the beginning of the storm, in order to preserve the safety of citizens in the event of any complications of this storm.

- The October period is more polluted than other periods and all the pollutants were originated from similar sources during fall season.
- PM_{10} is higher than $PM_{2.5}$ and PM_1 due to the southern winds are more blowing and usually carry PM_{10}.
- Based on the $PM_{2.5}/PM_{10}$, The studied area was affected on mixed and dust sources in September and November whereas in October period was affected on mixed to anthropogenic sources.
- The meteorological parameters were moderate positive correlated with PMs, which indicated that the increased in meteorological parameters were associated increased in PMs.
- CO_2 concentrations were similar distribution in fall season.

7. Recommendation

The main recommendation of this work as the follows:

- The areas of trees, parks, water bodies and fountains in the city must be increased to improve air quality.
- A forestation should be expanded around and within the city.
- The Apollonia tree is considered one of the best trees in reducing air pollution and gas emissions.
- Strict regulations must be implemented and the application of minimum environmental pollution standards can improve air quality. Implementing monitoring systems for industrial and automotive emissions and using modern and advanced technology and environmentally friendly materials contributes greatly to preserving the environment.
- Increasing the efficiency of using renewable energy instead of fossil fuels.
- Encouraging the use of public transportation, expanding the range of buses and train lines, and creating bicycle lanes. Reducing the number of private vehicles allowed in these areas.
- Promote the use of clean transportation, such as electric cars and hybrid vehicles.
- The burning of natural gases associated with oil must be reduced.
- Carbon dioxide emissions in cement factories and power plants must be monitored.
- It is necessary to install other AirVisual Outdoor monitoring in other cities in Libya so that we can obtain more data on air quality.
- It is necessary to install early warning devices for climate change.

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Statements and Declarations

Ethical Approval

Not applicable

Consent to Participate

Not applicable.

Consent to Publish

Not applicable.

Authors Contributions

Conceptualization, Fares, F.F. and El Oshebi, F.M.; methodology, Fares, F.F. and El Oshebi, F.M.; software, Fares, F.F. and El Oshebi, F.M.; validation, El Oshebi, F.M., Fares, F.F., Abogrean, E.M., Talib, A.B. and Saleh, A.S.; formal analysis, El Oshebi, F.M. and Fares, F.F.; investigation, Fares, F.F. and El Oshebi, F.M.; resources, El Oshebi, F.M., Fares, F.F., Abogrean, E.M., Talib, A.B. and Saleh, A.S.; data curation, El Oshebi, F.M., Fares, F.F., Abogrean, E.M., Talib, A.B. and Saleh, A.S.; writing original draft preparation, El Oshebi, F.M., Fares, F.F., Abogrean, E.M., Talib, A.B. and Saleh, A.S..; writing review and editing, El Oshebi, F.M., Fares, F.F., Abogrean, E.M., Talib, A.B. and Saleh, A.S.; supervision, Fares, F.F.; project administration, Fares, F.F. All authors have read and agreed to the published version of the manuscript.

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Authors only used AI in order to improve language and readability of the text