Chemical composition of PM₁₀ and its effect on in vitro hemolysis of human red blood cells (RBCs): a comparison study during dust storm and inversion

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Abstract

Purpose This study aimed to investigate chemical composition of PM₁₀ (particulate matter with aerodynamic diameter $\leq 10 \mu\text{m}$) during dust storm and inversion in Tehran and hemolysis effects.

Methods PM₁₀ was sampled in Tehran, Iran, during dust storm and inversion conditions. Water soluble ions (F^- , Cl^- , NO_2^- , NO_3^- , SO_4^{2-} , Na^+ , K^+ , NH_4^+ , Ca^{+2} , Mg^{+2}) and elements (Al, Ba, Cd, Co, Cr, Cu, Fe, Li, Mn, Mo, Ni, Pb, Se, Sn, Sr, V, Zn, Pt, Rh, Pd, As and Si) were analyzed by ion chromatograph (IC) and inductively coupled plasma optical emission spectrometer (ICP-OES), respectively. Hemolysis was examined as in vitro at PM₁₀ concentrations of 50–300 $\mu\text{g}/\text{ml}$.

Results Daily average of PM₁₀ concentrations in dusty and inversion days were 348.40 and 220.54 $\mu\text{g}/\text{m}^3$, respectively. Most prevalence ionic components were NO_3^- , Cl^- , SO_4^{2-} and Ca^{+2} during dust storm and SO_4^{2-} , NO_3^- , Cl^- and NH_4^+ during inversion. Si, Fe and Al had the maximum values in both conditions. Particles associated with both conditions induced hemolytic responses. PM₁₀ from dusty day showed a higher hemolysis percent ($10.24 \pm 4.67\%$) than inversion ($9.08 \pm 5.47\%$), but this difference was not significant ($p = 0.32$). Hemolytic effects were significantly intensified by increased PM concentrations ($p < 0.001$) in a dose-response manner.

Conclusions As the results, chemical composition of sampled particles from inversion days and dust storm was different from each other. Hemolytic effects of particles during dust storm were more than inversion days. However, this difference was not statistically significant.

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Introduction

Ambient air pollution is a global public health concern, especially in the metropolitan areas, that associated with cardio-respiratory diseases, reduced lung function, asthma, chronic bronchitis and increased hospital admissions [1–4]. Unfortunately, the atmospheric pollution is increasing due to the growth of population, increasing vehicles and urban expansion [5, 6]. The World Health Organization (WHO) reported 3.7 million deaths annually, representing about 6.7% of all deaths worldwide due to the ambient air pollution [7].

Air pollution is a heterogeneous mixture of substances, commonly gases, volatile organic compounds (VOCs) and particulate matter (PM) [8]. PM can be released from three main sources: (1) anthropogenic sources such as cars, planes, industries and residential heating; (2) natural sources such as sea spray, soil erosion, forest fires and dust storms; (3) atmospheric transformation of gases and vapors into secondary aerosols [9]. Over the past few decades, dust storm has become a major concern in the Middle East, but its main characteristics (intensity, extent and frequency) are not well known or, at least, have not yet been analyzed in a scientific and systematic way [10]. Middle East is a part of the well-known “dust belt” and the second major source of global dust after the Sahara Desert [11].

Air pollutants may enter the human bloodstream through the nose, mouth, skin and the digestive tract [12]. Most air pollutants can quickly reach the blood without previous bio-transformation and produce adverse effects on the blood, bone marrow, spleen and lymph nodes. Blood cells are constantly suffering turnover, making the blood system highly sensitive to environmental pollutants [13]. Hemolysis is the premature destruction of red blood cells (RBCs) which can lead to the release of RBCs into the plasma [14].

Poursafa et al. found a significant negative relationship between concentration of the air pollutants, mainly PM₁₀ (PM with aerodynamic diameter $\leq 10 \mu\text{m}$) and hemoglobin and RBCs values [15]. In comparison between PM collected at an urban-emitting site and a suburban-receptor site by Quintana et al., the latter induced greater hemolysis [16]. Also, Nikolic et al. observed a significant difference in the RBCs count and average of hemoglobin levels in the children after exposure to air pollutants including black smoke, nitrogen dioxide, sulfur dioxide and lead. There was a significant difference in the prevalence of anemia in children exposed to the higher concentrations [13]. Bahrami et al. reported that physical exercise in the polluted air can affect hemolysis and bilirubin level [17]. Wang et al. investigated the associations between exposure levels to the airborne polycyclic aromatic

hydrocarbons (PAHs) and RBCs abnormality risk in the petrochemical workers. Results showed that RBCs abnormality risk would be elevated with the increased PAHs exposure level [18]. Kargarfard et al. also reported decreased RBCs count after aerobic exercises in the polluted air [19].

Occurrence of dust storm in the Middle East besides the high levels of anthropogenic pollutants released from fuel combustion offered a necessity to compare chemical compositions and biological effects related to PM₁₀ from the dust storm and inversion. This study aimed to investigate chemical compositions of PM₁₀ in two air pollution conditions, dust storm and inversion, and evaluate toxicological effects of PM₁₀ collected in these conditions on the hemolysis of human RBCs as in vitro. To the best of our knowledge, there are limited studies on the comparison between the effect of PM₁₀ from dust storm and inversion on the hemolysis.

Material and methods

PM₁₀ sampling

PM₁₀ sampling was described in detail in our previous work [20]. Sampling was done in Tehran, the capital of Iran. Sampling site located in a dense urban area that exposed to the dust storm events and man-made pollutants from vehicles (35°70'66.00 N, 51°39'38.55 E) (Fig. 1). PM₁₀ was sampled using a high-volume sampler (1.3–1.7 m³/min) (Grasebey, USA) and fiberglass filter (CAT No. 18209932, 20.3 × 25.4 cm, grade G 653 Whatman, USA). Since, dust storm and inversion occur mainly in Tehran in the spring and autumn, respectively, 24 h samples were collected over two periods, April 26–June 6 and September 24–November 15, 2016. Filters were first heated during 2 h at 180 °C. Then, they were stored in a dark and dry place and weighed with an analytical balance ($\pm 10 \text{ mg}$) before and after sampling to calculate the trapped PM mass. Sampler was installed according to the United States Environmental Protection Agency (USEPA) criteria at the height of 10 m above the ground level and away from any obstruction to minimize the potential effects of natural and anthropogenic features on the air flow as well as PM concentration [21].

Differentiation of dust storm and inversion condition

Dust storm and inversion conditions must be differentiated to classify sampled particles. Dust storm was defined based on the Hoffmann index regarded to the visibility, wind speed and hourly average concentration of PM₁₀ [22]. Hourly average

Fig. 1 Map of study area and PM₁₀ sampling site

PM₁₀ concentrations were received from the nearest air quality monitoring station belongs to Tehran Air Quality Control Company (AQCC). Inversion days in the report of AQCC were considered as the inversion condition. Also, local weather information was obtained from a local meteorological monitoring station (Mehrabad) during the sampling period.

Determination of dust source

Backward trajectory method in “Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT)” model was used to track the possible origin of dust storm in the candidate day. This model has been introduced by the National Oceanic and Atmospheric Administration (NOAA) as a unique tool to research on the transport, dispersion and transformation of

each dust storm event around the world [23]. Meteorological data from Global Data Assimilation System (GDAS) was applied for modeling with backward trajectory method in 72 h before each dust storm event in three levels including 100, 500 and 1000 m.

Analysis of chemical compositions

Chemical compositions included water-soluble ions (anions: F^- , Cl^- , NO_2^- , NO_3^- , SO_4^{2-} and cations: Na^+ , K^+ , NH_4^+ , Ca^{+2} , Mg^{+2}) and elements (Al, Ba, Cd, Co, Cr, Cu, Fe, Li, Mn, Mo, Ni, Pb, Se, Sn, Sr, V, Zn, Pt, Rh and Pd as metals and As and Si as metalloids) were analyzed by the ion chromatograph (IC) and inductively coupled plasma optical emission spectrometer (ICP-OES), respectively that described in detail in

our previous studies. Detailed descriptions of procedure were provided in other our study [24].

Enrichment factors (EF) were applied to identify the potential origin (soil or anthropogenic) of detected elements. EF was calculated using the Eq. 1 [25]:

$$EF = (C_x/C_{Ref})PM / (C_x/C_{Ref})_{crust} \quad (1)$$

where C_x is the concentration of element x , C_{Ref} is the concentration of reference element. Subscript of PM and crust state particulate matter and crust composition, respectively. Al was selected as the reference element [26]. Chemical composition of the earth's crust was obtained from Taylor and McLennan study [27]. EF results are interpreted as follow: <1: elements related to the local crust, >10: elements related to anthropogenic sources, 1–10: elements related to the mixed sources [25].

PM₁₀ extraction for hemolysis assay

Particle extraction for hemolysis assay was done as the dry extraction method. Firstly, filters related to dust storm and inversion days were selected among the collected samples according to the mentioned criteria. Then, they were cut into the small pieces and placed in 50 ml centrifuge tubes. Tubes were placed in an ultrasonic bath (Elma-ultrasonic, Germany) for 45 min followed by sweeping with a smooth brush. PM₁₀ was collected into the endotoxin-free vials, weighted and then stored at −18 °C until their use [28–30]. Morphological structure of the blank filter and extracted samples were investigated by using a scanning electron microscope (SEM) (HITACHI, SU3500, Japan) (Fig. S1). Fiberglass fibers in the blank filter (Fig. S1a) were not observed in the extracted particles (Fig. S1b). Therefore, it can be concluded that dry extraction method used in this study prevented contamination of the PM₁₀ samples with fiberglass fibers. These fibers can cause toxic effects in the biological assay due to the their inherent toxicity [31].

Hemolysis assay

The number of blood donors and used method to assay hemolysis test were based on the ASTM standard E2524–08 (Standard Test Method for Analysis of Hemolytic Properties of Nanoparticles) with some modifications in the concentration of analyzed particles [14, 32]. Current study was approved by the ethics committee of Tehran University of Medical Sciences. Written informed consent was obtained from volunteers and their parents before starting the study. Whole blood samples (1 ml) were collected from three healthy donors 16–18 years old into a syringe containing heparin as an anti-coagulant and immediately transferred to the laboratory. The inclusion criteria

for volunteers were: being healthy at the time of taking blood, nonsmoking (no smoking at least 6 months before the study), no taking regular medication or supplements, no experiencing any inflammation and allergy symptoms during blood sampling and one week ago, and no occupational exposure to environmental pollutants. Pooled blood was prepared by mixing equal proportions of blood from each donor and used to assay hemolysis test. The concentration of total hemoglobin was measured using the cyanmethemoglobin method based on the standard curve at an absorbance wavelength of 540 nm. Total blood hemoglobin (TBH) was prepared from pooled blood that diluted ten times with Ca^{+2} , Mg^{+2} -free PBS (Biosera, France). Extracted particles from filters related to two sources, dust storm and inversion, were separately suspended in PBS at the final mass concentrations of 50, 100, 150, 200, 250 and 300 µg/ml. Aliquots (100 µl) of PM₁₀ suspension were added to microcentrifuge tubes, followed by the addition of 700 µl of PBS and 100 µl of diluted blood. Triton X-100 (Sigma-Aldrich, St. Louis, MO, USA) and PBS were respectively applied as the positive and negative control. The tubes were incubated in a 37 °C water bath for 3 h with gentle inversion of the tubes every 30 min. After the incubation, the tubes were centrifuged at 800 g for 15 min at room temperature to remove particles and intact RBCs. Each sample was analyzed in triplicate to confirm repeatability. The supernatant of samples and controls were mixed in a 1:1 ratio with cyanmethemoglobin (CMH) reagent (Sigma-Aldrich, St. Louis, MO, USA) and analyzed at 540 nm. Hemoglobin concentration in each sample was determined from the curve of hemoglobin standards (StanBio Laboratory, Boerne, TX, USA). Dilution factor 18 was accounted for samples and controls and 251 for TBH. Finally, the hemolysis percent was calculated from Eq. 2 by dividing each sample's hemoglobin concentration by the TBH.

$$Hemolysis (\%) = \frac{Hemoglobine\ in\ test\ sample}{TBH} \times 100 \quad (2)$$

Particles that could not be removed after centrifugation may show false positive results. These false positive results were corrected by aliquots of PM₁₀ suspension in PBS without blood. False negative results due to interaction between the particles and released hemoglobin in the supernatant were corrected by spiking cell-free supernatant, from the positive control after centrifugation, to particles at corresponding concentrations [14, 32] those used in the assay (50–300 µg/ml).

Hemolysis percent in samples is interpreted as follow: <2%: non-hemolytic, 2–5%: slightly hemolytic and > 5% hemolytic samples [14].

Statistical analysis

We used PM₁₀ concentrations at six levels (50, 100, 150, 200, 250 and 300 µg/ml) and exposure in two levels (dust storm and inversion) as the factorial independent variables.

The effect of mentioned independent variables on the hemolysis percent as response variable was investigated with R software version 3.4.3 [33, 34]. Results were defined statistically significant if p value was lower than 0.05. Response variable was normally distributed according to the Shapiro–Wilk statistic normality test ($p = 0.62$). Homogeneity of independent variables (i.e., exposure and PM_{10} concentration) was confirmed based on the p -values of Bartlett test respectively equal to 0.14 and 0.26. Analysis of variance (ANOVA) test was applied to compare mean values of hemolysis. Tukey test was used to compare the hemolysis percent between different PM concentrations.

Results and discussion

PM_{10} concentration and dust sources

Based on Hoffmann index, dust storm event occurred on June 6, 2016 as the light dust storm. Also, four days consists of November 12–15, 2016 were considered as inversion days. Air sampling data (Table 1) show that daily average PM_{10} concentration was 7 times higher than the WHO guideline (i.e., $50 \mu\text{g}/\text{m}^3$) for dust storm day. In the inversion days, the average of PM_{10} concentrations was more than 4 times more than WHO recommended value. The world meteorological organization (WMO) classified dust events according to the visibility into the four categories: (1) dust-in-suspension: visibility usually not greater than 10 km; (2) blowing dust: visibility 1 to 10 km; (3) dust storm: visibility between 200 and 1000 m; and (4) severe dust storm: visibility less than 200 m [35]. Dust storm day with the visibility of 5.95 km (Table 1) can be classified in the category of dust-in-suspension and blowing dust.

Backward trajectories in June 6 (Fig. 2) offered that deserts in Iraq and Syria were the main sources of dust storm in studied area during the study period. In the study of Givvehchi et al., these deserts were also reported as the main sources of dust in Tehran that more than 90% of the PM_{10} concentration related to dust could be attributed to them [36].

Results of ionic analysis

Descriptive statistics for mass of ionic components in PM_{10} samples (mg/g) are indicated in Table 2. The mass of ionic components in inversion condition ($10.52 \pm 13.45 \text{ mg/g}$) was higher than dust storm ($7.69 \pm 7.52 \text{ mg/g}$). Percent contribution of individual ion to the total ions in PM_{10} samples is exhibited in Fig. S2. Order of ionic components in particles followed $\text{NO}_3^- > \text{Cl}^- > \text{SO}_4^{2-} > \text{Ca}^{+2} > \text{Na}^+ > \text{K}^+ > \text{Mg}^{+2} > \text{F}^- > \text{NH}_4^+ > \text{NO}_2^-$ during dust storm (Fig. S2a) and $\text{SO}_4^{2-} > \text{NO}_3^- > \text{NH}_4^+ > \text{Cl}^- > \text{Ca}^{+2} > \text{Na}^+ > \text{K}^+ > \text{F}^- > \text{NO}_2^- > \text{Mg}^{+2}$ during inversion (Fig. S2b). Therefore, most frequent ionic component of particles was found NO_3^- , Cl^- , SO_4^{2-} and Ca^{+2} during dust storm (72.18% of PM mass) and SO_4^{2-} , NO_3^- , NH_4^+ and Cl^- during inversion (87.78% of PM mass). NO_3^- , SO_4^{2-} and Cl^- were the dominant ionic components in both conditions. Particulate NO_3^- is mainly produced during the photo-oxidation of nitrogen dioxide that released from the combustion processes. The heterogeneous or homogeneous reactions of sulfur dioxide may be led to the release of SO_4^{2-} aerosols [37]. Cl^- is a sea-salt species. The long-range transport of particles and the passage from the different areas may affect the particle components [16]. It is noticeable that the presence of Cl^- in PM from inversion days can be assigned to the sources such as combustion and release of ammonium chloride [38]. High contributions of secondary inorganic aerosols consists of NO_3^- , SO_4^{2-} and NH_4^+ (almost 80% of PM mass) in the samples from inversion approved their anthropogenic sources [37]. Existence of a high contents of Ca^{+2} during dust storm is due to its presence in the earth's crust [39].

Mass ratio of the ionic compositions in dust storm to inversion (mg/g to mg/g, dimensionless) (Fig. S3) show that Ca^{+2} , Na^+ , K^+ and Mg^{+2} had ratios more than 1 (1.94–4.31), F^- and Cl^- had mass ratios close to 1 (1.1) and NH_4^+ , NO_2^- , SO_4^{2-} and NO_3^- had ratios lower than 1. It can be stated that the mass of Ca^{+2} , Na^+ , K^+ and Mg^{+2} in dust storm were higher than inversion because they exist in the earth's crust [39]. Ratios less than unit for NH_4^+ , NO_2^- , SO_4^{2-} and NO_3^- confirmed the existence of anthropogenic air pollution sources in the inversion condition.

Table 1 Air sampling data during dust storm and inversion conditions

Condition	Date	PM_{10} mass (g)	Air volume (m^3)	Daily average PM_{10} ($\mu\text{g}/\text{m}^3$)	Average temperature ($^{\circ}\text{C}$)	Average wind speed (m/s)	Average visibility (km)
Dust storm	June 6	0.57	1634.32	348.40	30	3	5.95
Inversion	November 12	0.48	2028.32	236.60	14	0.5	4.38
	November 13	0.41	2051.22	201.20	14	1.37	4.50
	November 14	0.43	2031.98	211.32	16	2.12	4.88
	November 15	0.43	1840.35	233.05	15	1.25	4.06

Fig. 2 72 h backward trajectories of occurred dust storms on June 6, 2016 using HYSPLIT model

Results of elemental analysis

Descriptive statistics for mass of elements in PM_{10} samples can be seen in Table 3. The mass of elemental components in dust storm condition (1972.64 ± 5230.91 mg/g) was more than inversion days (888.93 ± 1477.91 mg/g). Percent contribution of each element to the total elements in samples has

been represented in Fig. S4. Percent contribution of some elements was very low, so sum of the percent contribution of these elements is depicted as other in this figure. For both dust storm and inversion days, Si, Fe and Al were identified as the dominant elements, 96.62% of PM mass in dust storm condition and 59.16% in inversion. The mass ratio of elements ($\mu\text{g/g}$ to $\mu\text{g/g}$, dimensionless) in dust storm to inversion in Fig. S5

Table 2 Descriptive statistics for mass of ionic components in PM₁₀ samples (mg/g) during dust storm and inversion

Ions	Inversion (n = 4)				Dust storm
	Mean	Median	SD*	Min-Max	
F ⁻	1.49	1.43	0.32	1.20–1.90	1.71
Cl ⁻	9.23	9.41	1.36	7.58–10.53	10.24
NO ₂ ⁻	1.12	1.13	0.10	1.00–1.24	0.22
NO ₃ ⁻	31.57	34.68	19.31	5.53–51.38	25.57
SO ₄ ⁻²	37.66	38.99	6.53	29.36–43.32	9.96
Na ⁺	3.06	3.21	0.69	2.12–3.70	9.72
K ⁺	1.74	1.94	0.63	0.83–2.26	6.73
Ca ⁺²	5.03	4.82	1.65	3.33–7.16	9.76
Mg ⁺²	0.41	0.30	0.28	0.19–0.82	1.75
NH ₄ ⁺	13.84	13.93	1.66	11.71–15.78	1.27
Total					
Mean	10.52				7.69
SD*	13.45				7.52

* standard deviation

represented ratios higher than unit, 5, 4 and 2 respectively for Si, Fe and Al. Other researchers reported that Fe and Al could be released through industrial activities at the high concentrations [40, 41]. According to the mass ratios for the mentioned

Table 3 Descriptive statistics for mass of elements in PM₁₀ samples (μg/g) during dust storm and inversion

Elements	Inversion (n = 4)				Dust storm
	Mean	Median	SD*	Min-Max	
Al	4631.40	4367.56	2818.18	1997.11–7793.37	10,145.68
As	59.60	60.11	4.29	53.90–64.30	3.05
Ba	1828.55	1805.32	182.64	1668.91–2034.63	149.00
Cd	88.11	89.46	12.38	72.58–100.95	0.34
Co	29.40	25.66	9.32	23.04–43.24	14.77
Cr	259.80	279.49	61.67	174.47–305.77	18.80
Cu	1330.11	1279.85	166.29	1192.33–1568.42	164.45
Fe	3091.79	2946.31	756.64	2432.82–4041.71	12,162.60
Li	49.16	51.28	11.09	35.04–59.03	14.00
Mn	1026.18	1006.63	157.01	858.15–1233.31	35.25
Mo	99.82	106.72	19.84	71.28–114.57	9.45
Ni	111.14	101.52	36.36	78.44–163.09	2.85
Pb	1831.79	1696.82	448.98	1451.49–2482.03	26.95
Se	0.40	0.41	0.03	0.37–0.43	0.27
Sn	7.01	7.46	5.88	0.00–13.14	3.78
Sr	935.04	948.87	272.70	649.57–1192.86	52.50
V	60.56	59.61	11.13	48.99–74.04	3.40
Zn	80.94	77.93	7.45	75.98–91.91	22.85
Si	4029.10	4258.41	796.78	2935.03–4664.56	20,566.50
Pt	2.02	2.05	0.13	1.84–2.14	1.35
Rh	4.37	4.35	1.40	2.96–5.81	0.20
Pd	0.21	0.17	0.10	0.16–0.36	0.10
Total					
Mean	888.93				1972.64
SD*	1477.91				5230.91

* standard deviation

elements, it is confirmed that their mass in dust storm was more than inversion. These elements are mainly released from local and regional soil and resuspension of road dust [42, 43].

The EF results to apportion PM sources are illustrated in Fig. S6. Elements with EF values less than unit included Mn, Ni, Se, V and Si in dust storm and Se and Si in inversion condition were attributed to the local crust. Therefore, Se and Si were released from natural sources in both episodes. Versus, As, Cd, Cu, Li, Pb and Sn in dust storm condition and As, Ba, Cd, Co, Cr, Cu, Li, Mn, Ni, Pb, Sn, Sr, Zn in inversion days had EF > 10 and their sources can be assigned to anthropogenic sources. So, As, Cd, Cu, Li, Pb and Sn in both conditions were originated from the anthropogenic sources, but mass ratios of these elements in Fig. S5 demonstrated that they could be mainly associated to fuel combustion in the vehicles in Tehran. The sources of other elements may be mixed sources. EF values for elements with unknown concentrations in earth's crust dose not represented in Fig. S6.

Hemolysis results

Variability of mean values of the hemolysis percent at PM₁₀ concentrations between 50 and 300 μg/ml are depicted in Fig. 3. The hemolysis percent more than 5% in both conditions (Fig. 3) approved that PM₁₀ samples at studied concentrations induced hemolytic responses on the RBCs. The hemolysis percent during dust storm ($10.24 \pm 4.67\%$) was totally higher than inversion days ($9.08 \pm 5.47\%$), but this difference was not significant ($p = 0.32$) (Table 4). Our result was not consistent with other studies in Mexico city that induced hemolysis through semi-urban PM₁₀ was more than urban PM₁₀ with significant difference ($p < 0.05$) [16, 44]. Other studies in

Fig. 3 Variability of mean values of hemolysis percent in different PM₁₀ concentrations during dust storm and inversion

Table 4 Comparison of mean values of hemolysis percent between analyzed PM₁₀ concentrations (50–300 µg/ml) and different exposures (dust storm and inversion)

Response: Hemolysis percent	Df	Sum Sq	Mean Sq	F value	Pr(>F)
PM ₁₀ Concentration	5	539.96	107.99	5.45	< 0.001*
Exposure	1	20.16	20.16	1.02	0.32
Exposure: PM ₁₀ Concentration	5	8.56	1.71	0.09	0.99
Residuals	48	950.35	19.80		

* Significant at $p = 0.05$

the Middle East have suggested that particles from dust and diesel exhaust caused the hemolytic effects [45, 46]. In another study, PM from dust exhibited a strong hemolytic nature [46]. In similar researches, the percentage of hemolysis was obtained 40–100% for PM in dust and 0.7–35% in urban pollution conditions [16, 44–46]. These inconsistent results [16, 44–46] can be due to the different concentrations and sources, climate conditions (seasonality) and diverse components of PM [47]. PM components such as endotoxin, metals and soil components may probably contribute to the biological effects attributed to the airborne particles [16]. The several parameters such as particle size, surface charge and hydrophobicity or hydrophilicity can affect distribution and the fate of particles injected into the blood stream [48]. Based on a positive dose-response association that is shown in Fig. 3, it can be stated that RBCs exposed to PM₁₀ could generate responses which were directly proportional to PM concentration. This result was in accordance with the study in Mexico [44]. In other study in the Middle East, hemolysis percent raised with increased PM concentration from dust events [46]. Also, mean values of hemolysis percent at different concentrations of PM₁₀ samples (50–300 µg/ml) were significantly different from each other ($p < 0.001$) (Table 4). Consequently, hemolytic effects could be significantly intensified by increased PM concentrations. Results of the Tukey test between different concentrations of PM₁₀ (50–300 µg/ml) showed a significant difference in the hemolysis percent between concentrations 300 and 50 µg/ml, 300 and 100 µg/ml, and 250 and 50 µg/ml. Hemolysis could induce by the mineral components adsorbed on the particles [44]. Biological responses associated to the particles could attribute to the interaction between PM and cell membrane, effect on integrity and function of the membrane receptors and cytosolic enzymes [16].

Finally, our study verified that PM₁₀ from natural sources can induce a higher biological effect, but non-significant, on the RBCs compared to the anthropogenic PM₁₀. Efforts should be pointed to control natural sources of particles

and occurrence of dust storm through the international approaches. Management of local air quality is alone unable to reduce the level of air pollutants and health impacts related to them in an area. These results will help policy makers in strategy establishment and prioritizing resources to reduce airborne particles. Future studies are suggested on the components such as organic carbon, elemental carbon and organic constituents and hemolysis responses with more compressive data to approve these results.

Conclusions

According to the results of this study, it can be concluded that airborne particle from dust storm condition had a diverse chemical composition, included water soluble ions and elements, compared to that from inversion condition. Particles have been mainly released from natural sources of air pollution in the dust storm condition, whereas they may be originated from anthropogenic sources in the inversion days. So, differences in chemical composition could be associated to the different sources of particles. Particles from dust storm condition were shown more hemolytic effects than those from inversion, that this difference was not significant.

Finally, it is suggested that attempts are allocated to control particles from the dust storm events beside anthropogenic sources for abatement adverse effects from the air pollution.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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