Assessment of mineralogical and chemical properties of airborne dust in Iraq

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Abstract

The mineral composition and chemical and physical analysis of dust particles are essential to assess the potential impacts of dust on climate, environment, soil and health. The aims of this study are to give an overview of the mineralogical and chemical properties of dust storms over Iraq. Also, this study aims to identify potential sources of dust storms over Iraq. The results of particle size analysis showed that clay and silt particulates form an average of 86.9% of a dust storm, whereas sand particles represent an average of 13.2% of all dust samples. The physical analysis of dust samples revealed that low percentages of sand occur in the north region, but they are high in the western and central regions. The results of XRD analysis suggest that kaolinite, gypsum, albite, quartz and calcite were the major mineral dust components. However, lower amounts of palygorskite, microcline, dolomite, illite, chlorite and halite were detected in some station samples. The XRF analysis suggested that Ba, Sr and Cl were the main trace element components in the airborne dust samples. In addition, the chemical analysis of dust samples revealed that high percentages of Zn and Pb occur in the eastern and central regions. The results of HYSPLIT backward trajectories analysis of air parcels revealed that the potential sources of dust storms were the Syrian Desert, North Africa Desert, An-Nafud Desert in Saudi Arabia, the dry lands in south-western Turkey and southwest Iran, and the alluvial plain, Al Jazeera and Western Deserts in Iraq.

Keywords Dust storms · Particle size · XRD · XRF · HYSPLIT · Iraq

1 Introduction

Dust events are considered to be an important issue and a major problem occurring annually in the Middle East region, including Iraq. Mineral dust has an important influence on the chemical and physical composition of the atmosphere, whereas dust sedimentation provides external organic and mineral matter to the ground surface and has an important influence on the biological, geological and chemical processes and environments on earth [1, 2]. Mineral dust emissions into the atmosphere are estimated to be between 1000 and 3000 Tg annually around the world, and this dust can be transferred into remote areas [3, 4]. For example, Muhs et al. [5] showed through geochemical evidence that African dust additions are significant for soil formation on islands around the Bahamas, Barbados and Florida in the western Atlantic Ocean. In addition, Muhs et al. [6] and Alastuey et al. [7] indicated through geochemical and clay mineralogical evidence (kaolinite, illite and palygorskite) that soils in the eastern Canary Islands are derived from local basalt together with different percentages of African dust from the Sahara and Sahel areas.

Dust activity has become a major environmental concern in the few last years in Iraq [8]. Frequent dust events occur in Iraq, mainly in summer, and severe dust storms are particularly related to north-westerly blowing winds (Shamal winds). Between 1980 and 2015, the highest dust

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frequency occurred in the south and central regions of Iraq [9, 10]. Dust events in Iraq possibly emerge from dried lakebeds, deserts and semi-desert areas in Iraq and adjacent countries are borne upwards and carried by wind [9]. Iraq contains wide regions of sandy desert (approximately 40% of the total area of Iraq) and represents a considerable source of airborne dust in the Middle East [11]. Desertification has increased in Iraq due to the intense drought since 1990, dam building in adjoining countries, the instability of the political process leading to military operations and war influences, improper territory uses and processes of deforestation [9, 12, 13]. Dust storm particles can affect farms and agricultural areas leading to negative impacts on agricultural production. Dust deposition may cause direct and indirect adverse effects on flora, fauna and human health on a regional scale [14]. Due to the intense drought during the last decade, dust events above Iraq have increased [9, 15]. Syrian, Jordan, Arabian and North African (Sahara) deserts are other major sources of dust storms that impact various regions of Iraq [16]. The long periods of droughts, scarcity of water and the huge variation in precipitation records were recorded on a regional scale in Iran [17], Kuwait [18–20] and Iraq [21].

Airborne dust consists of very small particles from soils and/or rocks lifted from the surface of the Earth due to wind abrasion and turbulence under specific weather and soils situations. Therefore, the chemical composition and physical characteristics of dust are considered to be a significant factor for identifying dust origin areas [22, 23]. In some cases, the provenance of dust storms can be tracked by examining the clay mineral content of dust particles [24]. For example, clay mineralogy and Pb and Nd isotopes were used to define sources areas for dust deposited in the polar Greenland ice sheet [1, 25].

Mineralogy of dust depends on the soil type in the provenance region and its weathering patterns. A mineralogical study of dust samples may help to reveal the major dust sources in the arid areas and sedimentary plains of Iraq and the Middle East region. Dust source can be determined by identifying the mineralogical content of dust and the air mass pathways [26]. Physical and optical dust characteristics are well identified in the northern hemisphere, while some research has also been carried out in the southern hemisphere [27]. Only a few studies [28, 29] offer a knowledge and understanding of the temporal–spatial variation in the mineral and chemical dust compositions. The variations in the dust physical and chemical properties were mentioned by a few researchers on the region scale in Iraq [16], Kuwait [18, 30–32], Saudi Arabia [33] and Australia [34].

The mineral composition of dust differs from one area to another area, depending on the distance from the source region and the chemical interactions that occur in the atmosphere [35, 36]. Quartz and silicate minerals constitute most of the mineral dust, with silica forming about 59% at a global scale [37]. In addition, the other main components include organic matter, Fe_2O_3, Al_2O_3 and $CaCO_3$ [37]. In the Middle East region, calcite and quartz represent major minerals in dusts, with smaller quantities of kaolinite, feldspar and dolomite [38]. While the geochemical and geological properties of mineral dust in different regions in the world have been examined [39–43], there are very few published studies about the mineralogical and chemical properties of dust storms in Iraq.

Mineral dust represents a key factor in cloud formation and the radiative balance of earth [44]. Its role depends on mixing operations within the atmosphere, its airborne duration, the source areas of dust, its particle size distribution and different chemical and physical conditions in the air [44]. Several atmospheric dust pollutants (insecticides) influence public health if these pollutants are transported above crowded population regions [45]. The chemical and physical analysis of dust is essential to acknowledge the potential impacts of dust on environment, soil, and health [37, 46, 47]. A huge dust storm in Baghdad on 9/08/2005 caused one person to die and led to about 1000 suffocation cases being reported to the Al-Yarmuk Hospital [37]. Chemical analysis of dust supplies useful details about the likely health risk from trace elements, such as lead (Pb), nickel (Ni), copper (Cu), cobalt (Co) and arsenic (As) [37, 48]. Dust aerosol particles can also cause an increase in breathing problems and lung injuries, because these particles include sulphur compounds and siliceous minerals [49]. Dust particles with diameters less than 10 μm (= PM10) have been related to chronic obstructive pulmonary diseases and asthma [50]. Particles less than 2.5 μm (= PM2.5) can cause problems like cardiac and respiratory disease in adults and children, if they are exposed to > 5 μg/m^3 for long periods [51]. Many studies have found that PM10 and PM2.5 concentrations could lead to premature death and breathing problems [52–54].

Moreover, the movement and backward trajectories of air masses can be tracked over a given time using the HYSPLIT (Hybrid-Single-Particle-Lagrangian-Integrated-Trajectory) model [55]. The vertical air motion, wind speed and direction were used in this model to compute the backward trajectories and track air masses [56]. Several researchers have effectively utilized the HYSPLIT model approach to determine dust sources by simulating and tracing the trajectories of dust particles [57–60]. The transport and dispersion of dust events worldwide can be determined by using the HYSPLIT model. For example, the HYSPLIT model was used for dust storm forecasting between 22 and 24/10/2002 in Australia [61], dust activity travelling to Antarctica from Argentina [62], and spatiotemporal assessment was used to forecast dust events

during 2008 and 2009 generated from northern Africa [63]. Considering the health risks posed by dust, the aim of this study is to provide examples of the mineralogical and chemical properties of dust storms in the major centres in Iraq and to identify potential sources of these dust storms.

2 Sample collection and methods

Ten samples of atmospheric dust storm deposits were collected during spring dust storms in 2017 from nine meteorological networks in different areas of Iraq, because spring is one of the main dust seasons in Iraq [11, 64, 65]. The dust samples were gathered from Hit and Ramadi cities near and to the west of the Euphrates River, Duhok, Machomre, Baiji, Tikrit, Khanaqin and Baghdad along the Tigris River basin, and Basra at confluence of the Tigris and Euphrates Rivers (Fig. 1, Table 1). Dust samples were collected by the Iraqi Meteorological Organization by using traps which were set up on the tops of buildings. Each sample was analysed separately. Dust storms have different physical and chemical properties depending on the source area temporarily and spatially. Although aerosol components are normally estimated on a volumetric basis in an air sampler, especially for PM2.5 and PM10 concentrations, such equipment was not available at the weather stations. Hence, because of time and resource limitations, the Iraqi Meteorological Organization used a simple method to collect dust samples. They placed an open-topped container [66] for two to three days during a dust storm on the roof of an elevated building at each meteorological station, where altitudes above sea level range from 4 m in Basra to 536 m in Duhok, as shown in Table 1. It is recognized that such samples will probably underestimate the finer fractions that have a lower settling velocity and could also be entrained by eddies within the sample container as the wind blew across it. Soil sampling in Iraq and adjacent potential source areas was severely restricted by the armed conflicts in these regions. Thus, soil sampling was limited to a few relatively safe areas to get a general idea of the soil composition in Iraq. Surface soil samples from 0 to 10 cm depth were collected using a plastic shovel from Erbil and Kirkuk in northern Iraq, Khanaqin

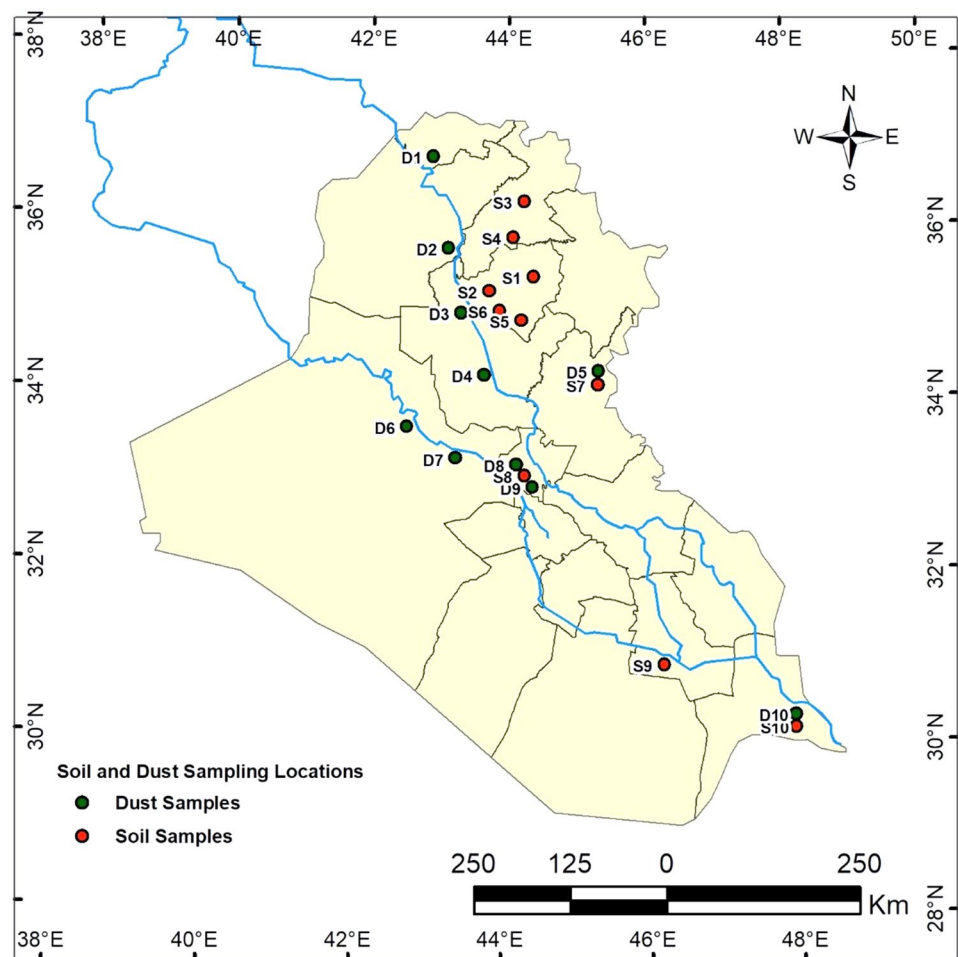**Fig. 1** Map of Iraq showed dust and soil sampling location

Table 1 Location of dust samples from Iraqi Meteorological Stations

Date	Site	Meteorological station	Latitude (°N)	Longitude (°E)	Elevation (m)
16/3/2017	D10	Basra	30 31 32	47 46 25	4
13/4/2017	D8	Baghdad1	33 18 54	44 21 57	29
20/4/2017	D9	Baghdad2	33 12 31	44 14 35	29
19/5/2017	D3	Baiji	35 01 04	43 26 42	143
19/5/2017	D7	Ramadi	33 26 11	43 16 05	49
19/5/2017	D5	Khanaqin	34 21 15	45 23 02	182
20/5/2017	D1	Duhok	36 52 47	42 56 18	536
20/5/2017	D2	Makhmur	35 45 29	43 35 51	270
20/5/2017	D4	Tikrit	34 37 56	43 39 30	116
24/5/2017	D6	Hit	33 38 36	42 49 31	70

Table 2 Location of soil samples from different parts of Iraq

Site	Region	Latitude (°N)	Longitude (°E)	Elevation (m)
S1	Erbil1	35 46 48	44 06 54	26
S2	Erbil2	36 24 13	44 15 13	841
S3	Kirkuk1	35 28 52	44 27 53	525
S4	Kirkuk2	35 27 51	44 35 06	522
S5	Kirkuk3	35.2851	44 31 55	526
S6	Kirkuk4	25 28 50	44 31 54	526
S7	Khanaqin	34 21 15	45 23 02	182
S8	Baghdad	33 18 34	44 21 54	29
S9	Nasiriya	31 02 23	46.2346	5
S10	Basra	30 33 27	47 47 25	3

in eastern Iraq, Baghdad in central Iraq and Nasiriya and Basra in southern Iraq (Fig. 1, Table 2).

The dust and soil samples were examined and analysed in the School of Earth, Atmospheric and Life Sciences at the University of Wollongong. The particle size distribution of each sample was determined by using a Malvern Mastersizer 2000 (Malvern laser particle size analyser) with the average from three analyses each measuring 10,000 points. Before chemical analysis, each sample was passed through a 2-mm sieve to remove any larger rock fragments and plant material. The samples were then dried at 60 °C before being crushed in a Tema chrome steel ring-mill. About 5 g of the resultant powder was mixed with polyvinyl alcohol and pressed into an aluminium cup at 2000 psi before being dried at 60 °C. The compacted pellets were then analysed for trace elements using energy-dispersive X-ray fluorescence spectrometry (XRF) on a Spectro Xepos XRF instrument. For mineralogical analysis, the powdered samples were analysed by X-ray diffraction spectrometry (XRD) using a Spellman generator running at 1 kW with Philips goniometer and Philips Cu tube. The samples were run from 2 to 60° 2θ at 1°/min, and the resultant traces were analysed using Traces and Siroquant software.

Draxler developed the HYSPLIT (Hybrid-Single-Particle-Lagrangian-Integrated-Trajectory) model at the Air Resources Laboratory, which is part of the National Oceanic and Atmospheric Administration (NOAA) agency in the USA, and Bureau of Meteorology in Australia [67–69]. HYSPLIT uses a computational approach of a hybrid that characterizes both Eulerian and Lagrangian methods. This model computes the horizontal movement of the air and its spreading in Lagrangian scope, whereas measurements were computed on a constant network [68]. The HYSPLIT model utilizes the dispersion of a particulate in both vertical and horizontal directions [69]. For the purpose of evaluating the dispersion process of the emitted small air parcel from a specific site, meteorological information is utilized as inputs; this information has been taken from NCEP (National Centre for Environmental Prediction) datasets, which contain reanalysis data, and the Global Dataset Assimilation System (GDAS) data. These NCEP datasets include basic parameters (e.g. u and v wind, humidity and temperature). The accuracy and precision of the backward trajectory analysis of the HYSPLIT model relies on the meteorological data resolution [70, 71]. The GDAS data have the best resolution (1° × 1°), and many studies have used the GDAS data in the HYSPLIT model to create backward trajectories [72–77]. Potential dust source regions and trajectories were done by backward trajectories analysis using the HYSPLIT model with GDAS data accuracy 1° × 1° (https://ready.arl.noaa.gov/HYSPLIT.php [67]).

The HYSPLIT model was employed to identify the potential sources and transfer trajectories of the individual sampled dust storms. The backward trajectory analyses were determined for computed air masses over a duration of 48 h at three elevations (100 m, 500 m and 1000 m).

3 Results

3.1 Identification of possible dust sources

To determine the source areas of individual dust storms for which dust samples were collected in spring 2017 in different parts of Iraq, remote sensing, in conjunction with the HYSPLIT (Hybrid-Single-Particle-Lagrangian-Integrated-Trajectory) model, was used to determine the potential sources and the dust storm pathways through the 48 h before their arrival in the study regions in Iraq.

The track of the dust storm on the 16 March 2017 in Basra (Fig. 2a) displayed that the potential source areas of airborne dust activity were the dry lands along the Iraqi–Iran border, the An-Nafud Desert, Western Desert and alluvial plain area. The HYSPLIT backward trajectory for the Baghdad dust storm on 13 April 2017 displayed possible dust source areas situated to the east on the border of Iraq and south-western Iran (Khuzestan province) and the alluvial plain in Iraq (Fig. 2b). In contrast, the Baghdad dust storm on 20 April 2017 came from the Syrian, Al Jazeera and Western Deserts (Fig. 2c).

One dust storm that reached Iraq on 19 May 2017 affected three cities (Baiji, Ramadi and Khanaqin). Separate HYSPLIT backward trajectory analysis from each city showed that the likely source areas of the dust storm were the Syrian Desert and the Al Jazeera and Western Deserts in Iraq (Fig. 2d–f). The An-Nafud Desert in Saudi Arabia was an additional source for Khanaqin (Fig. 2e), and some high-level dust possibly from this source reached Baiji (Fig. 2d). The analysis for Ramadi city also included the alluvial plain area in Iraq (Fig. 2f).

On the next day (20 May 2017), another dust storm reached Iraq and affected three cities (Duhok, Makhmur and Tikrit). The HYSPLIT backward pathway for 48 h before the dust storm reached both Duhok and Makhmur reveals that the likely dust source areas were the Al Jazeera and Western Deserts and the alluvial plain area between the Euphrates and the Tigris Rivers in Iraq (Fig. 2g–h). Some dust at Makhmur may have also come from desert areas in Syria, the An-Nafud Desert and arid lands in eastern Jordan (Fig. 2h). The path of the dust storm on 20 May 2017 in Tikrit city (Fig. 2i) was similar to the two previous cities with the main potential sources of the dust being the An-Nafud Desert in northern Saudi Arabia and the Southern Desert in Iraq.

According to HYSPLIT backward pathways during 48 h before a dust storm reached Hit city on 24 May 2017, the possible dust source areas were the Syrian and North African deserts and the Al Jazeera and Western Deserts in Iraq (Fig. 2j).

The findings of the current research reveal that the potential dust storm sources during spring include the An-Nafud Desert in Saudi Arabia, the Syrian Desert, south-western Iran, the Tigris-Euphrates alluvial plain and Al Jazeera and Western Deserts in Iraq.

3.2 Particle size analysis of airborne dust and soil samples

Particle sizes were measured and classified as sand for particle larger than 62.5 and less than 2000 microns, silt for particles between 4 and 62.5 microns and clay for particle less than 4 microns [78]. The findings of the particle size analysis suggest that all airborne dust samples consisted predominantly of silt (average = 67.1%, maximum = 77.9% and minimum = 54.9%), with moderate amounts of sand (average = 13.2%, maximum = 32.4% and minimum = 1.0%) and clay (average = 19.8%, maximum = 31.8% and minimum = 12.0%). The relatively low proportions of clay-sized material may be partly related to the sampling method, whereby turbulence during the dust storm may have prevented some of the clay from settling. The dust sample classification showed a large proportion (86.9%) of clayey silt compared with a lower proportion (80.3%) of sandy silt. Thus, most dust compositions were characterized by high silt and clay percentages with lower sand ratios. The modal size of the silt ranges from 10.4 to 63 μm with most of the samples consisting of fine to medium silt size. The modal sand size ranges from 222.5 to 413.8 μm, i.e. fine to medium-grained, and this large model size may be related to various grains bouncing around the building roofs. Three samples have no sand size mode, while the sample from Machomre has the coarsest sand size mode. The northern dust samples are unimodal that is a single source, while the mid and southern sectors of Iraq are bimodal (multiple sources).

The mean particle sizes of all the analysed dust sample particles range between 15.4 and 91.2 μm with an average of 41 μm. The particle sizes statistics for the collected dust samples are displayed in Fig. 3 and Table 3. The particle sizes of dust for Baghdad 1 and 2 consist of high proportions of silt and sand with a smaller percentage of clay, while the particle size of dust for Dhock, Machmore, Baiji and Basra consist of high proportions of silt and clay with small percentages of sand. The amount of PM10 was maximum in Baiji, Basra and Dhock cities (60.8%, 52.8% and 51.7%, respectively), while the amount of PM2.5 was highest in Baiji, Dhock and Basra cities (19.3, 17.9 and 15.2%, respectively). The percentages of sand in the dust samples were low in the northern region and high in the western and central regions. The particle size of dust plays is an important source consideration since dust from the alluvial plain is finer than dust from western Iraq.
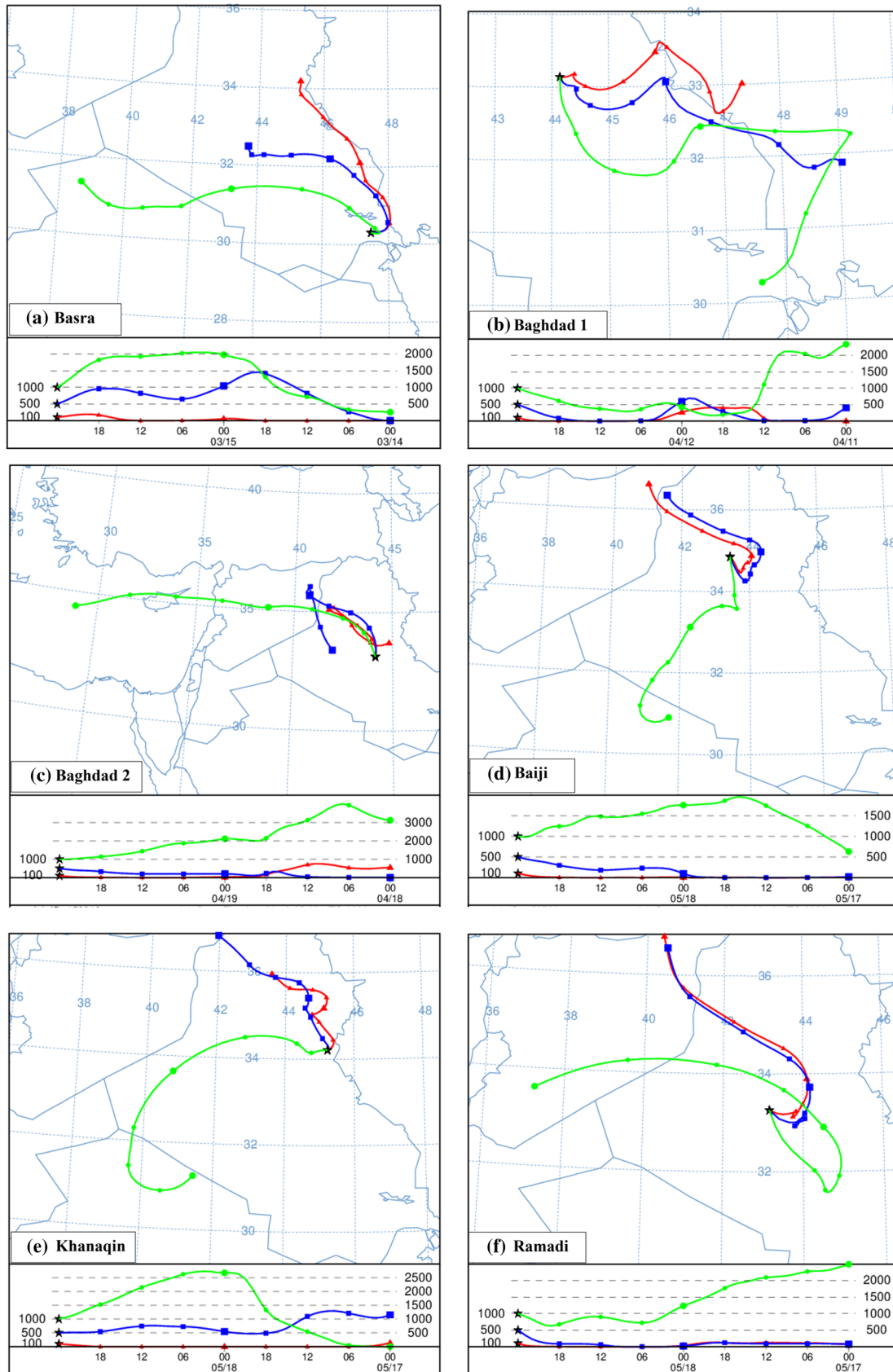
Fig. 2 Analysis of HYSPLIT backward trajectories of individual dust storms in Iraq
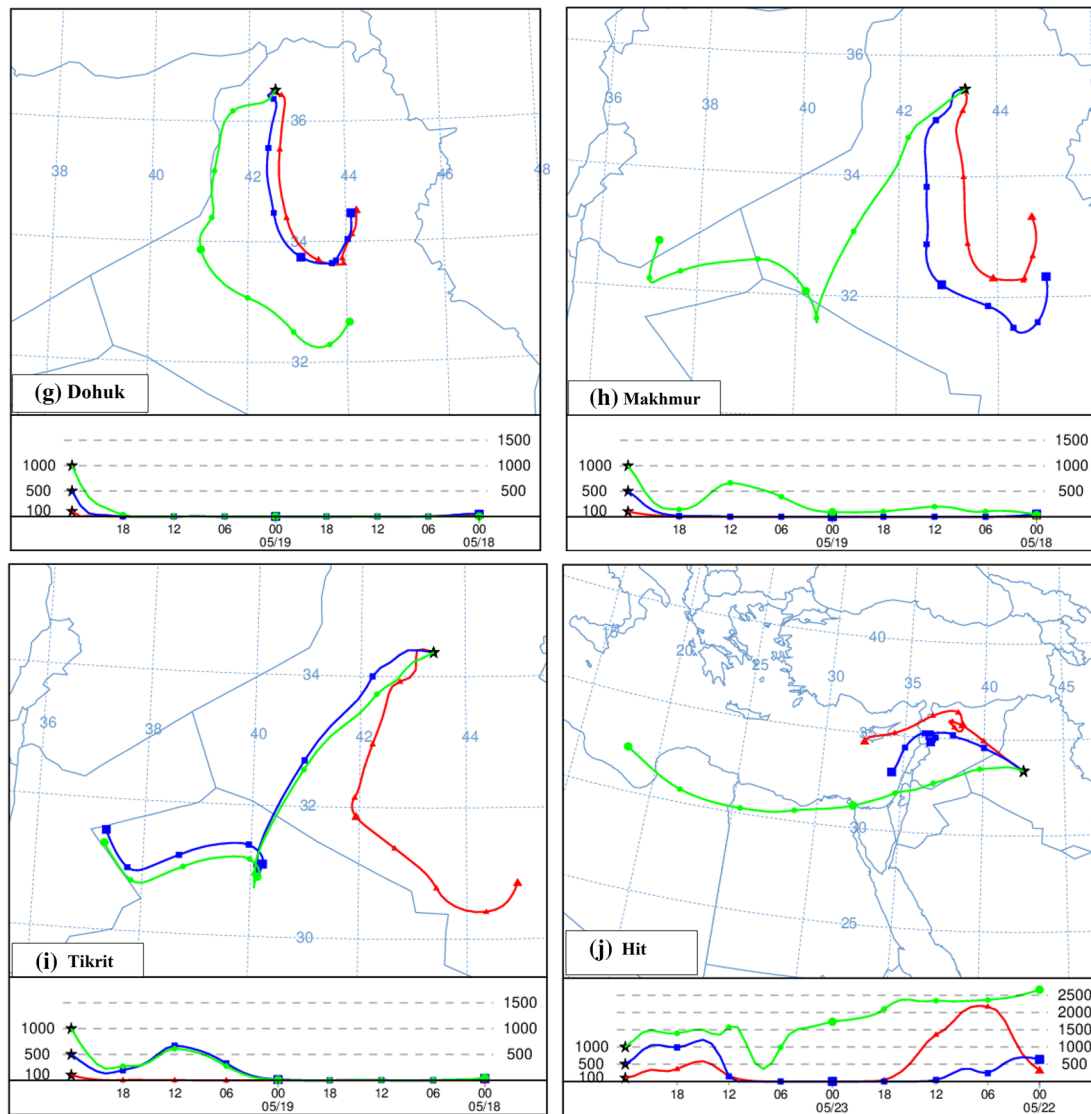
Fig. 2 (continued)

The ten soil samples have a mean percentage of 61% silt, 16% sand and 22.9% clay. The soil sample particle sizes are presented in Table 4 and are displayed in Fig. 4. Using the soil texture triangle of the United States Department of Agriculture (USDA) for the ten collected soil samples showed that most of the soil textures are silt loam (Fig. 5). The results of the particle size distribution (Table 4) displayed that the particles < 10 μm were at a maximum in the Basra, Kirkuk4 and Erbile1 sites (59, 54 and 48%, respectively), while the amounts of PM2.5 were higher in the Basra, Kirkuk4 and Nasiriya sites (20, 19 and 16%, respectively).

3.3 Mineralogical characteristics of dust aerosols and soil samples

Mineral compositions of dust from different regions in Iraq were acquired using the XRD technique. Figures 6 and 7 and Tables 5 and 6 show the average mineralogical composition of the dust and soil samples.

The mineralogy of airborne dust collected during dust storms in different areas of Iraq is shown in Fig. 6 and Table 5. The main mineral components of dust samples are silicates and carbonates (quartz and calcite). Calcite is the dominant mineral (17.2 to 57%) in all the Iraqi study
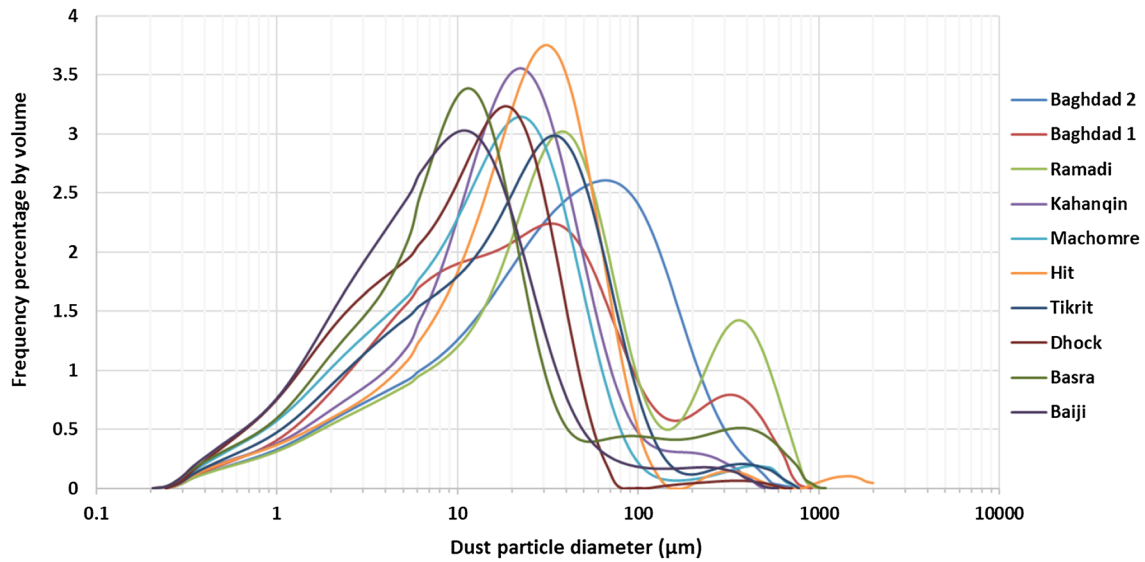
Fig. 3 Particle size distributions for the ten airborne dust samples at different sites in Iraq

Table 3 Particle size analysis of all dust samples from various Iraqi areas

Dust samples	Sand %	Silt %	Clay %	Mean grain size (microns)	Mode 1 (microns)	Mode 2 (microns)	PM2.5% by mass	PM10% by mass
Dhock	1.0	70.6	28.4	15.4	17.7	0.0	17.9	51.7
Machomre	5.1	72.7	22.2	25.7	21.5	413.8	13.9	42.2
Baiji	3.8	64.5	31.8	16.4	10.4	222.5	19.3	60.8
Tikrit	11.2	69.7	19.1	33.5	32.8	360.6	11.7	36.1
Kahanqin	8.3	76.6	15.1	28.7	21.3	0.0	9.5	32.2
Baghdad 1	20.4	61.7	17.9	58.0	31.8	311.2	10.5	36.3
Baghdad 2	32.4	54.9	12.7	59.1	63.0	0.0	8.0	23.9
Hit	8.3	77.9	13.8	38.9	29.8	306.8	8.8	28.3
Ramadi	28.6	59.4	12.0	91.2	36.5	346.6	7.6	22.6
Basra	12.4	62.9	24.8	42.6	11.0	352.3	15.2	52.8
Average	13.2	67.1	19.8	41.0	27.6	231.4	12.2	38.7

Table 4 Particle size analysis of the soil samples from various Iraqi regions

| Soil sample	Sand %	Silt %	Clay %	Mean grain size	Mode 1 (microns)	Mode 2 (microns)	< 2.5 µm	< 10 µm
Erbile 1	9.6	66.4	24.0	31.1	12.7	321.8	14.0	48.1
Erbile 2	8.5	67.2	24.3	26.8	18.5	0.0	14.6	46.3
Kirkuk 1	10.7	71.9	17.4	50.8	28.4	270.0	10.2	35.3
Kirkuk 2	11.4	68.4	20.2	42.9	19.0	338.6	11.6	41.0
Kirkuk 3	21.3	65.3	13.4	41.4	48.3	0.0	8.3	26.2
Kirkuk 4	4.0	66.5	29.5	21.1	13.2	454.0	19.0	54.3
Khanaqin	38.9	44.0	17.1	122.4	90.5	12.1	10.6	31.5
Baghdad	13.4	64.1	22.5	65.4	24.9	1008.5	13.6	41.4
Nasiriya	24.9	48.4	26.8	75.2	8.5	339.0	16.5	46.4
Basra	17.2	49.1	33.7	114.2	5.8	632.9	20.2	59.1
Average	16.0	61.1	22.9	59.1	27.0	337.7	13.9	43.0
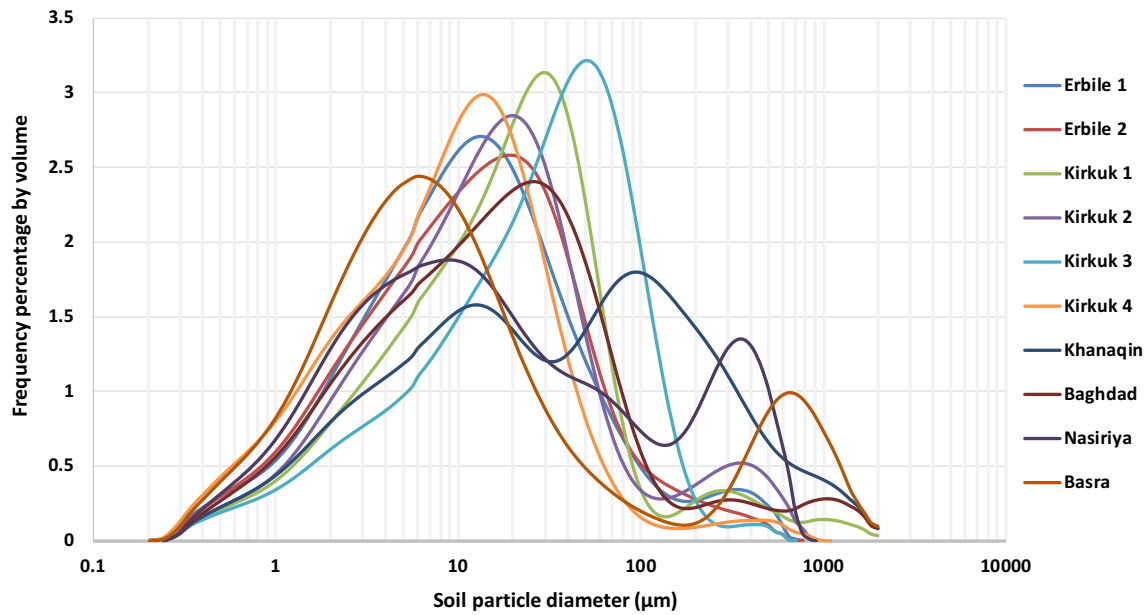
Fig. 4 Particle size analysis of the ten soil samples from the different sites in Iraq

Fig. 5 Soil texture triangle of the ten samples displays the particle size plot by USDA
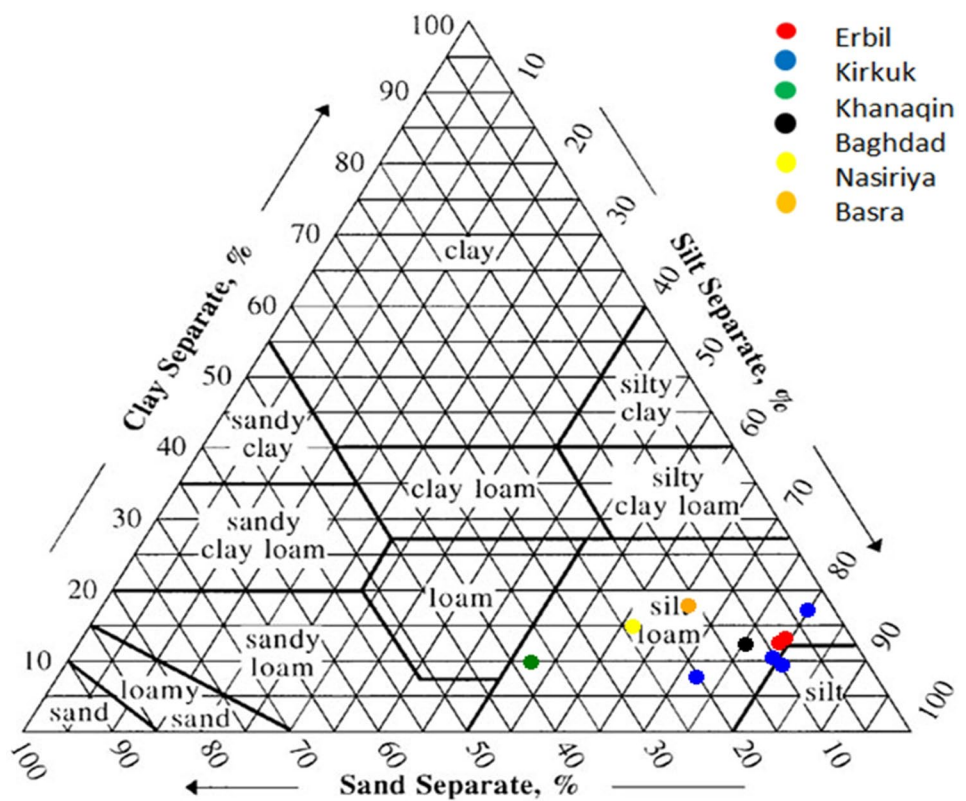
regions. Quartz is the second most common mineral in the Iraqi samples with a mean percentage of 18.3%, whereas albite forms about 6.7% and gypsum around 6.2%. The total feldspar content in each sample, except Basra, is less than the quartz percentage. The remaining minerals

occur in much lower amounts in the dust samples, but kaolinite (mean 4%) is obvious in each dust sample in all areas. Other minerals, such as palygorskite, dolomite, illite, chlorite and halite, are only present in a few samples with different proportions. There is a high percentage of
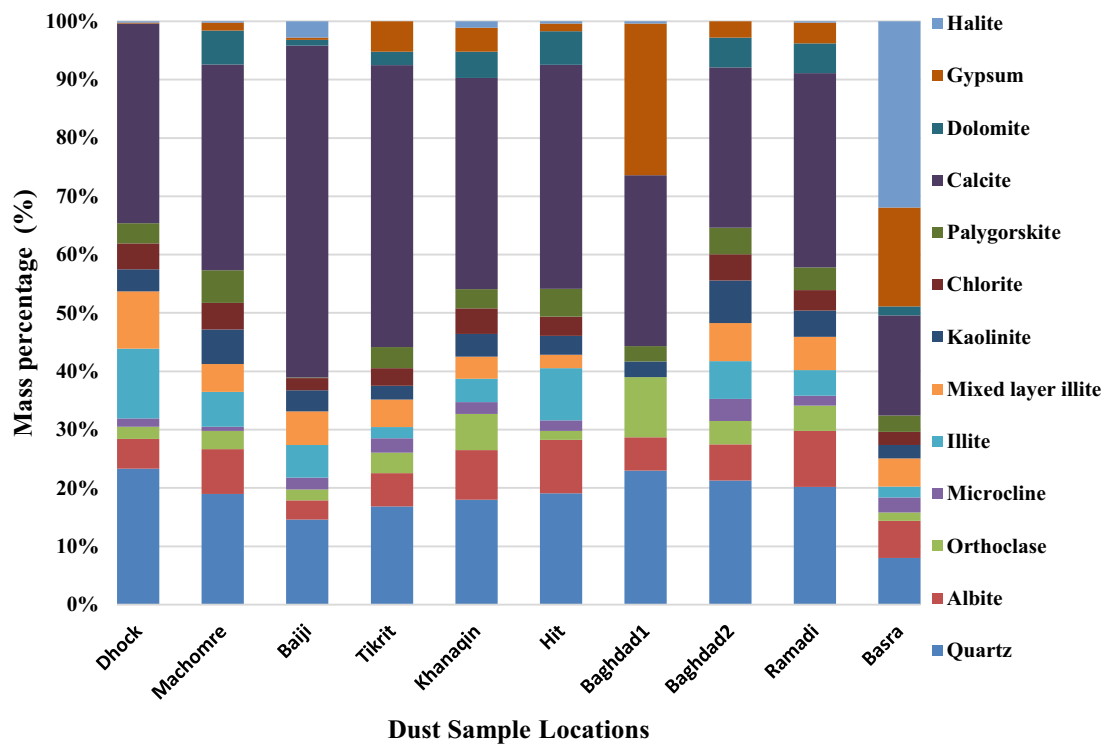
Fig. 6 Mineralogical compositions from XRD in dust aerosol samples obtained from various regions
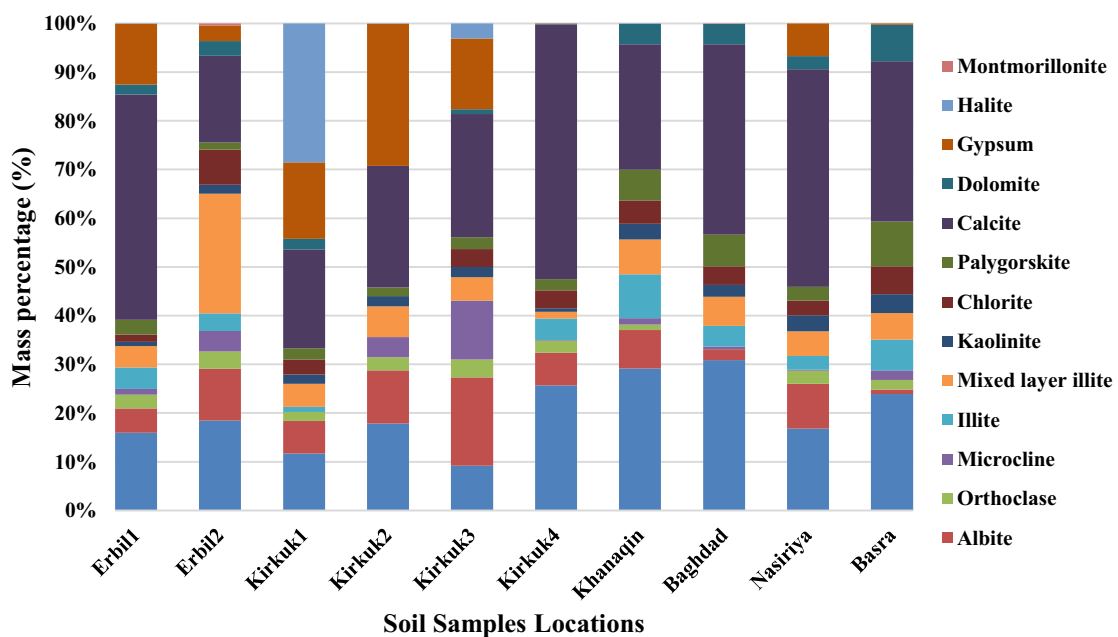
Fig. 7 Mineralogical compositions from XRD of soil samples from different sites in Iraq

halite in dust from Basra. Gypsum is found in most samples and reflects the arid source areas contributing to the occurrence of airborne dust activity in southwest Asia. Baghdad2 and Basra samples have the highest gypsum

percentages. HYSPLIT backward trajectories display that air flows reaching these two cities in Iraq (Fig. 2c and a) came from the An-Nafud Desert, Syrian Desert, Al Jazeera Desert and arid areas in southern Iraq. This result indicates

Table 5 Mineralogical compositions of dust aerosol samples from the study region by XRD technique

	Dhock	Machomre	Baiji	Tikrit	Khanaqin	Hit	Baghdad1	Baghdad2	Ramadi	Basra
Quartz	23.3	19.0	14.6	16.8	18.0	19.1	23.0	21.3	20.2	8.0
Albite	5.1	7.7	3.3	5.7	8.5	9.2	5.7	6.2	9.6	6.4
Orthoclase	2.1	3.1	1.9	3.5	6.2	1.5	10.3	4.0	4.3	1.4
Microcline	1.4	0.7	2.0	2.5	2.0	1.8	–	3.8	1.7	2.6
Illite	12.0	6.0	5.6	1.9	4.0	9.0	–	6.5	4.4	1.9
Mixed layer illite/smectite	9.8	4.8	5.8	4.7	3.8	2.3	–	6.5	5.7	4.8
Kaolinite	3.8	5.9	3.6	2.4	3.9	3.2	2.7	7.3	4.5	2.3
Chlorite	4.4	4.6	2.1	3.0	4.4	3.3	–	4.5	3.5	2.3
Palygorskite	3.5	5.6	0.1	3.6	3.3	4.8	2.6	4.6	3.9	2.8
Calcite	34.2	35.3	57.0	48.3	36.2	38.4	29.3	27.5	33.3	17.2
Dolomite	–	5.8	1.0	2.3	4.5	5.8	–	5.1	5.1	1.5
Gypsum	0.2	1.4	0.4	5.2	4.1	1.3	26.0	2.8	3.6	17.0
Halite	0.2	0.2	2.8	–	1.1	0.4	0.4	–	0.2	32.0

Table 6 Mineralogical compositions of soil samples from the study region by XRD technique

	Erbil1	Erbil2	Kirkuk1	Kirkuk2	Kirkuk3	Kirkuk4	Khanaqin	Baghdad	Nasiriya	Basra
Quartz	16.0	18.3	11.7	17.9	9.2	25.7	29.2	30.9	16.8	23.9
Albite	5.0	10.6	6.7	10.9	18.1	6.7	7.9	2.2	9.2	0.9
Orthoclase	2.8	3.5	1.8	2.7	3.7	2.5	1.1	–	2.7	2.0
Microcline	1.2	4.2	–	4.2	12.1	0.1	1.3	0.5	0.2	2.0
Illite	4.4	3.6	1.1	–	–	4.4	9.0	4.3	2.8	6.3
Mixed layer illite/smectite	4.4	24.4	4.7	6.3	4.8	1.4	7.2	6.0	5.1	5.4
Kaolinite	0.9	1.8	1.9	2.1	2.1	0.7	3.2	2.4	3.3	3.9
Chlorite	1.5	7.2	3.1	–	3.7	3.7	4.8	3.8	3.0	5.7
Palygorskite	3.0	1.4	2.3	1.8	2.4	2.3	6.3	6.5	2.8	9.2
Calcite	46.4	17.7	20.3	25.0	25.3	52.3	25.8	39.1	44.7	32.9
Dolomite	2.0	3.0	2.2	–	1.0	0.1	4.2	4.2	2.7	7.5
Gypsum	12.5	3.1	15.7	29.2	14.5	0.1	–	–	6.7	0.3
Halite	0.1	–	28.5	0.1	3.1	–	0.1	–	–	–

that dust coming from these sources is loaded with gypsum, possibly because of the presence of dry Lake Tharthar in Al Jazeera and dried marshlands in southern Iraq.

In addition to dust sample analysis, soil samples were obtained from ten sites in different Iraq regions, from depths between 0 and 10 cm below the soil surface. The mineralogical analysis of soil samples is shown in Fig. 7 and Table 6. It is difficult to identify dust sources by using mineralogy because the composition of most dust and loess sediments is similar to upper continental crust in the Earth's surface [5, 79–84]. The mineralogical analysis is used to give an overview of the mineralogical components of soils in Iraq. The northern region (near Erbil and Kirkuk cities) contains calcite, quartz and gypsum as the main minerals, as well as smaller quantities of feldspars and kaolinite. The central and southern regions, including Baghdad city near the Tigris basin, Khanaqin city in eastern Iraq and Nasiriya and Basra cities in southern Iraq contain calcite and quartz as the main minerals, as well as smaller quantities of feldspars, dolomite and kaolinite. The sample from Nasiriya, which is located on badly drained river-valley soils, contains 6.7% gypsum that probably originated from dust emissions from the arid gypsiferous area to the southwest. Two samples from Kirkuk city (Kirkuk 1 and Kirkuk 3) contain about 28.5% and 3.1% halite, respectively, which reflects the salty soil near this city.

Table 7 Trace elements in dust samples from the study region by XRF technique

Parts per million (ppm)	Dhock	Machomre	Baiji	Tikrit	Hit	Ramadi	Kahanqin	Baghdad1	Baghdad2	Basra	Mean
Cl	93	2234	257	2348	2630	7504	20,910	3215	4163	211,400	25,475
Sr	183	335	210	454	567	480	608	651	351	454	429
Ba	254	291	146	284	320	256	305	160	278	110	240
Rb	71	50	46	47	45	42	41	19	55	20	44
Zr	159	171	105	182	218	152	154	80	172	42	144
Ni	171	99	141	92	83	126	110	48	77	37	98
V	139	111	109	107	110	107	103	41	117	5	95
Co	34	22	22	25	23	29	32	14	23	14	24
Cu	41	33	33	76	49	82	43	67	36	12	47
Zn	87	141	105	144	110	149	308	534	120	20	172
Pb	15	21	17	26	21	41	177	52	21	7	40
As	10	7	6	6	6	6	10	3	7	2	6
Ga	13	11	8	9	10	9	8	5	12	2	9
Ge	2	2	<1	2	<1	1	1	<1	2	<1	2
Se	1	1	1	1	1	1	1	1	1	1	1
Br	3	10	7	6	8	9	13	7	22	34	12
Y	25	23	16	21	22	19	18	7	23	6	18
Nb	14	14	9	12	13	12	10	4	12	4	11
Mo	1	1	1	1	1	1	1	1	1	1	1
Sn	3	3	3	3	3	3	3	8	5	3	3
Sb	3	3	3	3	3	3	3	3	3	3	3
Cs	4	4	4	4	4	4	4	4	4	4	4
Hf	3	4	1	4	4	3	2	1	3	1	3
Ta	1	1	1	1	1	1	1	1	1	1	1
W	1	1	1	1	1	1	1	1	1	1	1
Hg	3	4	1	33	2	3	2	2	3	2	6
Bi	1	1	1	1	1	1	1	1	1	1	1
Th	7	7	4	6	6	5	6	2	7	2	5
U	2	2	2	1	3	1	1	1	1	2	1

## 3.4 Evaluation of trace metals and their impacts

The average values of trace elements (Table 7) in all dust samples in ascending order from the lowest concentrations are 24 ppm Co, 40 ppm Pb, 43 ppm Rb, 47 ppm Cu, 95 ppm V, 98 ppm Ni, 143 ppm Zr, 172 ppm Zn, 240 ppm Ba and 430 ppm Sr. The highest average concentration was 25,475 ppm Cl. The high and low values of trace elements (Table 7, Fig. 8) and their health effects are discussed below.

The high percentage of chlorine reflects salinization of lands in the lower part of Tigris and Euphrates Rivers and their tributaries and marshlands, and it could also come from coastal areas around the Arabian Gulf. The soils in these areas are strongly salinized because of agricultural activities and arid climate in addition to salinization of the dried marshlands in the southeast of Iraq [85, 86]. The high concentration of Barium (Ba) is related

to airborne dust source regions in Iraq and neighbouring countries, e.g. Saudi Arabia [35] and high concentration of Strontium (Sr) may be correlated with calcite and dolomite derived from limestones [85]. The presence of Rb is probably correlated with clay contents. The other high concentrations of metals are likely to be anthropogenic. Furthermore, Ba was the dominant trace element at Dhock city in the north of Iraq. Other components showed variations in their percentages at all stations. The percentages of likely harmful and toxic elements, such as Cu, Pb and Co, are low at all stations, but, Zn, Zr, Ni and V showed mildly elevated percentages. The high Ni and V concentrations at Dhock may reflect derivation from an ophiolite source.

The mean values of heavy metals for all the selected soil samples (Fig. 9 and Table 8) are displayed in ascending order from the lowest concentrations, 12 ppm Pb, 25 ppm Co, 28 ppm Cu, 46 ppm Rb, 58 ppm Zn, 92 ppm V, 102 ppm

Fig. 8 Chemical compositions from XRF for dust samples from different sites in Iraq, **a** all chemical compositions and **b** all chemical compositions without Cl


(a)

(b)
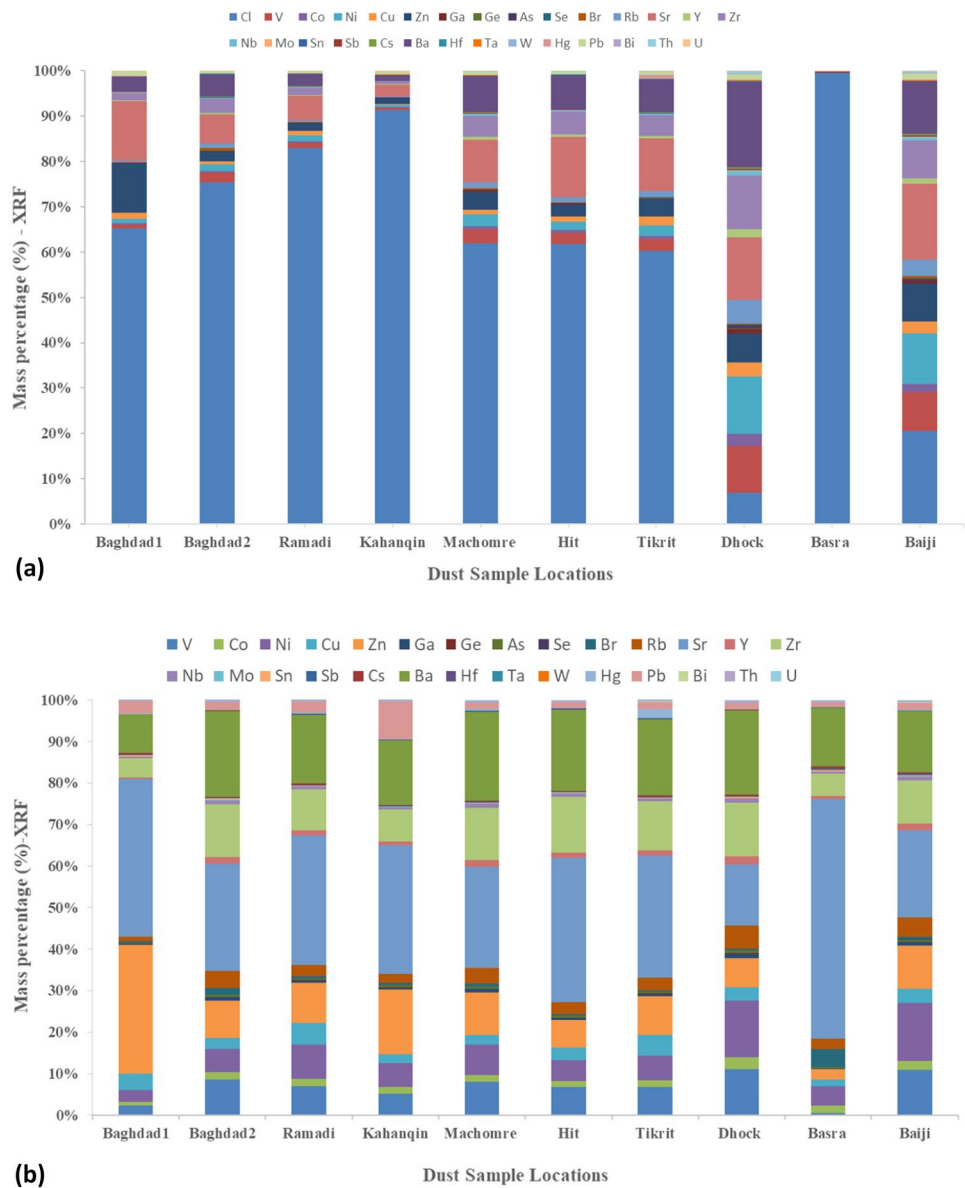
Zr, 122 ppm Ni, 248 ppm Ba and 431 ppm Sr, and lastly the highest concentration was 51,323 ppm Cl.

It is important to know if the concentrations of heavy metals could cause harm to human health. Because there are no guidelines on heavy metals specified by the department of quality control in Iraq, the trace element concentrations in different regions of Iraq were compared with the Dutch soil geochemical guidelines as displayed in Table 9. This comparison defined whether the trace element concentrations were environmentally acceptable (below the target value) or seriously polluted (above the intervention value). Concentrations between the target and intervention values indicate potential pollution that may have an impact on public health, and which may require more investigation and study. Apart from the soil

sample from Basra, the Ni concentrations in all the other soil and dust samples are higher than the Dutch target value. The Pb concentration is lower than the Dutch target value in all soil and dust samples except in Khanaqin and Baghdad1 dust samples which were 177 and 52 ppm, respectively. Cu concentrations in Erbil1, Kirkuk1 and two soil samples and Machomre and Baiji dust samples are close to the Dutch target value 36 ppm, whereas Baghdad soil and all other dust samples except Basra are higher than the target value. All the soil Zn concentrations are less than the Dutch target value, while Zn concentration in Machomre, Tikrit and Ramadi dusts was more than the target value and the highest concentrations were in Kanqeen and Baghdad-1. Apart from the soil sample from Basra, the Ba concentration in the soil is higher than the

Fig. 9 Chemical compositions from XRF for soil samples from different sites in Iraq. **a** all chemical compositions and **b** all chemical compositions without Cl
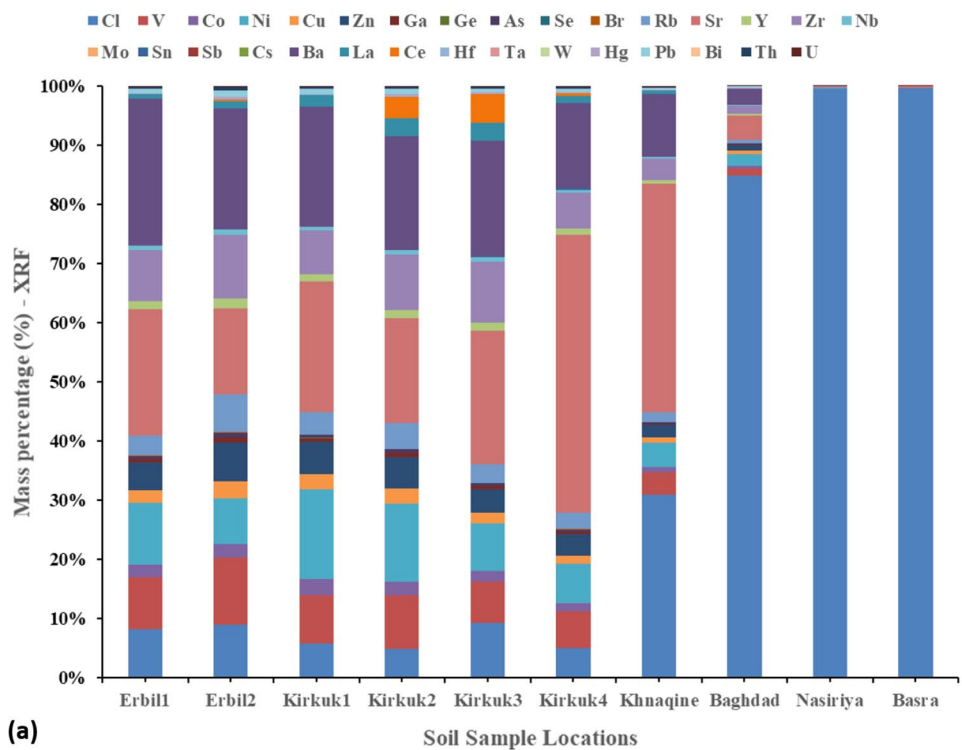
(a)
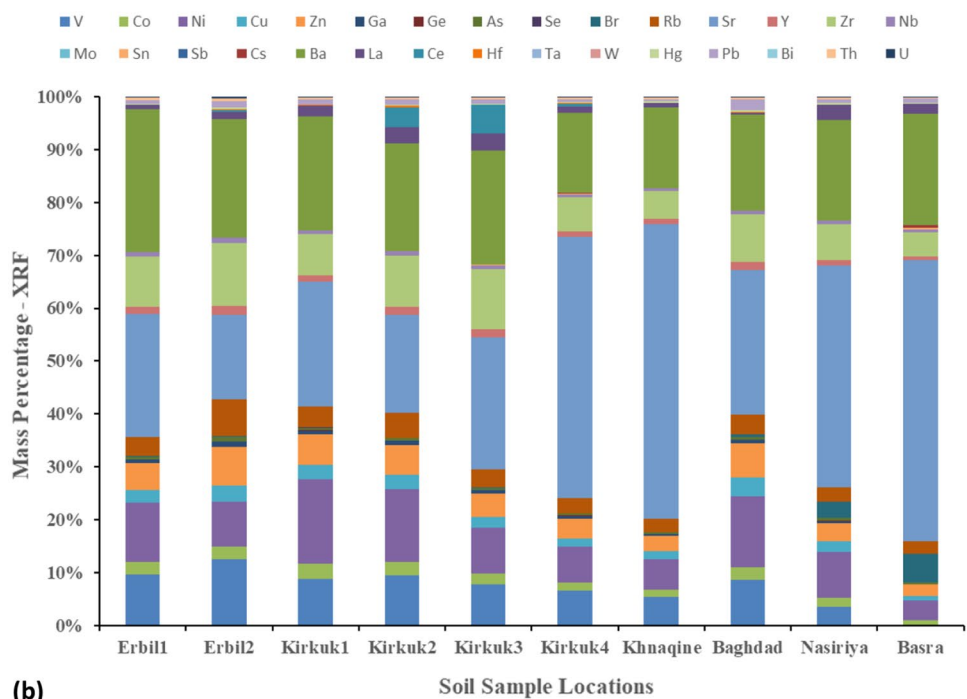
(b)

Dutch target value. In addition, Ba concentration in all dust samples except Basra, Baiji and Baghdad-1 was more than the target value. None of the soil or dust samples had trace element concentrations higher than the intervention values. The high Ni concentrations may again reflect derivation from an ophiolite source.

4 Discussion

Because dust particles could be transported for long distances in the air and these particles could stay suspended for long times in the air, they, therefore, impact global, regional and local climate and weather [88, 89].

Table 8 Trace elements in surface soil samples in the study region determined by XRF (ppm)

Element	Erbil1	Erbil2	Kirkuk1	Kirkuk2	Kirkuk3	Kirkuk4	Khanaqin	Baghdad	Nasiriya	Basra	Mean
Cl	99.8	104	80	63	121	92	689	6983	275,700	22,930	51,323
Sr	260.7	168	309	230	297	863	857	343	556	431	431
Ba	302.8	235	283	251	258	266	235	228	251	172	248
Rb	39.6	73	52	58	40	50	38	48	37	20	45
La	9.5	14	26	38	39	20	15	4.6	39	15	22
Y	16.4	19	17	18	18	19	14	18	14	6.0	16
Ce	1.9	3.9	1.9	47	63	9.3	1.9	1.9	1.9	1.9	13
Zr	106.4	125	103	121	135	111	82	113	89	37	102
Ni	126.3	89	211	171	104	121	89	168	115	30	122
V	107.7	132	115	118	92	114	83	107	47	0.6	92
Co	26.7	26	38	30	25	26	22	31	22	7.7	25
Cu	26.5	32	35	34	24	27	22	45	27	7.9	28
Zn	57.1	75	76	69	53	65	45	81	46	17	58
Pb	9.2	12	13	12	8.7	10	7.6	27	10	6.4	12
As	5.9	8.3	6.4	7.1	5.5	6.4	4.4	5.5	7.1	1.9	5.9
Ga	8	12	9	10	7	8	6	9	4	1	7
Ge	<0.5	<0.3	2	<0.1	<0.5	1	<0.5	<0.5	1	<0.3	1
Se	0	0	0	0	<0.1	0	0	0	0	0	0
Br	2	2	1	<0.5	1	1	1	5	40	44	11
Nb	9	11	9	10	9	10	7	9	8	4	9
Mo	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	
Sn	0	<3.0	<3.0	<3.0	1	3	<3.0	<3.0	<3.0	2	2
Sb	<3.0	<3.0	<3.0	<3.0	<3.0	<3.0	<3.0	<3.0	<3.0	<3.0	
Cs	<4.0	<4.0	<4.0	<4.0	<4.0	1	<4.0	<4.0	2	4	2
Hf	<0.7	2	2	3	1	1	<1.0	2	<0.7	<1.0	2
Ta	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	1	<1.0	1
W	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	
Hg	1	2	1	3	3	3	3	3	3	2	3
Bi	<0.3	<0.3	<0.3	<0.3	<0.3	<0.4	<0.3	<0.3	<0.3	<0.3	
Th	4	7	5	5	5	6	4	4	4	2	4
U	2	3	2	2	2	3	3	2	2	1	2

Table 9 Soil reference values (Dutch Target and Intervention values; [87])

Parameter	Dutch target value mg/kg (ppm)	Dutch Intervention value mg/kg (ppm)	Average dust concentrations in this study	Average soil concentrations in this study
As	29	55	6	5.9
Ba	200	625	240	248
Cd	0.8	12	–	–
Cu	36	190	47	28
Hg	0.3	10	6	3
Mo	10	200	1	<1.0
Ni	35	210	98	122
Pb	85	530	40	12
Zn	140	720	172	58

A number of factors impact the lifetime of airborne dust particles, including particle size of dust, wind velocity, wind blowing period and turbulence, climatic conditions, precipitation, and elevation of mountain ranges. Moreover, dust particles at a regional scale are negatively related to public health [90]. Iraq is a good location to examine and analyse the nature of dust storms because it is exposed to enormous quantities of dust from the extended Syrian and Al Jazeera Deserts and the alluvial basin between the Tigris and Euphrates Rivers.

The results of particle size analysis showed that clay and silt particulates form an average of 86.9% of a dust storm, whereas sand particles represent an average of 13.2% of all dust samples. The physical analysis of dust samples revealed that low percentages of sand occur in the north region, but they are high in the western and central regions. The analysis of grain size revealed that most dust samples consist of clayey silt, while sandy silt dust samples were less abundant. The particle size distribution relies on the capacity and speed of the winds that form dust storms and transfer these particles over a regional range. As the coarse particles are heavier than fine particles, they could have been deposited before the dust plume arrived at the selected study region, while fine particles have the ability to reach distant places because of their light weight [91]. Sand particulates are transported for short distances and predominantly entrained locally [92]. This study used the HYSPLIT model to understand potential dust storm sources and their transport pathways over different parts of Iraq. Thus, the small size particles (clay and silt) probably came from neighbouring sources of dust over which air parcels pass before reaching the Iraqi cities, (e.g. Syrian Desert, An-Nafud Desert, southwest Iran, the alluvial plain and the Al Jazeera and Western Deserts as these were the potential sources of dust shown Fig. 2). In contrast, the coarse dust particles were probably picked up from local sources. Jish Prakash et al. [93] indicated that soils have the ability to lift into the atmosphere and generated dust when they contain a clay mass of less than 10% and a silt mass higher than 50%; a soil texture of silt loam that is similar to all the analysed soil textures. These particle size criteria provide a significant indicator to determine if an area or location has the ability to act as an important dust source region [94]; the area also needs to be dry. The < 10 µm particles typically represent a natural origin, while particles of anthropogenic origin are usually < 2.5 µm [95]. PM10 and PM2.5 dust particles could transfer pollutants including morphological, mineralogical and chemical compounds that could be risky to population health [28] since the respiratory system is more influenced by < 10 µm particulate matter that could penetrate to the gas exchange areas of lungs [96].

Airborne dust descriptions were derived from an analysis of mineralogy from the XRD technique and chemical analysis of trace elements via the XRF method. The findings revealed that kaolinite, gypsum, albite, quartz and calcite were the major mineral dust elements, in ascending order, above Iraq, and were present in every collected dust aerosol sample. However, lower amounts of palygorskite, microcline, dolomite, illite, chlorite and halite were also detected, because these components manifested in samples from just a few stations. The high percentage of quartz and calcite in each sample suggested a detrital sedimentary source for the dust storm provenance [28]. A study in Saudi Arabia showed similar mineralogy with prevailing silicate and carbonate minerals for the deposited dust samples [33]. In addition, the predominant quartz and carbonate minerals were found during the occurrence of dust storms over surrounding regions such as Iran and southwest Asia [28, 97, 98]. The high percentage of halite in Basra may originate from dry lake and marshlands near the Iraq–Iran border as shown by HYSPLIT modelling (Fig. 2a). Palygorskite is widespread in the desert and semi-desert lands with variable climatic systems and with a rainfall of about 300 mm or less [99]. This mineral possibly comes from lacustrine sediments [100]. Palygorskite is found in the sediment and soil surfaces of Jordan, the Arabian Peninsula and desert lands in southern and northwestern Iraq [101–103], and hence, the dust storms in Iraq may have been derived from these areas. The existence of kaolinite among the clay minerals also reflects the dry and semi-dry weather situations [104–107]. The main minerals in dust storms over eastern Asia are similar to the Middle East and consist of dolomite, calcite, plagioclase feldspar, alkali feldspar, quartz, chlorite, kaolinite and illite [108]. In contrast, prevalent minerals in Harmattan dust over Africa are quartz and feldspar [109]. Halite and gypsum minerals are produced as a result of chemical equilibrium processes and are commonly distributed in saline soils [110]. Some studies found halite and gypsum minerals related to coastal cyanobacterial mats in dry areas such as around the Arabian Gulf [111, 112]. The airborne mineral dust in different parts of Iraq was examined. The results showed that the highest proportions of siliceous dust were in Tikrit and Taji while the lowest was in Al Asad. The highest percentage of gypsum was in Al Asad. Baghdad city also has high percentages of evaporate minerals, due to salinized agricultural soils and irrigation processes along the Tigris River valley over the past millennia [85]. Some studies of particle size and mineralogical percentages of deposited dust in the Middle East and global dust samples are shown in Table 10.

Calcite covers the south-eastern Syrian Desert and forms more than 20% of total Syrian Desert soil. Gypsum occurs in the middle and south of Iraq (Mesopotamia

Table 10 Average particle size and mineralogical percentages of deposited dust in the Middle East and global dust samples

Sector	Source	Size %		Minerals %				
		Mud	Sand	Quartz	Feldspars	Clay	Carbonates	Others
Ahwar-Iraq	[113]	97	3	13	8	0	80	0
Manamah-Bahrain	[114]	87	12	32	10	3	41	15
Kuwait	[115]	63	37	38	10	2	45	5
South Saudi	[116]	61	40	62	24	1	13	0
Ain-Emirates	[32]	4	97	26	20	1	52	0
Dubai-Emirates	[117]	82	17	21	6	0	45	27
Amman-Jordan	[118]	70	30	21	4	0	68	7
Tripoli-Libya	[119]	81	20	64	5	4	27	0
Biougra-Morocco	[120]	88	12	46	8	1	46	0
Cartagena-Colombia	[121]	90	10	66	33	0	0	1
Cairo-Egypt	[122]	90	10	51	15	0	34	0
Bald Hill-Australia	[34]	90	9	57	21	14	0	7
Average		75	25	41	14	2	38	5

area) and the northern Syrian Desert where it also forms around 20% of Syrian Desert soils [123]. The Zubair Desert in the southern part of Iraq contains sediments that consist of calcareous materials [124]. This indicates that airborne dust above Iraq may be emitted regionally as well as locally, such as from the Syrian Desert and the area between Tigris and Euphrates River valleys in Iraq, while in some instances it could also have had long-scale transport from remote areas.

The results of the chemical analysis revealed that the main trace elements in the airborne dust samples were Ba, Sr and Cl. This analysis showed that high percentages of Zn and Pb occur in the eastern and central regions. The barium and strontium are most likely to be related to limestone sources, and the highest Cl content was in Basra, which is correlated with the halite content from XRD analysis. Chemical dust analysis gives useful observations on possible dangerous trace elements (e.g. As, Pb and other heavy metals such as Zn, Ni, Cu, Cr and Co [37, 48]. Dust particles can transport pollutants including heavy metals (e.g. Cr, Sb, Pb and Zn) for long distances by winds during dust storms [125]. Winds that moves above the land surface would lift a diversity of suspended materials including soil particulates, anthropogenic pollutants, organic matter and salts [37]. The occurrence of trace elements and their risk to humans during the dust storms in the central and southern Iraq were examined. The results showed that dust storms contain high concentrations of metals and high polluted elements including Cd, followed by Pb, Zn and Ni [126]. The trace element concentrations in the dust are of little health concern apart from the higher zinc (Zn) and lead (Pb) concentrations in Kahanqin and Baghdad-1 that probably represent local pollution. The likely human origins for Pb were solid waste combustion, industrial processes and leaded gasoline [127].

Copper is one of the non-significant components in the human body, but if its concentration increases it can become a poisonous element. An increase of Cu in the liver tissues and blood cells of humans would lead to Wilson disease that causes harmful impacts on the cornea, liver and brain. The exposure to lead has a negative impact on neurodevelopment and behavioural performance of children [128]. Cobalt represents a significant element for animals and humans as it has a role in the chemical haemoglobin construction. When the average cobalt concentration declines, it will affect oxygen transfer via haemoglobin. However, if its concentration rises, this will lead to trouble in some living organisms. The analyses of airborne dust trace elements in Iraq revealed that the results are of little environmental concern and did not exceed the recommended pollution levels; this may be because weather stations are not located close to or in a wind direction coming from industrial factories. The higher zinc and lead values in Kahanqin and Baghdad-1 probably represent local pollution, where the slightly higher concentrations of Pb come from leaded petrol used in motor vehicles in Iraq [85].

The potential dust storm sources over different parts of Iraq were analysed using the backward trajectories analysis of air parcels by the HYSPLIT model. The findings of the current research reveal that the potential dust storm sources during spring including North Africa deserts, An-Nafud Deserts in Saudi Arabia, the Syrian Desert, dry lands in south-western Turkey and southwest Iran, and the alluvial plain, Al Jazeera and Western Deserts in Iraq. North Africa, Saudi Arabia, Iraqi, Syrian Deserts as well as the dry lands in south-western Turkey and southwest Iran are considered to represent important dust sources in the world [11, 64, 65].

5 Conclusions

The physical, chemical and mineralogical characteristics of airborne dust samples in Iraq were analysed. The physical analysis showed that high amounts of dust storms consisted of clay and silt particles with low amounts of sand particles. The mineralogical analysis showed that calcite, quartz albite, gypsum and kaolinite were the major minerals in the descending order with low amounts of palygorskite, microcline, dolomite, illite, chlorite and halite. The chemical analysis showed that Ba, Sr and Cl elements were the main trace elements in the airborne dust samples. The analyses of airborne dust trace elements showed that concentrations were acceptable environmentally and did not exceed the recommended pollution levels. Also, the HYSPLIT back trajectory simulations of air parcels showed that Syrian Desert, desert areas in Africa, An-Nafud Desert, the arid lands in south-western Turkey and southwest Iran, and the alluvial Plain, Al Jazeera and Western Deserts in Iraq were the potential dust sources on dust storm days. This study provided information on physical and chemical analysis of airborne dust to acknowledge the potential impacts of dust on the environment, soil and health. This study recommends the government and society to plant trees in urban areas and in empty spaces around the urban cities and out-of-city streets to build windbreaks from many lines of trees and to enhance the visibility ranges in these streets. Using clay mineralogy and Pb and Nd isotopes to define sources areas for deposited dust could be studied in the future.

Compliance with ethical standards

Conflicts of interest The authors declare no conflict of interest.

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