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Original Research

Airborne dust particles originated from sand and gravel quarries: Mineralogical, geochemical and size distribution constraints on their potential health impacts

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Abstract

Dust particles derived from sand and gravel mining have been considered one of the possible sources of airborne particles in Tehran, the capital city of Iran. In this research, the size, morphological, and geochemical characteristics of airborne particles originating from open mines were investigated. Twenty-two samples from different heights (3 to 21 m) were collected from a sand and gravel quarry in Shahriar, as a representative of the numerous quarries in western Tehran. The selected samples were further analyzed using X-ray powder diffraction (XRD) and Scanning

Electron Microscopy with Energy Dispersive X-ray Spectroscopy (SEM-EDS). The mineralogy of airborne dust was dominated by quartz, followed by albite and calcite. The size distribution of deposited particles at different heights ranged from 0.05 μm to 100 μm, and about 80% of them were respirable (<10 μm) and available for transport through the atmosphere. Si/Al ratios mainly ranged between 4 and 10. Most nanoparticles were deposited in agglomerated forms.

Keywords: Airborne dust particles, Sand and gravel mining, Crystalline quartz, Dust mineralogy, Dust morphology

1. Introduction

Epidemiological studies associate the concentration of particulate matter in the air with a range of human health effects, such as cardiovascular and pulmonary diseases, morbidity, and mortality (Lin et al., 2018; Paltinean et al., 2016; Rusca et al., 2023). Mineral processing may release dust-sized particles or particulate matter (PM) into the air, which are often invisible to the naked eye. The smallest of these particles can become airborne and remain suspended for extended periods (Paltinean et al., 2016; Rodriguez et al., 2019; Rusca et al., 2023). Depending on their chemical composition, particulate matter may exhibit hazards beyond those associated with size-related health risks (Kumar et al., 2010). Significant environmental and public health risks may be associated with increased quarrying activities (Ekpa et al., 2022; Ziarati et al., 2024). Residents living near sand and gravel quarries and processing plants are potentially exposed to respirable crystalline minerals, including quartz and other phases. Long-term inhalation exposure to respirable crystalline silica can cause silicosis and fibrotic lung diseases (Soutar et al., 2000; Naghizadeh et al., 2011; Park et al., 2012; Verma et al., 2013).

However, hazardous minerals are not the only concern affecting air quality near mine sites. Depending on the activity and geochemical characteristics of the mines, potentially toxic elements (e.g., Pb, Mn, Al, V, Zn) may also be released and transported into the atmosphere and surrounding environment (Shojaee et al., 2020).

Identification of the mineralogical composition of dust particles plays an important role in understanding their reactivity with microscopic atmospheric components and available gaseous compounds (Usher et al., 2003). The study of dust mineralogy is also useful for assessing the geological characteristics of dust-producing regions and serves as an indicator of the impact of dust particles on the receiving soils (Krueger et al., 2005).

Sand and gravel quarries and processing plants play a vital role in the construction sector of Tehran Province, with up to 2,500 workers employed at these mine sites (Khaksar et al., 2014). Many quarries are located in the west and southwest of Tehran (Figs. 1a, b), particularly in the vicinity of Qods, Eslamshahr, Shahriar, and Malard (Statistical Center of Iran, 2016). Due to the geographical positioning of these mines and the prevailing west-to-east wind direction in Tehran (Ghanbari and Azizi, 2009), particulate matter generated by mining, grinding, sizing, transportation, and storage activities is likely to affect not only the workers and nearby residents but also the population of Greater Tehran.

The main objective of this study was to investigate the mineralogy, geochemistry, size, and morphology of airborne particles released from a quarry considered representative of those in the region, in order to assess their potential toxicological impacts (Donaldson and Borm, 2006; Kumar et al., 2010; Raja et al., 2014).

To collect representative air samples, a new Settleable Particulate Height-Separator (SPHS) device was designed and constructed for sampling and separating airborne particles at different heights (Fig. 1c).

In addition to the invention of this sampling device, the novelty of this study lies in its focused investigation of the nanoscale properties of quarry dust, providing a direct correlation between quarrying activity and the generation of nanocrystalline mineral phases—an aspect rarely reported in previous studies. Beyond mineral identification, this study reveals, for the first time in the country, that mechanical weathering produces a significant fraction of nanocrystalline quartz and albite. This finding offers a new mechanistic understanding of how quarry operations significantly reduce crystallite size, increasing the specific surface area, bio-reactivity, and environmental persistence of dust. This advancement provides a critical link to the potential health impacts of airborne dust, which is essential for revising environmental and public health risk assessments.

2. Methods and Materials

The selected sand and gravel quarries are located at coordinates 35° 41′ 30″ N, 51° 05′ 08″ E in Shahriar, Tehran Province, Iran. The mine site covers an area of approximately 180,000m2, with extraction taking place at a depth of 20 m. Crushers are situated at a level of -10 m relative to the surrounding ground. The mine adheres to HSE (Health, Safety, and Environment) guidelines and uses water spray systems to suppress dust. Field observations indicated that the main sources of dust emission include the movement of heavy machinery along 1.5 km of dirt roads, as well as crushing, sieving, loading, and unloading operations.

A soil sample was collected from a quarry pit, excavated by loaders at a depth of 20 meters (sample SQ). Approximately 1 kg of soil was prepared by mixing five subsamples (1–2 cm deep) taken from the corners and center of an imaginary 2×2 m square. Debris, plant material, and coarse grains were removed before the sample was packed into sealable plastic bags.

Dust samples were collected over one week (five working days) in October from a quarry in Shahriar using a passive sampling method for settleable dust. Sampling was performed with a Settleable Particulate Height-Separator (SPHS), which was designed by the first author as part of her Ph.D. dissertation (Menhaje-Bena et al., 2018). Due to the similarity of alluvial deposits in the western and southwestern regions of Tehran, the results obtained from this quarry can be generalized to sand and gravel quarries across the area.

The SPHS device (Fig. 1b) was built to collect dust samples and assess the proportion of deposited particles at various heights. The passive tower was equipped with six containers, including a smaller-scale attachment. Compared to the Bergerhoff instrument (Gregor et al., 2015), the SPHS includes a PVC screen to increase the surface area for capturing fine particulates, especially those that may be lost at higher wind speeds. Additionally, carbon adhesive tape was installed at the top corners of the PVC screens to collect airborne particles.

The tower, with a height of 21 m, was assembled near the crusher and included six sampling points at heights of 6 m, 9 m, 12 m, 15 m, 18 m, and 21 m above ground level. Deposited dust samples were collected and weighed using pre-weighed containers (±0.0001 g). Adhesive tapes were removed and transferred into sterilized Petri dishes, which were then sealed and labeled. The dust containers were closed with lids, sealed, stored in a box, and promptly transferred to the laboratory for further analysis.

A portion of each sample was analyzed using Scanning Electron Microscopy (SEM). Morphology, size distribution, and geochemical composition were examined using SEM-EDX (Philips XL30 ESEM, Netherlands), which offers variable accelerating voltage (0.2–30 kV) and a magnification range from 10× to 500,000×. Due to the low conductivity of the samples, a thin layer of gold was applied prior to imaging to obtain suitable resolution.

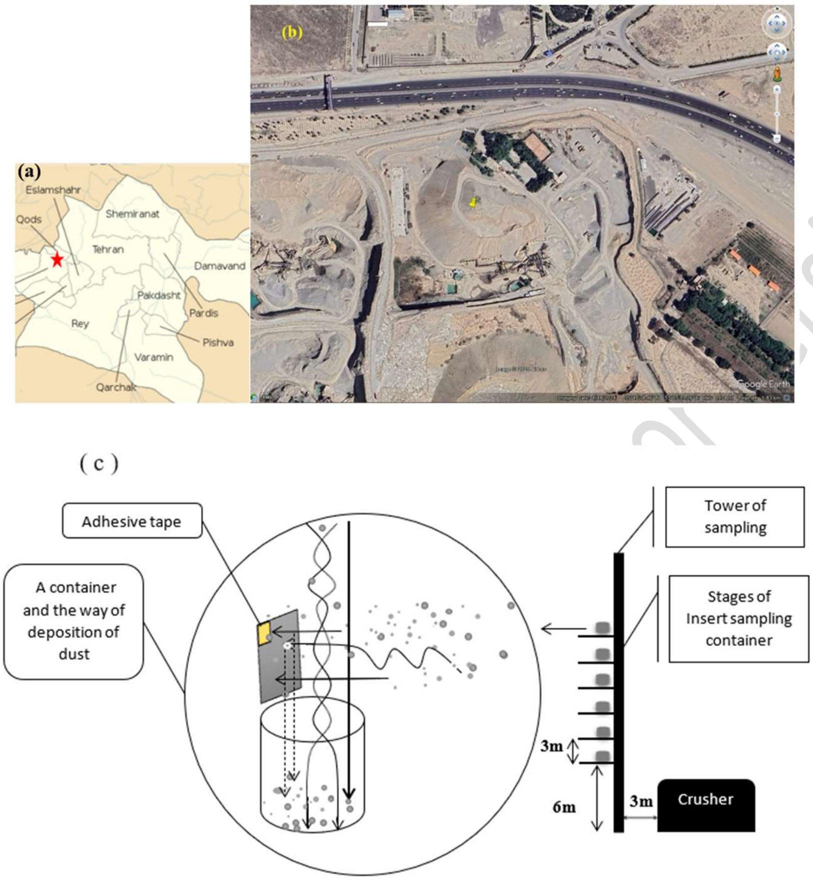


Figure 1. (a) Geographic location and (b) Google Earth image of the study area (marked with a red asterisk). Image © 2025 Airbus, Map data © 2024, used under fair use for academic research and in accordance with Google's attribution guidelines. (c) Diagrammatic representation of dust sampling at different heights. The dust sampler is a passive tower equipped with six containers, a screen to increase surface area for collecting fine particles, and carbon adhesive tape at the top corners of the screens to capture airborne particles. The tower, with a height of 21 m, was assembled near the crusher and consists of six sampling points at heights of 6 m, 9 m, 12 m, 15 m, 18 m, and 21 m above ground level.

X-Ray Diffraction (XRD) analysis was carried out to determine the mineralogical composition of the soil and airborne dust particles. Three samples, collected at heights of 6 m, 15 m, and 21 m from the quarry face, were analyzed using a Philips PW1800 diffractometer (with a Cu Kα X-ray source, λ = 1.5418 Å, operating at 40 kV and 30 mA) at Kansaran Binalood Labs, located at the Pardis Science and Technology Park, Tehran, Iran. The scanning range was 2θ = 2° to 70°.

To compare elemental ratios of particles across size classes, three samples at different heights and 30 individual particles from three size fractions (≤ 20 µm, ≥ 70 µm, and 20 µm < X < 70 µm) were analyzed using Energy-Dispersive X-ray Spectroscopy (EDX), with the XL30 ESEM device equipped with an EDAX energy-dispersive X-ray detector with an ultra-thin window. Due to the presence of carbon in the adhesive tape, carbon content could not be measured.

For particle size analysis, the longest dimension (Feret's diameter) was measured for over 200 particles in SEM images taken at 1000×, 2000×, and 10,000× magnifications. Measurements were made using a fixed reference line in all images, and particle size distribution diagrams were plotted accordingly (Ghias al-Din, 2006).

3. Results and Discussion

3.1. Mineralogy of soil and airborne dust

The mineralogical composition of the dust samples, analyzed by X-ray powder diffraction (XRD) for soil and airborne particles deposited in containers at different heights, is shown in Figs. 2a-d and Table 1. The main mineral phases in the soil are quartz, albite, and calcite, with minor and trace amounts of orthoclase and chlorite.

At first glance, the XRD patterns of the soil and dust samples suggest that an amorphous phase is dominant in the dust fractions (Figs. 2b, c, d). However, this is a typical characteristic of intensely weathered materials, due to mechanical crushing and chemical weathering (Avram et al., 2024; Paltinean et al., 2016; Kanbar et al., 2021). The XRD patterns show sharp, well-defined peaks for quartz (Qz) and albite (Ab), indicating the presence of coarse crystalline material. This confirms that not all the material is fine-grained. The broad scattering "hump" between approximately 15° and 35° 2θ, often interpreted as an amorphous phase, is more likely due to severely broadened peaks from nanocrystalline and/or microstrained weathering products (e.g., clay minerals), rather than truly amorphous material. This peak broadening, well-described by the Scherrer equation, results from very fine crystallite sizes (<100 nm), where adjacent peaks overlap and create a continuous hump that can resemble the signal of non-crystalline (glass-like) material.

Table 1. Mineralogical phases of soil and dust samples in the study area.

Locations	**quarry pit soil sample (SQ)**	**6m Mine site**	**15m Mine site**	**21m Mine site**
Major Phases	quartz, albite, calcite	amorphous?	amorphous?	amorphous?
Minor Phases	orthoclase, chlorite	quartz, calcite, albite,	quartz, calcite, albite	quartz, albite
Trace phases	-	-	-	calcite

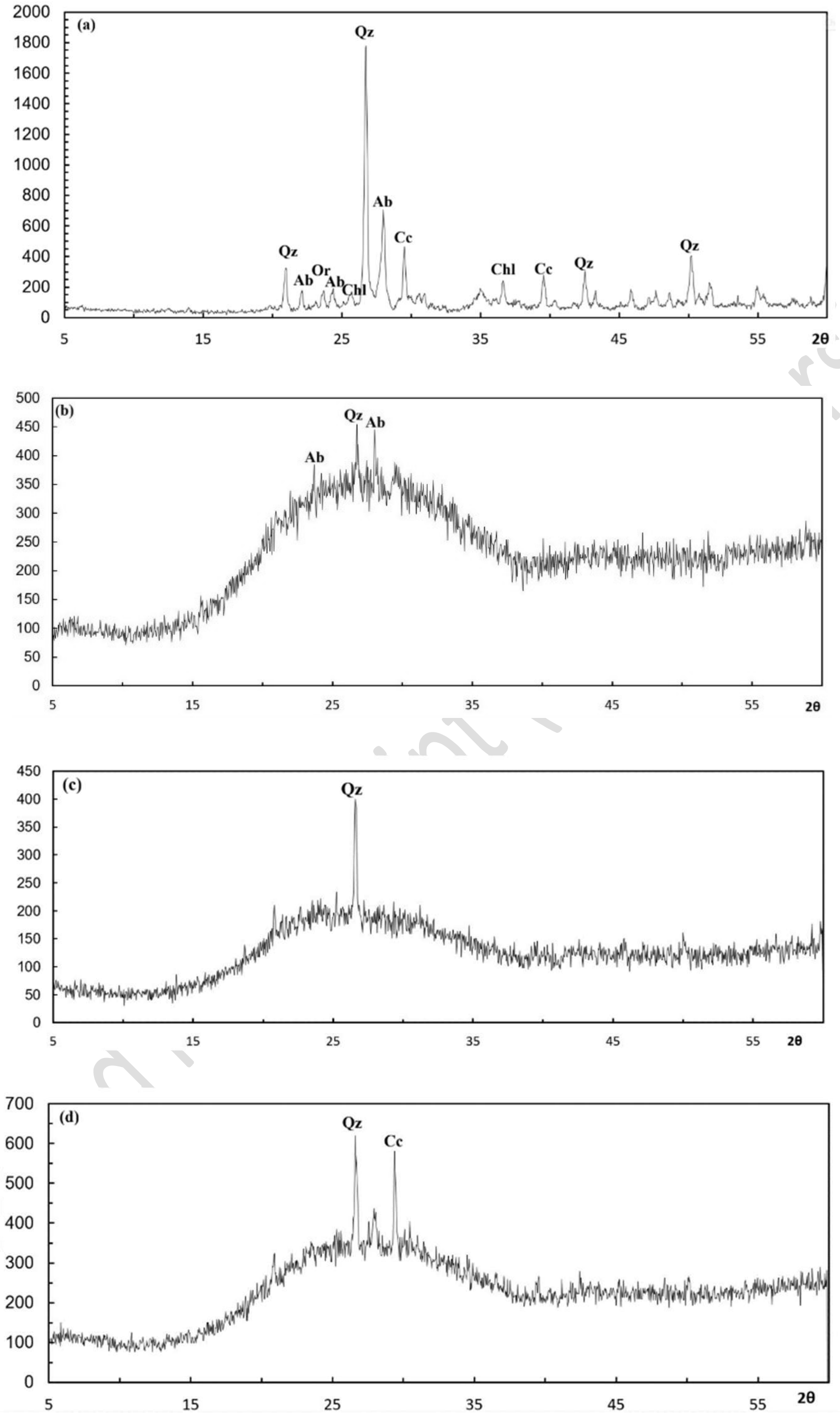


Figure 2. X-ray diffraction patterns of (a) a soil sample taken from the quarry (SQ) and dust collected at (b) 21 m, (c) 15 m, and (d) 6 m using the SPHS method. Patterns were obtained using Cu Kα radiation (λ = 1.5418 Å). Key: Ab = Albite, Cc = Calcite, Chl = Chlorite, Or = Orthoclase, Qz = Quartz.

Quartz and albite were identified as the major crystalline mineral phases in the collected dust samples. A higher amount of calcite was found in the 6 m and 15 m samples, while its content at the 21 m level was very low. Mineralogical analysis of samples collected at different heights confirmed that the amount of calcite decreases with increasing sampling height from 6 m to 21 m (Fig. 2).

The apparent increase in amorphous phases in higher samples could be attributed to poorly crystalline aluminosilicates or clay minerals formed during crushing, abrasion, and sieving. The presence of non-crystalline particles in airborne dust complicates the identification of the main sources of dust pollution in Tehran Province. Quartz and albite, which are consistently observed in all samples, are more likely to remain airborne and be found near the source than other compounds. Calcite was only a minor phase at 21 m and likely appears in coarse particles. Due to its relatively high density and low hardness compared to quartz, calcite is more likely to undergo solubilization or transformation and settle out before reaching higher altitudes.

Quartz and albite can therefore be considered good indicators of dust from the studied mine site and surrounding alluvium in the Tehran region.

These estimated crystallite sizes (40–200 nm) suggest that quarrying activity has generated a substantial amount of nanocrystalline material. This nanoscale range significantly increases the dust's specific surface area, enhancing its reactivity, potential health effects, and ability to be transported by wind. The smaller size of albite compared to quartz corresponds with its lower hardness and greater susceptibility to mechanical comminution and chemical weathering. These findings, supported by the agglomerated nanostructures observed in SEM images (Figs. 4 and 5), demonstrate that quarrying generates reactive, fine-grained particulate matter with potential environmental and health impacts.

3.2. Size fractions and morphology of dust collected at different heights:

The weight percentage of samples collected at different heights gradually decreased from lower to higher elevations (Fig. 3).

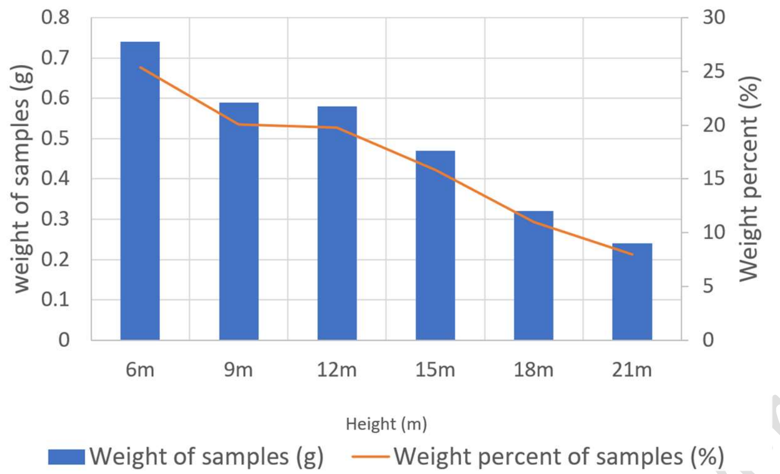


Figure 3. Mass and weight percent of dust samples collected in containers at each height using the SPHS sampling system.

The Feret's diameter (Df) of the largest deposited particle was 101.17 µm. Approximately 85% of the particles collected in containers at various heights were ≤10 µm in diameter. About 40% were ≤2.5 µm, while only around 2.5% were ≥40 µm (Fig. 4).

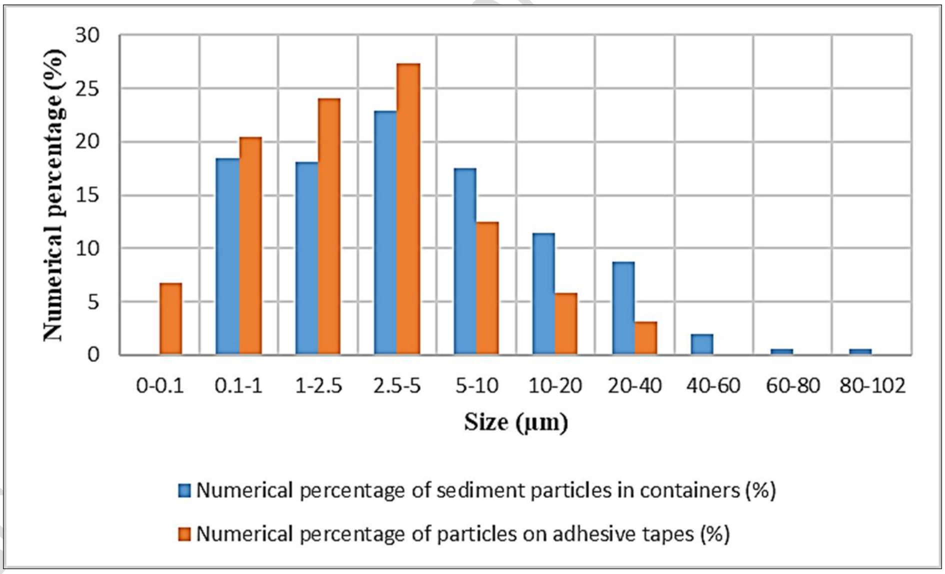


Figure 4. Mass percentage of all dust particles by size in both the container and adhesive tape samples collected at all heights using the SPHS method.

The highest recorded wind speed during the sampling period was 8 m/s. Based on this study, particles in the size range of 50 nm to 100 µm can be transported up to 21 meters in height under these wind conditions. A comparison of particle size distributions in sedimented dust at each height, collected in SPHS containers, is shown in Fig. 5. The particle distribution in the 2.5–5 µm range dominated samples at 9 m, although the distribution was somewhat irregular. At 6 m, particles in the 0.1–1 µm and 2.5–5 µm ranges were dominant, while those in the 1–2.5 µm range were less frequent.

The distribution pattern is likely influenced by the proximity of the sampling location to the crusher. The dust stream and the amount of deposited material are affected by several factors, including the crusher's power, the type, density, crystallinity, hardness, and moisture content of feed minerals, as well as environmental conditions such as humidity and local wind patterns.

With more than 60 sand and gravel quarries in the region, wind speeds reaching or exceeding 8 m/s can resuspend submicron particles and transport them over long distances. Therefore, the potential health impacts of these particles should be considered seriously.

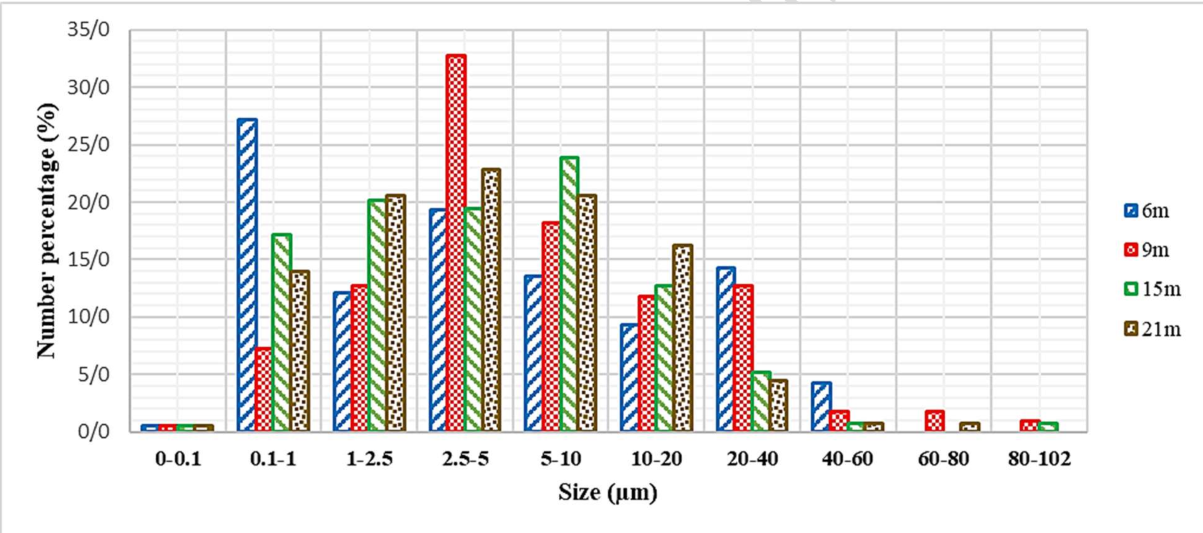
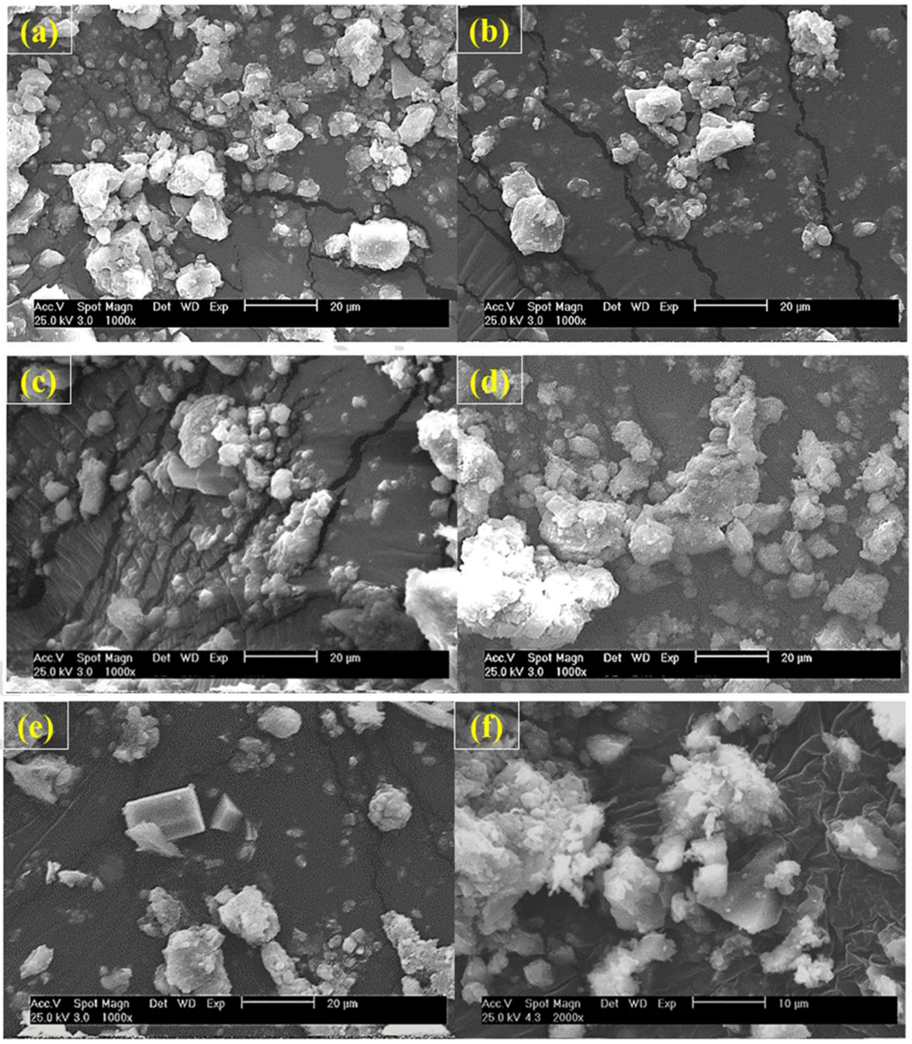


Figure 5. Particle size distributions of dust collected in containers at different heights: 6 m, 9 m, 15 m, and 21 m.

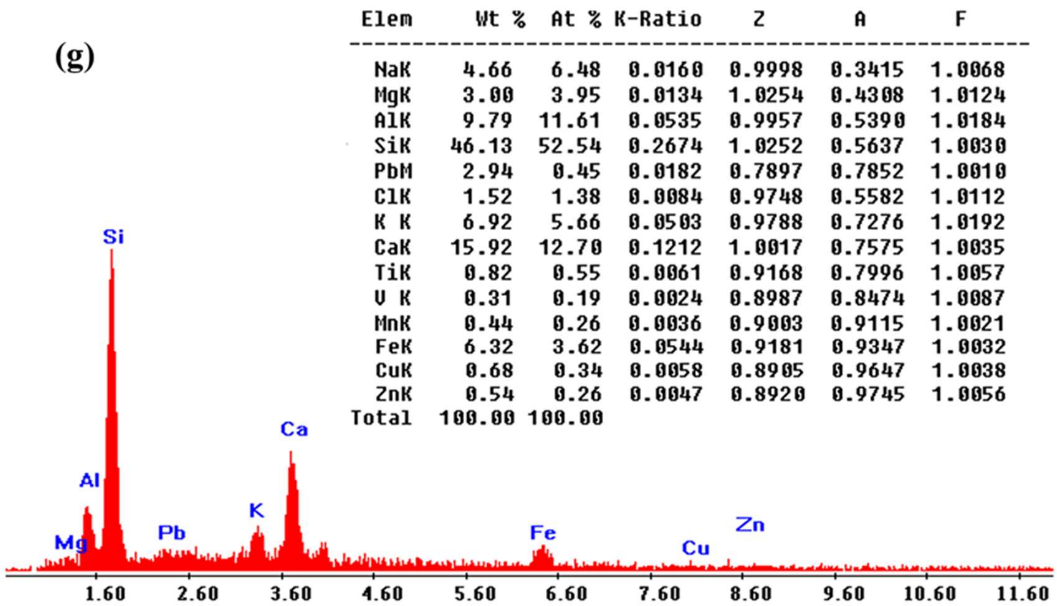
Results show that the percentage of particles collected on adhesive tape in the ≤5 µm, ≤1 µm, and ≤0.1 µm ranges were 78.6%, 27.16%, and 6.73%, respectively. In contrast, the corresponding percentages in dust sampling containers were approximately 59.44%, 18.5%, and 0%. This suggests that the adhesive tape method is more effective for capturing fine and nanoscale particles. According to this study, adhesive tape is a simple and effective alternative to conventional settling methods for dust sampling.

Physical processes such as conveyor belt vibration, sieving, vehicle movement on dirt roads, crushing, and strong local winds contribute to the resuspension of fine and ultrafine clay particles. These particles often exist in nucleation mode and subsequently cluster to form larger particles (Reijnders et al., 2018). Due to their high surface area and electrostatic/intermolecular forces, these particles tend to accumulate and form agglomerates. This aggregation may lead to underestimation of the proportion of fine and nanoparticulate fractions, which is particularly important in toxicological assessments (Bakand et al., 2012).

Comparison of particle morphology using both sampling methods in SPHS indicates that the airborne particles are similar in appearance across different heights. Most particles appear as non-spherical aggregates with irregular, rounded, prismatic, or rhombic forms (Figs. 6a-f and 7).

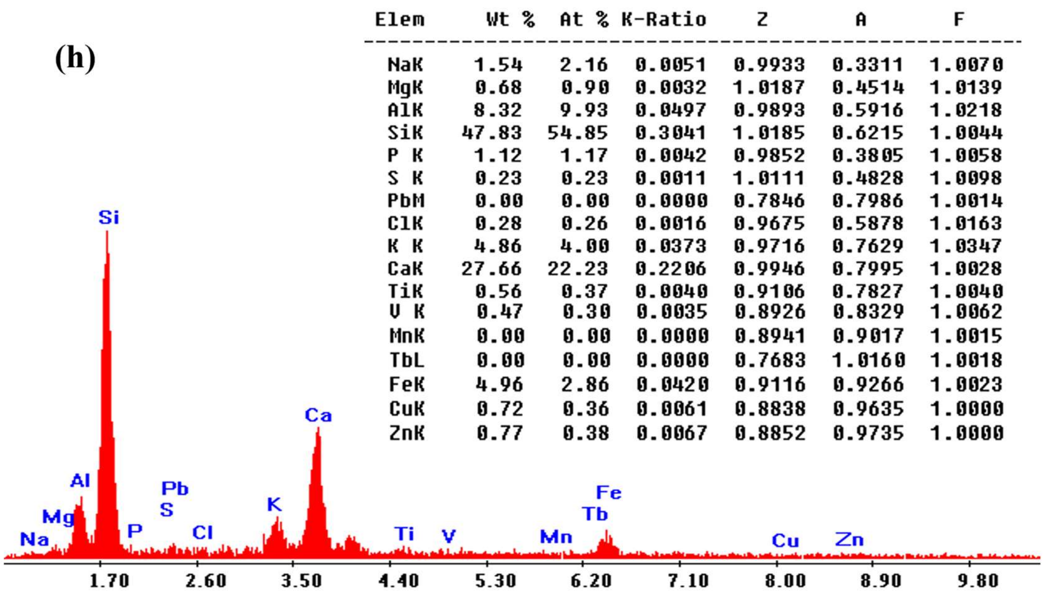


(g)



Elem	Wt %	At %	K-Ratio	Z	A	F
NaK	4.66	6.48	0.0160	0.9998	0.3415	1.0068
MgK	3.00	3.95	0.0134	1.0254	0.4308	1.0124
AlK	9.79	11.61	0.0535	0.9957	0.5390	1.0184
SiK	46.13	52.54	0.2674	1.0252	0.5637	1.0030
PbM	2.94	0.45	0.0182	0.7897	0.7852	1.0010
ClK	1.52	1.38	0.0084	0.9748	0.5582	1.0112
K K	6.92	5.66	0.0503	0.9788	0.7276	1.0192
CaK	15.92	12.70	0.1212	1.0017	0.7575	1.0035
TiK	0.82	0.55	0.0061	0.9168	0.7996	1.0057
V K	0.31	0.19	0.0024	0.8987	0.8474	1.0087
MnK	0.44	0.26	0.0036	0.9003	0.9115	1.0021
FeK	6.32	3.62	0.0544	0.9181	0.9347	1.0032
CuK	0.68	0.34	0.0058	0.8905	0.9647	1.0038
ZnK	0.54	0.26	0.0047	0.8920	0.9745	1.0056
Total	100.00	100.00				

(h)



Elem	Wt %	At %	K-Ratio	Z	A	F
NaK	1.54	2.16	0.0051	0.9933	0.3311	1.0070
MgK	0.68	0.90	0.0032	1.0187	0.4514	1.0139
AlK	8.32	9.93	0.0497	0.9893	0.5916	1.0218
SiK	47.83	54.85	0.3041	1.0185	0.6215	1.0044
P K	1.12	1.17	0.0042	0.9852	0.3805	1.0058
S K	0.23	0.23	0.0011	1.0111	0.4828	1.0098
PbM	0.00	0.00	0.0000	0.7846	0.7986	1.0014
ClK	0.28	0.26	0.0016	0.9675	0.5878	1.0163
K K	4.86	4.00	0.0373	0.9716	0.7629	1.0347
CaK	27.66	22.23	0.2206	0.9946	0.7995	1.0028
TiK	0.56	0.37	0.0040	0.9106	0.7827	1.0040
V K	0.47	0.30	0.0035	0.8926	0.8329	1.0062
MnK	0.00	0.00	0.0000	0.8941	0.9017	1.0015
TbL	0.00	0.00	0.0000	0.7683	1.0160	1.0018
FeK	4.96	2.86	0.0420	0.9116	0.9266	1.0023
CuK	0.72	0.36	0.0061	0.8838	0.9635	1.0000
ZnK	0.77	0.38	0.0067	0.8852	0.9735	1.0000

Height (m)	Mg	Al	Si	Pb	K	Ca	Fe	Cu	Zn	Cl	Ti	Na
21m [g]	3.00	9.79	46.13	2.94	6.92	15.92	6.32	0.68	0.54	1.52	0.82	4.66
6m [h]	0.68	8.32	47.83	0.00	4.86	27.66	4.96	0.72	0.77	0.28	0.56	1.58

Figure 6. SEM images of particles deposited in containers at various heights: (a) 21 m, (b) 18 m, (c) 15 m, (d) 12 m, (e) 9 m, and (f) 6 m. EDX spectra of deposited particles at (g) 21 m and (h) 6 m. The table presents elemental compositions corresponding to EDX spectra in Figs. 6g and 6h.

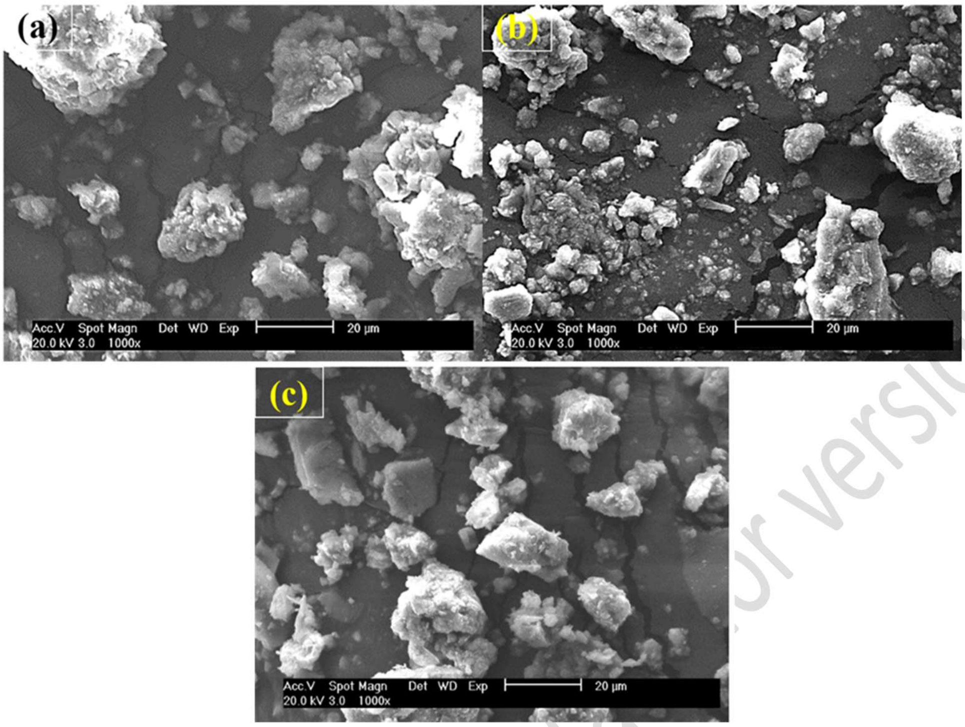


Figure 7. SEM images of particles collected on adhesive tape at heights of (a) 9 m, (b) 12 m, and (c) 15 m above ground level at the study site.

A key challenge in assessing the health risk of airborne particles is the low collection efficiency for nanoparticles (Kumar et al., 2010). Therefore, the use of advanced techniques such as dynamic light scattering (DLS) and other modern methods is recommended to better determine the proportion and characteristics of deposited, agglomerated, or aggregated nano-sized particles (Knippertz et al., 2014).

3-2 Geochemical data of dust collected at different heights in the SPHS method:

Due to the low mass concentration of fine particles, EDX analysis was used to determine elemental composition (Table 2, Figs. 6: g and h). The total silicon and calcium contents in EDX results were consistent with values obtained from coarse particles. In finer particles, a slight decrease in silica content was observed. Calcite, identified as a major phase at 6 m and a minor one at 21 m in the XRD patterns, showed a similar trend in Ca/Al ratios (Fig. 8).

Comparison of Si/Al ratios indicates that the content of Si relative to Al in all samples was significantly higher than the Earth's crust average (3.83) (Taylor and McLennan, 1995), with observed ratios ranging from 4 to 10 in this study. These elevated ratios correspond to the high quartz content in the samples. Quartz is insoluble and remains stable in the atmosphere without reacting with aerosols or gases.

Si/Al ratios typically fall between 2 and 7, reflecting mixtures of quartz and aluminosilicates, in agreement with the mineralogical results. Interestingly, these trends were not reported in previous studies (Scheuvens et al., 2013).

Iron content was higher in coarse particles up to a height of 18 meters. In most samples, Fe/Al and Ca/Al ratios were also higher than average crustal values (Taylor and McLennan, 1995). Iron-bearing particles were often observed on the surfaces of silicate particles, possibly due to both natural processes and anthropogenic activities.

Magnesium content was similar to that of the Earth's crust, and based on the geo-accumulation index and enrichment factor (Menhaje-Bena et al., 2021), the site soil is not contaminated with magnesium.

These geochemical results can provide insight into the weathering, alteration, and atmospheric mixing processes affecting mineral dust and its interaction with other pollutants.

Table 2. Changes in the ratios of Si, Ca, Mg, and Fe to Al in total particles based on EDX analysis at different sampling heights (21 m, 18 m, 15 m, 12 m, 9 m, and 6 m).

Height	21m	18m	15m	12m	9m	6m
Si/Al	4.37	4.21	5.28	4.26	4.93	5.52
Ca/Al	1.86	2.05	2.47	1.78	2.09	2.87
Mg/Al	0.17	0.24	0.13	0.52	0.12	0.13
Fe/Al	0.70	0.51	0.79	0.56	0.78	0.81

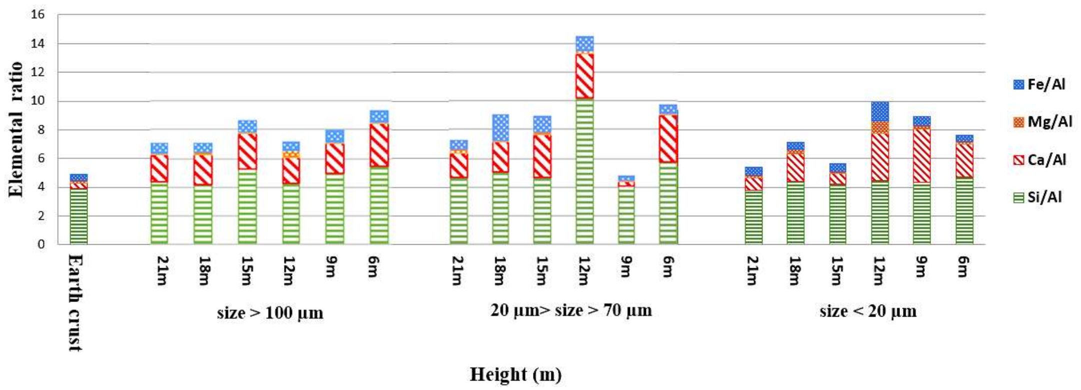


Figure 8. Comparison of elemental ratios (Si/Al, Ca/Al, Mg/Al, Fe/Al) in dust samples collected at different heights with reference values from the Earth's crust.

4. Conclusion

The size of airborne particles collected at different heights ranged from 50 nm to 100 µm. Approximately 80% of the total particles were smaller than 10 µm, small enough to penetrate the lungs as deep as the pulmonary alveoli. According to this study, mechanical processes in mining activities can increase the production of fine and ultrafine particles by up to 72%.

The Si/Al ratios of the collected dust samples were higher than the average values in the Earth's crust, which can be attributed to the mineralogical composition of the samples (e.g., quartz and albite).

A compilation of the compositional data shows that mineral dust is compositionally heterogeneous, making it very difficult (if not impossible) to define a typical dust composition across different mining sites.

The characteristic hump observed in the XRD patterns, which appears pseudo-amorphous, is attributed to severe peak broadening caused by nanocrystalline weathering products with estimated crystallite sizes below 200 nm, rather than a truly amorphous phase.

According to the literature (e.g., Knippertz et al., 2014), regional compositional trends indicate that average mineral dust from various source areas is characterized by specific features (Scheuvens et al., 2013; Formenti et al., 2011). These compositional traits, in turn, influence the environmental and human health impacts (Paltinean et al., 2016). Quartz and albite, as tectosilicate minerals and reliable indicators of mining activity in the studied region, may pose risks to the lungs (e.g., fibrosis, silicosis, and cancer), the immune system, and the kidneys through prolonged or repeated inhalation exposure. Depending on the level of exposure, periodic medical examinations are recommended (Donaldson and Borm, 2006; Knippertz et al., 2014; Menhaje-Bena et al., 2021).

5. Recommendations for Future Works

While this study provides a preliminary insight into the characteristics of dust from sand and gravel quarries around Tehran, it also highlights the need for more advanced analytical techniques to fully quantify the associated health and environmental risks. Future studies should build upon these findings by applying:

i) Quantitative X-ray diffraction methods, such as Rietveld refinement using software like *Siroquant*, to accurately determine the abundances of crystalline phases. The inclusion of an internal standard (e.g., corundum or zinc oxide) using the spiking method could also help quantify any amorphous content. This information would be critical for comprehensive risk assessments.

ii) Laser diffraction particle size analysis to provide more precise and continuous grain size distribution data.

iii) Bulk X-ray fluorescence (XRF) analysis to determine the major elemental composition of the dust.

iv) Targeted analysis of the respirable fraction (<10 μm) to accurately quantify hazardous mineral phases—especially quartz—within this critical size range. This is essential for a more complete evaluation of the health risks associated with quarrying dust.

v) Based on the results of this study, future investigations should aim to isolate the nanocrystalline fraction identified via XRD. This could be achieved through aqueous dispersion techniques, enabling the separation of cohesive ultrafine particles from larger grains. These isolated particles could then be examined using Transmission Electron Microscopy (TEM) or Atomic Force Microscopy (AFM) to gain detailed insights into their mineralogy, morphology, and surface properties. Such investigations would provide valuable information on the most environmentally and biologically reactive fractions of quarry dust.

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