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Concentration, sources and health effects of silica in ambient respirable dust of Jharia Coalfields Region, India

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Abstract

Background: The concentration of silica in occupational conditions is well defined and estimated around the world. Many countries in the world have developed air standards for occupational conditions based on the percent silica in ambient air. This is due to the pulmonary effect caused by silica yielding diseases like silicosis and pneumoconiosis. In India, occupational exposure to silica dust is regulated by Directorate General of Mine Safety (Tech.) (S&T) Circular No. 1 of 2004 Under Reg. 123 of Coal Mines Regulations, 1957 for any metal/non-metal mining operations estimated gravimetrically. As no silica standards are prescribed in India for non-occupational conditions, venturing into such analysis was well envisaged and perceived.

Methodology: Air sampling was done at identified locations through high-volume samplers for 24 h, twice a week in pre-monsoon season (March to June) and the Whatman filter paper was sonicated at sufficient speed to isolate dust particles for energy dispersive X-ray.

Results: The percentage of silica in "PM_{10}" was found lowest in mining sites (15%), and highest in transportation sites (35%) and mid-value for mixed sites (24%). Thus, risk level gets magnified due to addition of finer dust generated in transportation and mixed sites than mining due to diesel driven vehicles. Burning of any fossil fuel generates high percentage of finer dust (< 2.5 µm).

Conclusions: There should be proper prescribed standard for silica for non-occupational conditions.

Keywords: Silica, Toxicity, Jharia coalfield, Mining, Non-occupational

Background

Crystalline silica occurs abundantly in nature and is referred as free silica (SiO_2, CAS No. 7631-86-9) due to its unreactive state. Quartz, crystobalite, tridymite, and tripolite are the combined forms available in nature. They may be chemically similar but structurally different. Crystobalite and tridymite are seen in volcanic ash due to high temperature [1] and are very rare in industrial samples [2].

Silica is known far and wide for its toxic effects. It has been classified as an active carcinogen by National Institute for Occupational Safety Health [2], International Agency for Research on Cancer [3], and the U.S. National Toxicology Program [4]. An exposure time and the state of silica decides the endeavoured risk of silica [3]. Numerous studies have found carcinogenic effects of silica in the work-zone area. Lung cancer is prominently seen in marble, glass and metal industries, a glaring storehouse of quartz-generating source [3].

Jharia coalfields (JCF) region possess abundant of coal mining and metal industries. The sites selected were dominated either by coal mining (mining), vehicle movement (transportation) or mixed. Along with mining, a lot

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of ancillary units such as iron ore processing, brick kilns, smokestacks, stone crushers, geogenic blasting, unpaved roads, building construction and other fugitive sources of air emissions were also present.

Silicosis in India

Saiyed and Tiwary [5] reviewed the occupational health research carried out in India. National Institute of Occupational Health, Ahmedabad, did some excellent studies on different industries (Table 1). Out of all, silicosis is the most prominent.

Mukherjee et al. [18] has studied the silica effects in coal mining areas of eastern India (Table 2). The highest percent of samples containing silica is in OC mining followed by long wall and board and pillar methods. Abundance of OC operations for coal mining are the major source of ambient dust generation in JCF. Altogether 19 OC coal mines are presently in operations in JCF [19]. Most of them cross the threshold value of 3 mg/m^3 limits of dust generation. The drilling, blasting, crushing, screening, transportation, pulverization, galvanizing, metallic processes, etc., leads to generation of lot of dust and resultant silica in the atmosphere.

Table 1 Prevalence of some of the occupational lung diseases studies carried by the National Institute of Occupational Health [5]

Industry	Morbidity	Prevalence (%)
Slate pencil [6]	Silicosis	54.5
Agate polishing [7]	Silicosis	38
Stone quarries [8]	Silicosis	21
Potteries [9]	Silicosis	15.2
Stone crushing [10]	Silicosis	12
Coal mines [11] (U/G)	Coal workers' pneumoconiosis	2.84
Coal mines [11] (U/G)	Other respiratory morbidities	45.4
Coal mines [11] (OC)	Coal workers' pneumoconiosis	2.1
Coal mines [11] (OC)	Other respiratory morbidities	42.2
Asbestos mine and mill [12]	Asbestosis	11
Asbestos textile workers [13]	Asbestosis	9
Asbestos cement [14]	Asbestosis	3–5
Textile mills (blow room) [15]	Byssinosis	30
Textile mills (card room) [15]	Byssinosis	38
Jute mills [16, 17]	Byssinosis and other chronic obstructive lung diseases	48.8

U/G, underground; OC, opencast

Table 2 Free silica content (%) in air-borne mine dust and the method of working [18]

Mining method	No. of samples	Min.	Max.	Mean	% of samples, > 5% silica
Board and pillar	29	0.1	04.6	1.2	Nil
Long wall (2 mines)	8	0.4	12.5	2.7	12.5
Open cast (2 mines)	16	1.1	17.4	5.3	25

Bhagia et al. [20] has described non-occupational exposure effects of silica dust in different industries such as sand quarry, slate pencil industry, agate industry and their possible effects (Table 3). The air dust contained a sufficient amount of silica, and their exposure time and levels decide the occurrence of silicosis.

Kumari et al. [21] has described the mean exposure level of quartz in coal mining (JCF) and metal mines such as Zn and Mn with comparative health risks as per Indian and US standards. The related health risks are minimal in coal mines and highest in zinc mines due to higher percentage of quartz in dust samples (Table 4). The highest quartz for zinc mines is 88.2% while in manganese mines, it is 62.3%. The lowest is negligible in both the mines. Coal mines have a relatively much less quartz percentage. Thus, the quartz concentration and exposure time decide the prevalent risk levels of silicosis. Apparent deaths were seen at the marble and chips workings in Kota, Jaipur, Alwar, etc., in Rajasthan, India [22].

Materials and methods

Location

The Jharia Coalfields Region spreads between 23°49′0.63″ N to 23°38′36.50″ N latitude and 86°08′49.91″ E to 86°25′54.92 E longitude covering nearly 393 sq. kms in area IV of Bharat Coking Coal Ltd. (BCCL), a subsidiary of Coal India Ltd. in Dhanbad District of Jharkhand, India (Fig. 1 and Table 5). The area comprised mostly OC coal mines, washeries, coke-ovens, brick kilns, stone crushers along with thermal power plants. Red lateritic to alluvium is the dominating soil types with minimal organic nutrients. Gondwana superstratum lies below the soil cover embedded with coal deposits. Archean rocks with sandstone of fine-to-medium texture, micaceous shale, siltstones and strata containing coal deposits are found. The site is selected based on population exposed to the dust containing silica.

The district represents tropical climate with very warm summer (March to June) and very cold winter (November to February). The lowest temperature during summer is 15 °C in March, and highest of 46 °C during June.

Table 3 Non-occupational exposure of silica dust near various industries [20]

Industry	Location	PM_{10} quartz conc. (µg/m^3)	Mean quartz content
Sand quarry	Exposed (vicinity)	1.22	6–7
Slate pencil industry	Exposed (vicinity)	49.15 (10)	15–18.79
	Control (away)	3.51 (5)	2.91
Agate industry	Exposed (vicinity)	15.28 (20)	5.61
	Control (away)	3.03 (14)	1.87

Figures in the parenthesis indicate number of samples

PM_{10}, particulate matter less than 10 µm

Table 4 Dust and quartz concentration in different mines and their associated health risk [21]

Area	Dust conc. (mg/m^3)	% quartz in dust	MEL (mg/m^3) India	MEL (mg/m^3) US	Health risk
JCF	0.26–2.37	Trace-0.8	3	2	Low-V.V.H
Zn mines	0.22–15.88	Trace-88.2	Trace-3	0.11–3.57	Low-V.V.H
Mn mines	0.14–9.90	Trace-62.3	0.24–3	0.15–2	Low-V.V.H

MEL, mean exposure level; V.V.H, very very high

In the winter months, a high of 35 °C in November and low of 8 °C in January is recorded. Rainy season begins in July and ends in October with 16–36 °C temperature and 36–94% RH. Rain is accompanied by thunderstorms with normal fall in temperature. Average precipitation is 1000–1200 mm from July to September with little in winter [23].

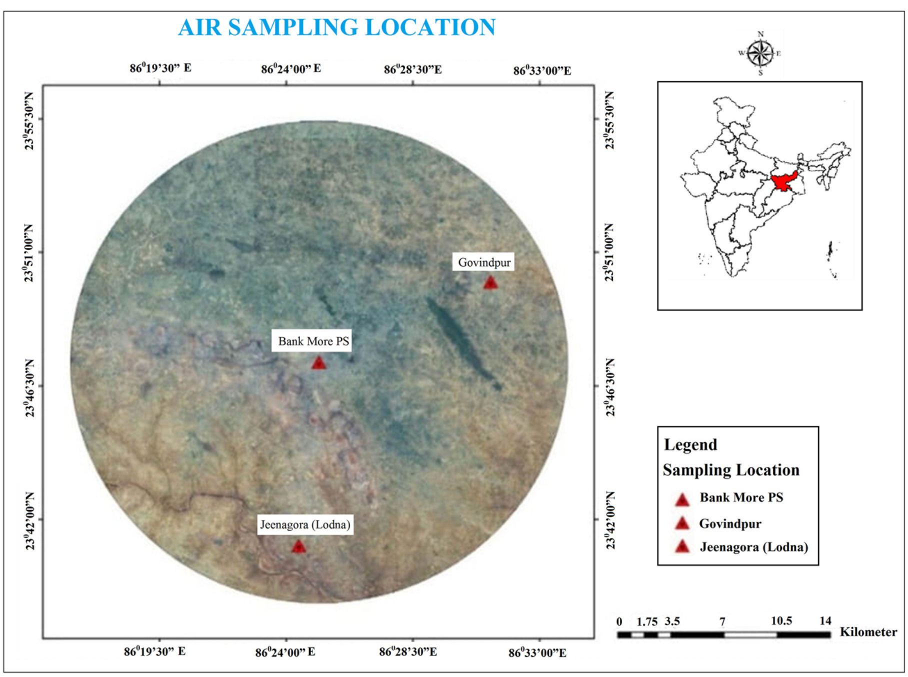

Fig. 1 Air sampling location in JCF, India

Table 5 Details of monitoring locations

Sr. no.	Location	Code	Latitude (N)	Longitude (E)	Nature
1	Bank More PS	S1	23 47′ 17″	86 25′08″	Mixed
2	Govindpur	S2	23 49′ 54″	86 31′ 10″	Highway
3	Jeenagora (Lodna)	S3	23 42′08″	86 26′235″	Mining

PS, police station

Fig. 2 A panoramic view of Bank More (S1), Dhanbad, India (18 April 2020)

Fig. 3 A panoramic view of NH19, Govindpur (S2), Dhanbad, India (5 March 2020)

Fig. 4 A view of mine-fire area at S3 [(Jeenagora (Lodna), Dhanbad, India (20 April 2020)]

Bank More police station (PS)

It is one of the busiest and heavily crowded place in the Dhanbad with rotary tri-junction (Fig. 2) at two points to Jharia, Bokaro-Ranchi, Purana Bazar and Dhanbad Rly station. Due to large marketing complex and banks, roads are narrower leading to traffic jams which sometimes continue for hours. Non-existent of parking facilities add another dimension to crowding and congestion.

Govindpur

It is an outer area of Dhanbad located at NH19 with a high population density and links with Dhanbad other part of Jharkhand like Giridih, Jamtara, Hazaribagh, Ranchi, etc. (Fig. 3). The traffic density and vehicle movement are very high; bus and auto stand aggravate the situation.

This place is on NH19 located just outside the Dhanbad township. It relates to Dhanbad through City Centre-Barwadda Road. Huge movement of commercial vehicles is observed at this place due to highway nearby. Mini market exists at both sides of the road. Fine particulate sampler was placed in a school campus.

Jeenagora (Lodna)

It is encircled by working OC mines having U/G fire all around. As per the Government order, this area must be vacated due to fire hazards and subsidence. The area has high haul road and gaseous emission, dense movement of heavy transport vehicles along with large-scale open burning of coal by the local dwellers (Fig. 4).

Principles of sampling

Air sampling at the selected locations was done through high-volume respirable dust samplers (RDS). The sampling was done for 24 h, twice in a weak for pre-monsoon season (March to June) at the identified locations in the year 2020. Total of 34 samples were collected at each location. The model Ecotech AAS 217 was used for sampling (Fig. 5). Air enters through a size-selective inlet of size 20.3 × 25.4 cm at a flow rate of 1132 L/min. Particles with aerodynamic diameter < 10 µm are deposited on the Whatman filter paper (FP) (Fig. 6) and > 10 µm in a cup. The difference in initial and final weight divided by the volume of air sampled determines the PM_{10} concentration. The sampled filter paper was sonicated in a medium at a suitable speed to remove dust particles for EDX images (Fig. 7).

Fig. 5 PM_{10} sampler (Model-Ecotech AAS 217)

Fig. 6 Whatman filter paper after 24 h of sampling (PM_{10})

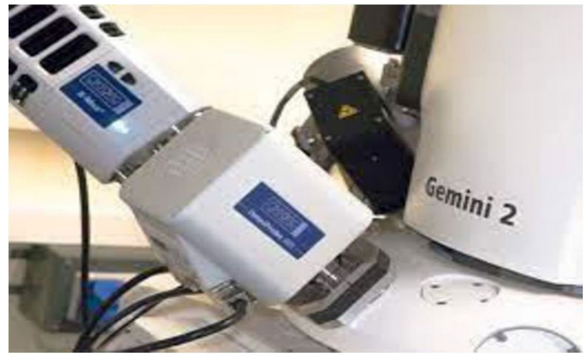

Fig. 7 EDS detector from Zeiss Merlin [24]

Table 6 Cluster sites with silica concentration (%) in PM_{10}

Site	Cluster representative	Mean silica conc. (%)
Bank More PS	Mixed	24.0
Govindpur	Transportation	35.0
Jeenagora (Lodna)	Mining	15.0

PS, police station

Table 7 Mean dust and silica conc. in PM_{10} at the selected sites

Site	No. of samples	Mean dust conc. (μg/m^3)	Mean silica conc. (μg/m^3)[a]
Bank More PS	34	406	97.44
Govindpur	34	311	108.85
Jeenagora (Lodna)	34	490	73.50

PS, police station

[a] Calculation based on % mean availability as in Table 7

Results and discussion

Silica and respirable dust

As can be seen from mean dust and silica conc. in PM_{10} (Tables 6, 7 and Figs. 8, 9) and the EDX images (Figs. 10, 11, 12), the highest percent of silica occurred in transportation (34%) and the lowest in mining (15%). Mixed cluster possessed 24%, in between the two values mentioned above. The higher percent of silica indicates high risk levels of lung infection [21]. The relationship between dust and silica concentration is not proportionate to each other (Table 7; Fig. 9). The mean dust concentration is highest with 490 μg/m^3 in mining cluster [Jeenagora (Lodna)] with lowest mean silica concentration of 73.50 μg/m^3 (15%). Similarly, the mean dust concentration is lowest in Govindpur representing

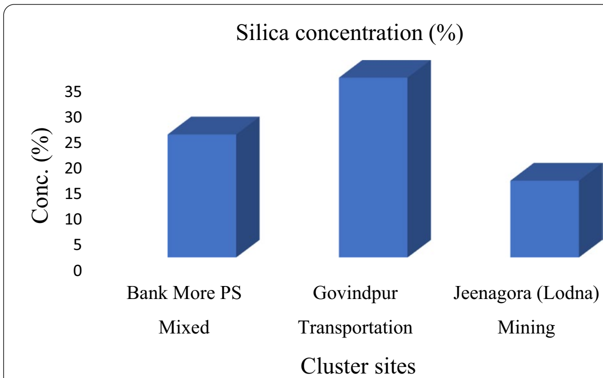

Fig. 8 Silica conc. (%) in PM_{10}

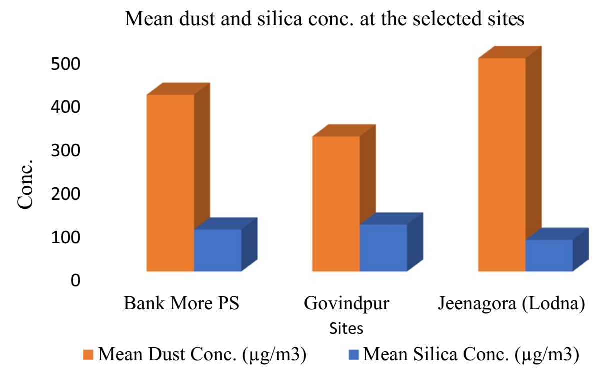

Fig. 9 Mean dust and silica conc. (µg/m^3) at the selected sites

transportation cluster with 311 µg/m^3 with highest mean silica concentration of 108.85 µg/m^3 (35%). This is attributed to the dominant activities present in the cluster concerned. Thus, the activities present in transportation cluster include building and road construction, stone chip industry, sand mining, mineral drilling, blasting, crushing, and screening, brick kilns, refractories and other geogenic sources containing quartz as the principal component while the activities present in mining cluster is represented by drilling, blasting, transportation, coal burning, pulverization, etc. The chief silica-generating source is only geogenic depending upon the rock types present in the mining area such as sandstone.

Health effects

Health effects of crystalline silica magnifies after size reduction due to wear and tear in the mineral processing and construction industries involving drilling, grinding, crushing, screening, size grading and silica particles which are of particular concern ranging between 1 and 10 µm [25] with mid-value of 5 µm which are inhalable and penetrates deep into the lungs (Fig. 13).

The health effects are generally outlined in terms of pulmonary effects referred as silicosis which reduces lung ability to take oxygen. The stages can be described as chronic, accelerated and acute. The symptoms of the first stage involve scarring with upper lung infection, while in accelerated stage observed symptom include bluish skin referred as cyanosis, chest pain, etc., [25]. Acute stage symptoms include inflamed lung with liquid exudates, shortness of breath with fatigue, weight loss and cough [25]. This can lead to tuberculosis in due course of time [25]. The detailed lung X-ray images after silicosis are shown in Fig. 14 with development of nodules after fibrosis [26].

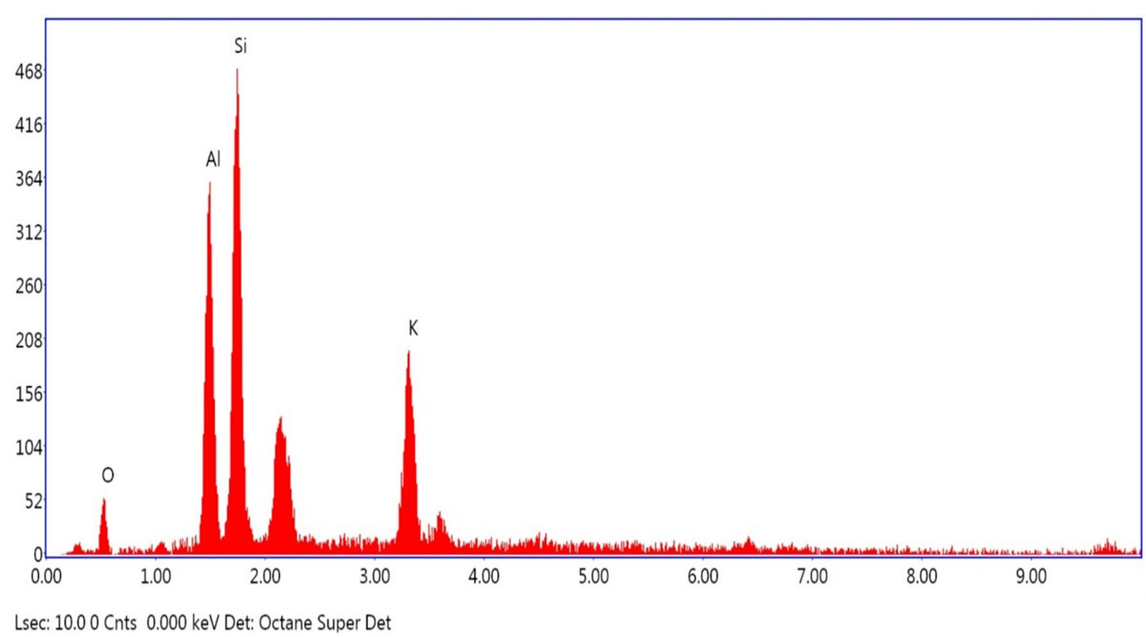

Fig. 10 EDX graph of coarse (PM_{10}) particulates of S1 (Bank More PS)

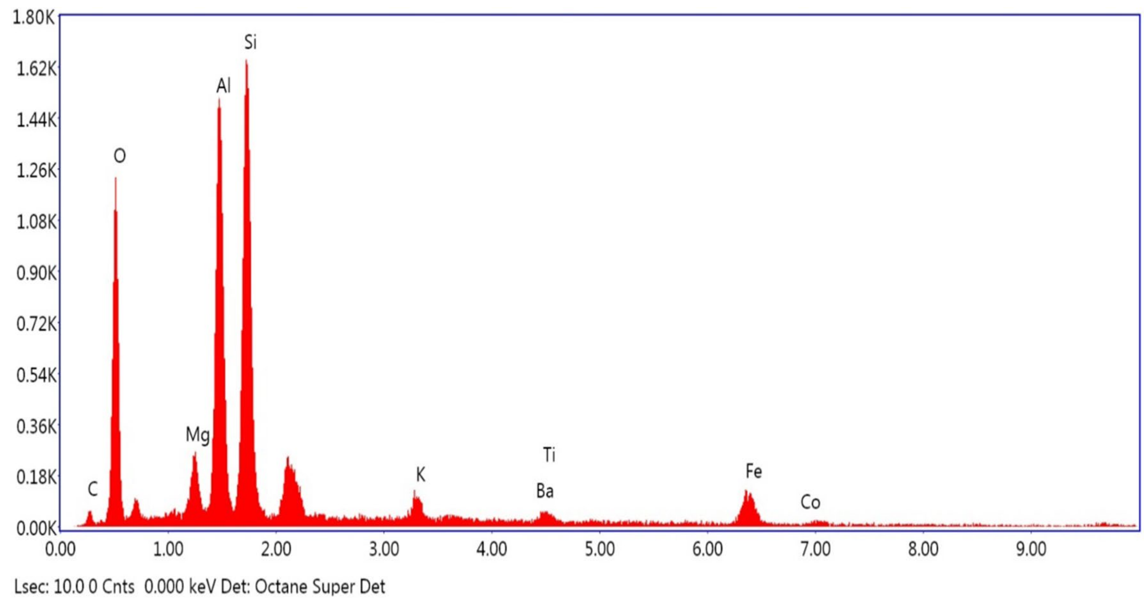

Fig. 11 EDX graph of coarse (PM_{10}) particulates of S2 (Govindpur)

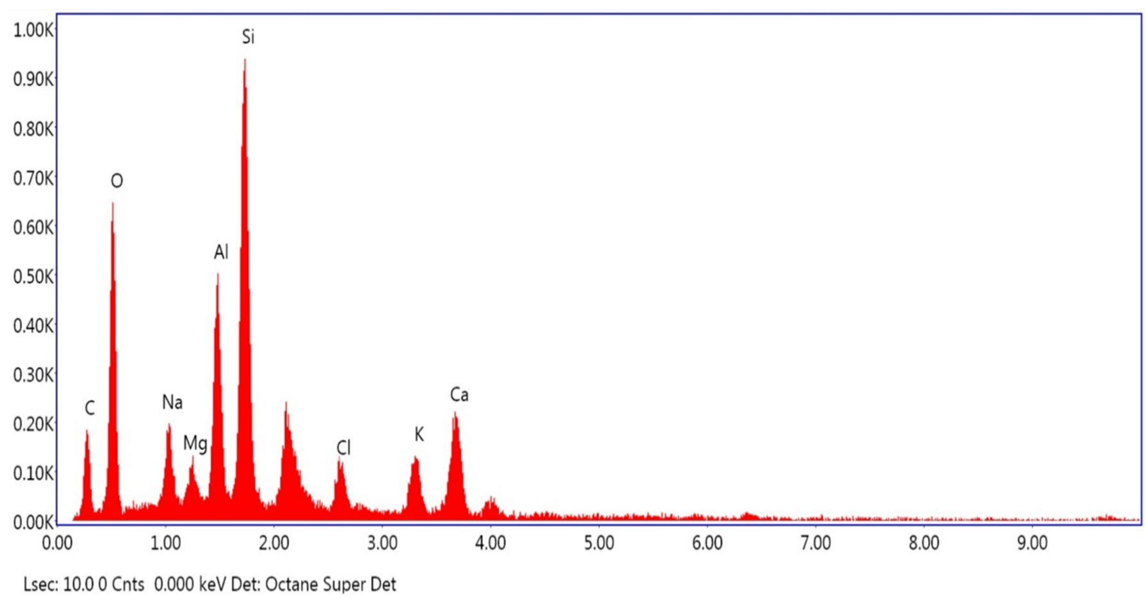

Fig. 12 EDX graph of coarse (PM_{10}) particulates of S3 [Jeenagora (Lodna)]

Standards

Respirable dust standards for coal mines in major countries of the world

Major developed countries have devised standards for respirable mine dust with percent crystalline silica as the key factor (Table 8). The standard cannot be simply compared from one country to another due to variations in sampling procedure, such as frequency, number and location [27]. Table 8 describes standards based on silica concentration in ambient dust (gravimetric) in coal mines of the various countries of the world. The chief sources include quartz (cristobalite, tridymite) in both fine and coarse dust. The proportionate values vary from one country to the other depending upon their preference on the criteria detailed above.

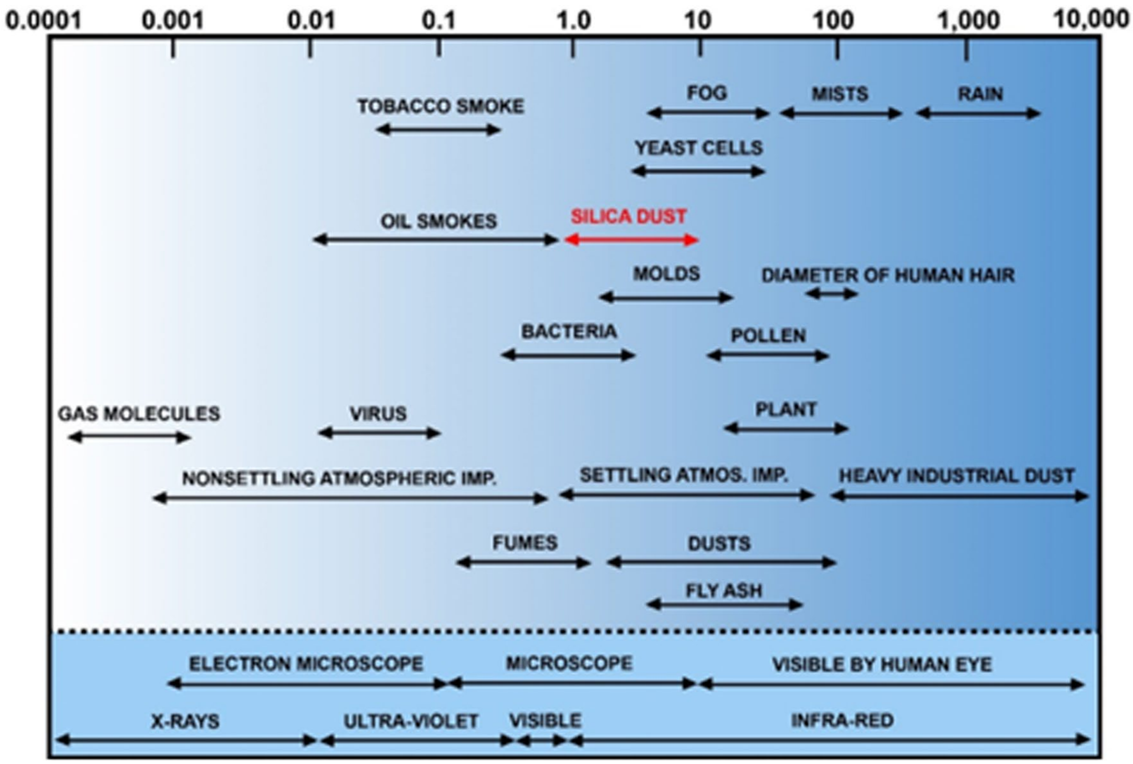

Fig. 13 Relative size chart of common air contaminants (μm) [24]

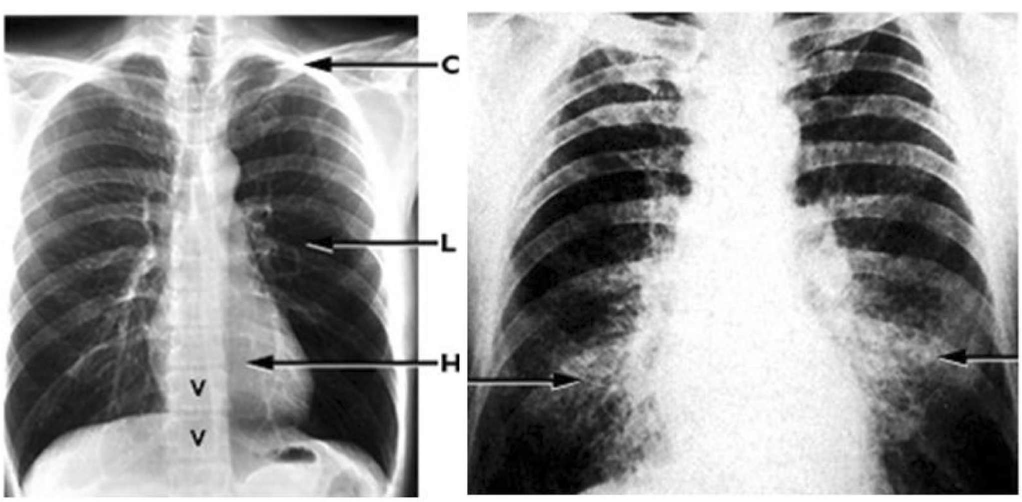

Fig. 14 **a** A normal chest X-ray, **b** and chest X-ray after silicosis. Chest X-ray after silicosis shows multiple nodules (arrows) caused by silicosis. C—collar bone; L—lungs; H—heart; V—vertebrae [26]

Table 8 Standards for respirable dust for the coal mines in major countries of the world [28]

S. no.	Country	Recommended value (gravimetric)	Comment
1	Australia[a]	3 mg/m^3	Coal dust with ≤ 5% respirable free silica
2	Belgium	10 mg/m^3 % respirable quartz + 2	
3	Brazil	8 mg/m^3 % respirable quartz + 2	
4	Finland	2.0 mg/m^3 0.2 mg/m^3 0.1 mg/m^3	Coal dust Quartz (fine dust < 5 pm) Silica: cristobalite, tridymite
5	Federal Republic of Germany[b]	0.15 mg/m^3 4.0 mg/m^3	Quartz (including cristobalite and tridymite) Fine dust containing quartz (1% or greater quartz by weight)
6	Italy	3.33 mg/m^3 10 mg/m^3 q + 3, where q = % of quartz (mass)	Coal dust with < 1% quartz Coal dust with > 1% quartz
7	Netherlands	2.0 mg/m^{3c} 0.075 mg/m^3	Coal dust (less than 5% respirable quartz) Silica: cristobalite, tridymite
8	Sweden	0.05 mg/m^3	Silica: cristobalite, tridymite
9	UK[c]	3.8 mg/m^3	Coal mine dust (average concentration at the coal face)
10	US (MSHA)	2.0 mg/m^3 10 mg/m^3 % SiO_2, 10 mg/m^3 % respirable quartz + 2 Half of the value for quartz	Coal dust with — 3% silica Coal dust with > 5% silica Silica: quartz Silica: cristobalite, tridymite
11	Yugoslavia	4 mg/m^3 0.07 × 100 mg/m^3 % FCS 0.07 mg/rn^3	Fine dust with < 2% free crystalline silica Fine dust with > 2% free crystalline silica Pure quartz (fine dust)

Source: WHO [I986] (except as otherwise noted)

[a] Source: Coal Mines Regulation Act 1982 (New South Wales); Coal Mines Regulation, Respirable Dust 1978 (Queensland)

[b] Source: German Research Institute [1992]

[c] Source: Jacobsen [1984]. Recommended value is based on maximum allowable concentration of 7 mg/m^3 in the return-airway during the working shift

Indian standard

Many countries in the world have developed standards based on the percentage silica. This is due to the pulmonary effect caused by silica. Overexposure to respirable silica dust can lead to the development of human diseases like silicosis, a debilitating and potentially fatal lung disease. In India, exposure to silica dust is limited by regulations enforced by Directorate General of Mines Safety (DGMS) (Tech.) (S&T) Circular No. 1 of 2004 Under Reg. 123 of Coal Mines Regulations, 1957 [29]. DGMS may ask for silica dust concentration in occupational conditions in any metal/non-metal mining operations through gravimetric analysis. The prescribed limit is 3 mg/m^3 for < 5% of silica in the sample. If the percent of silica in the sample exceeds 5%, then the maximum exposure limit (in h) is obtained by:

$$\frac{15}{\text{Percentage of silica}}.$$

Occupational and non-occupational guidelines for silica exposure depend on whether it is based on larger (PM_{10}) or respirable (< 5 μm) particulate size, but are certainly guided by limits developed for occupational exposures. USEPA (1996) [30] developed non-cancer limits for amorphous and crystalline silica for ambient conditions as *10% of crystalline silica contained in* PM_{10} particulates. In India, there is no prescribed limit of silica for ambient conditions as notified by NAQQS, 2009. [31] DGMS describes limits only for the occupational conditions.

As a major chunk of fine-sized particles in non-occupational ambient conditions are generated from diesel burning, atmospheric reactions involving SO_2, etc., do not adequately represent the actual respirable concentration in air. This is a very important aspect as the crystalline silica are based on percentage of silica deposited on the filter paper. The non-silica particles are proportionately high on the filter paper, thus the calculated silica % would be inaccurately high.

Most of the silica particles are > 2.5 μm in size, but are sufficiently < 10 μm. Their optimal size is around 5 μm and are predominantly respirable and can travel deep into the lungs causing swelling, scarring, fibrosis, etc. They account 0–25% and 10% proportion of the coarse (PM_{10}) particulates by number and weight, respectively, in different regions of US [32]. Accounting respirable % silica in the dust to devise standard is a very difficult task. Most of the sources of silica in JCF region are brick kilns, smokestacks, stone chip industry, drilling, crushing, geogenic blasting, unpaved roads, road and building construction and other fugitive emissions.

Statistical analysis

The statistical analysis indicates that the mean silica concentration is not proportionate to the dust concentration (Fig. 15). Thus, silica concentration in ambient dust is more related to the activities generating silica rather than dust concentration.

Conclusion

Silica content in respirable fractions of atmospheric dust is a serious issue in JCF region particularly in non-occupational areas. The effects are far and wide. Though the prevalent incidence in JCF is rare, the exposure risk is increasing due to silica-generating sources containing quartz as the principal component, such as building and road construction, stone chip industry, mineral crushing and screening, brick kilns, refractories, sand mining and other geogenic sources additive to coal mining. The transportation sites showed the highest while mining sites the lowest. The mixed sites cross the threshold level concentrations. Referring to the health risk associated, it is much above the threshold concentrations levels as per the international norms prescribed.

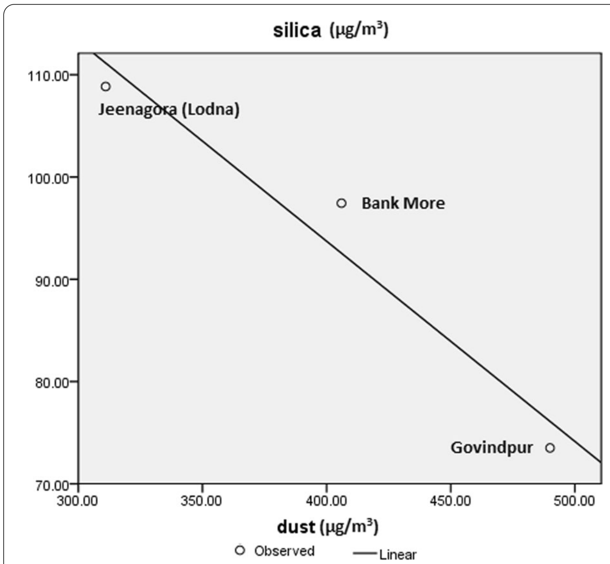

Fig. 15 Variation of mean dust & silica conc. at three selected cluster sites in JCF region

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Author contributions
Mr. RKS helped acquire field data and laboratory analysis, Dr KKS, Dr RKS and Dr SS helped in preparing the manuscript. All authors read and approved the final manuscript.

Authors information
All the authors have been informed to submit the manuscript for publication in *Environmental Sciences Europe*. The authors declare that the manuscript has not been published or submitted for publication elsewhere.

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Availability of data and materials
All data generated or analysed during this study are included in the article.

Declarations

Ethics approval and consent to participate
The study was conducted according to the National Ambient Air Quality Standards (2009), India. Institutional consent was taken as per the existing rules of Institute.

Consent for publications
Consent for publications was taken as per the approved rules of CSIR-CIMFR, Barwa Road, Dhanbad, India.

Competing interests
The authors declare they have no competing interests.

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