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Spatio-temporal variation of air pollutants around the coal mining areas of Jharia Coalfield, India

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Abstract Jharia Coalfield (JCF) is one of the oldest coalfields in the eastern part of India and falls under critically polluted areas as per CPCB/MoEFCC Notification. Therefore, a study of air pollution and its management is the demand of the day. This study had been undertaken to know the current status of JCF concerning air quality. Ambient air quality monitoring with reference to particulate matter (PM_{10} and $PM_{2.5}$), SO_2, NO_x and trace elements had been conducted in the coal mining areas of JCF. The study area was divided into two groups, mainly fire and non-fire for the sampling of air. Principal component analysis (PCA) identified coal mine fire as a major source of air pollution in the mining areas of JCF. Air quality index (AQI) was calculated which revealed that the air quality index of coal mine fire-affected areas was nearly 1.5 times higher than that of the non-mine fire areas.

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Keywords Jharia Coalfield · Particulate matter · Trace elements · Principal component analysis · Air quality index

Introduction

India ranks 177 out of 180 countries in the world with respect to environmental issues handling practices (Environmental Performance Index (EPI), 2018). According to World Air Quality Report 2018, out of the 10 highest polluted cities, 7 are present in India (Greenpeace South East Asia, 2018). Jharia Coalfield (JCF) present in Dhanbad, also known as "Coal Capital of India", shares nearly 20% of the total coal production of the country (CIL n.d.) which falls under 43 critically polluted industrial clusters with the rank 13th due to its comprehensive environmental pollution index (CEPI) value 78.63 (Central Pollution Control Board). The occurrence of coal mine fire has a prolonged background of worldwide significance and has contributed to the loss of natural resources. It also has a strong detrimental effect on ecosystem as well as human health. Coal fires are now a problem worldwide; nevertheless, they are of significant concern in Asia, USA, China, South Africa, Australia, Indonesia, Turkey and Germany (Kuenzer et al. 2007; Kuenzer and Stracher 2012). JCF in India is comprised of 23 large underground and 9 large opencast mines. Mine fire became widespread in India after 1930, with the occurrence of several major fires in JCF and RCF (Raniganj coalfield) (BCCL 1991; Pandey et al. 2016). At present, more than

40 coal mines at 80 locations, covering an area of 10 km^2, are experiencing active coal mine fire in JCF (NRSA 2006; CMPDIL, 2008). JCF fire is known to be one of the most challenging coal mine fire in the country which occurs as a result of spontaneous heating or endogenous coal fires, which rely on different mining, geological and environmental factors (Song et al. 2014). A number of physico-chemical processes are responsible for spontaneous combustion of coal seams and associated strata, such as temperature increase, mineral oxidation, smoke emission, changes in rock colour, formation and deposition of new materials on the surface and subsidence on the surface with multiple cracks (Guan and Van Genderen 1997; Zhang et al. 2004).

Mining activities are the leading cause of air pollution directly or indirectly in the coal mining areas (Baldauf 2001; Collins et al. 2001). Drilling, blasting, loading and unloading of coal, active and excessive coal mine fire hotspots, contribute significantly to air pollution (Ghose and Majee 2000a). Apart from these, mining and its associated activities like proximity to a railway siding, open burning of coal and heavy vehicular load are the major reasons for higher concentration of air pollutants around JCF (Dubey et al. 2012; Singh et al. 2014; Yadav et al. 2019). These sources ultimately lead to an increase in the concentration of particulate matter (Patra et al. 2016) and gaseous pollutants (SO_2 and NO_x) in the surrounding areas of coal mines (Tripathi and Gautam 2007) which adversely affect ambient air quality and thereby threaten the life of humans residing close to those areas (Gautam et al. 2016). Particulate matter has been considered group I contaminants by the International Agency for Research on Cancer (IARC 2013), and they are the conveyor of several trace elements such as As, Cd, Cr, Cu, Zn, Pb and Ni into the ambient air (Brunekreef and Holgate 2002).The trace elements are a small fraction of the total particulate matter (PM) mass, but they are sufficient to damage human health (Jena and Singh 2017). Trace elements concomitant as respiratory particles are found to increase heart and lung-related injuries in humans (Lee et al. 2005; Shaheen et al. 2005). Thus, trace elements are responsible for a wide variety of health issues. Previous studies have indicated that Pb and Cd could be probable carcinogens in human. In addition to carcinogenic outgrowth, Pb induces kidney failure, neuropathy and encephalopathy (ASTDR 1993; USEPA 1990), and Cd also interferes with proper kidney function (Park et al. 2004). Cr causes lung cancer (Mancuso 1975), skin ailments (Afridi et al. 2011; Pedersen 1982) and shows both teratogenic and human carcinogenic effects (Cr (VI)) (Danielsson et al. 1982; Iijima et al. 1983; Matsumoto et al. 1976). The toxicity of the elements and their obstinate existence makes it a primary concern for research (Hall 2002). Previous investigations carried out across the globe have revealed the composition of trace elements in atmospheric particulate matter (PM_{10}) (Abulude et al. 2003; Banerjee 2003; Bhuyan et al. 2010; Feng et al. 2009; Karar et al. 2006; Leili et al. 2008; Limbeck et al. 2009; López et al. 2005; Senlin et al. 2007). Since trace elements share a correlation with various sources of anthropogenic origin, the trace elements have been used as a tracer to define the source of PM in various studies (Birmili et al. 2006; Weckwerth 2001). Trace elements have found application in various source apportionment studies (Basha et al. 2014; Roy et al. 2012; Gummeneni et al. 2011; Meena et al. 2016; Pathak et al. 2013; Shridhar et al. 2010). The JCF in Dhanbad has also been contaminated by several airborne heavy metals in the order of Fe > Cu > Zn > Mn > Cr > Cd > Pb > Ni due to its several mining activities, soil dust re-suspension, biomass burning and heavy transportation load (Dubey et al. 2012; Roy et al. 2012; Pandey et al. 2014). In Jharia coal mining areas of Dhanbad, several studies have been done which revealed that Dhanbad not only falls under critically polluted areas but also serves as cancer-prone area due to its chronic exposure to poor air quality caused by the active coal mine fire in the JCF (Roy et al., 2017). This study had been undertaken to estimate the ambient air quality concerning PM_{10}, $PM_{2.5}$, SO_2, NO_x and PM_{10}-bound trace elements in the mine fire-affected and non-mine fire coal mining areas of Jharia Coalfield as well as to identify the possible sources of these atmospheric pollutants.

Materials and methods

Study area and its monitoring locations

JCF is located in the heart of the Damodar River Valley in the district of Dhanbad, Jharkhand, India. It is situated approximately 260 km northwest of Kolkata and 1150 km southwest of Delhi. JCF is limited between 23° 38′ 00″ N–23° 52′ 00″ N latitude and 86° 08′ 00″ E–86° 30′ 00″ E longitude. It stretches 38 km from east to

west and 19 km from north to south, covering a geographical area of 450 m^2 (380 km^2 coal-bearing area).

A total of nine monitoring locations were selected based on coal mine fire and non-fire areas in JCF and depicted in Fig. 1 and discussed in Table 1 (as per sampling criteria IS: 5182 Part XIV). Monitoring at IIT (ISM) Dhanbad Campus was done as background site.

Monitoring frequency

The monitoring had been conducted on three consecutive seasons, i.e. summer, post-monsoon and winter. The monitoring for PM_{10}, $PM_{2.5}$, SO_2 and NO_x was done twice a week (for 24 h) at uniform intervals and for the trace elements (Pb, Zn, Cd, Cr, Mn, Cu, Fe and Ni) was done once in a month during the monitoring period. The details of the instruments and methods used for sampling and analysis are given in Table 2.

Results and discussion

Concentrations of particulate matter and gaseous pollutants

The ambient air concentrations of PM_{10}, $PM_{2.5}$, SO_2 and NO_x were monitored at nine sites of JCF and one reference site on three consecutive seasons, i.e. summer, post-monsoon and winter. The concentration levels of PM_{10}, $PM_{2.5}$, SO_2 and NO_x at ten selected monitoring locations during summer, post-monsoon and winter seasons are presented in Fig. 2. The results revealed a significant variation in pollutant concentrations (PM_{10}, $PM_{2.5}$, SO_2 and NO_x) in mining areas (mine fire and non-mine fire area) and institutional area in all the seasons.

The maximum PM_{10} concentration (547 μg/m^3) was recorded at Lodhna Police Station (PS) (S3) during the winter followed by Tetulmari PS (S1) (532 μg/m^3), Jogta 14 Pit (S7) (520 μg/m^3), Bastacolla Colliery (S5) (513 μg/m^3), Kujama Colliery (S9) (503 μg/m^3), Katras (S8) (436 μg/m^3), Kenduadih PS (S4), (424 μg/m^3), Loyabad PS (S2) (413 μg/m^3), Sijua Stadium (S6) (397 μg/m^3) and IIT (ISM) Campus (S10) (82 μg/m^3) (Fig. 2a). The concentration of PM_{10} in the ambient air of the ten selected sites varied between 0.71 and 547 μg/m^3 being minimum and maximum at Lodhna PS and IIT (ISM) Dhanbad respectively.

The observed $PM_{2.5}$ values of the studied sites were found in the range of 45 μg/m^3 to 326 μg/m^3 during winter (Fig. 2b). The ambient air of Lodhna PS and IIT (ISM) Dhanbad Campus exhibited the highest and lowest concentration of $PM_{2.5}$ respectively during the period of monitoring. The concentrations of $PM_{2.5}$ in the ambient air varied between 45 and 326 μg/m^3 during

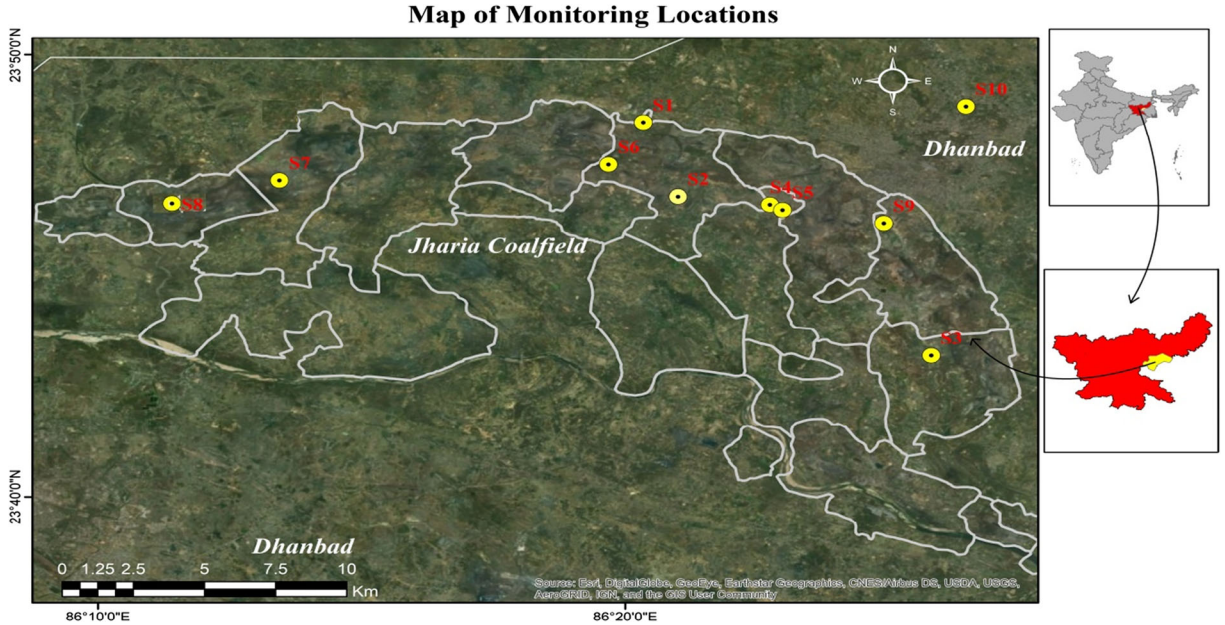

Fig. 1 Map of the study area depicting monitoring locations

Table 1 Studied sampling sites and their characteristics

Location ID		Monitoring sites	Latitude	Longitude	Description
S1	Mine fire area	Tetulmari PS	23.808° N	86.339° E	Tetulmari Police Station (PS) is present adjacent to opencast (OC) coal mine Katrasgarh, which is affected by mine fire.
S2	Non-mine fire area	Loyabad PS	23.780° N	83.350° E	Loyabad PS is present near the Loyabad (OC) coal mine which is not affected by mine fire.
S3	Mine fire area	Lodhna PS	23. 720° N	86.430° E	Lodhna PS is present just beside the Goluckdih opencast (OC) coal mine, which is affected by mine fire; Sudamdih Coal Washery is also present nearby.
S4	Non-mine fire area	Kenduadih PS	23.777° N	86.379° E	Kenduadih PS is present adjacent to Kusunda (OC) coal mine which is not affected by mine fire.
S5	Mine fire area	Bastacolla Colliery	23.775° N	86.383° E	This site is located near the Ghanoodih (OC) coal mines, which is affected by mine fires; coke-oven plants present at the vicinity.
S6	Non-mine fire area	Sijua Stadium	23.792° N	86.328° E	This site is located near the Sandra Bansjora (OC) coal mine, where mine fire is now under control.
S7	Mine fire area	Jogta 14 Pit	23.786° N	86.224° E	Jogta 14 Pit is present adjacent to Jogta (OC) coal mine which is affected by mine fire.
S8	Non-mine fire area	Katras	23.775° N	86.193° E	Katras has Salanpur opencast (OC) coal mines which are not affected by mine fire.
S9	Mine fire area	Kujama Colliery	23.770° N	86.415° E	This site is present near the Jealgora Colliery which is suffering from both underground (UG) and opencast (OC) mine fire.
S10	Reference	IIT (ISM) Campus	23.814° N	86.441° E	Used as a reference station as isolated from any industrial activities.

winter, 37 and 275 μg/m^3 during summer and 25 and 165 μg/m^3 during post-monsoon. Lodhna PS (S3) is located at a distance of 2.2 km from Goluckdih opencast (OC) coal mine, experiencing highest concentration of particulate matter in all three seasons (445 ± 63 μg/m^3 in summer, 375 ± 42 μg/m^3 in post-monsoon and 547 ± 59 μg/m^3 in winter respectively). Similarly, Tetulmari PS (S1), Bastacolla Colliery (S5), Jogta 14 Pit (S7) and

Table 2 Sampling instruments used during monitoring and the methods of analysis

Pollutants—particulate matter and gaseous pollutants	Instruments used for monitoring	Method of analysis	Detection limit
Particulate matter as PM_{10}	Respirable dust sampler (RDS) (Envirotech APM 460 NL)	Gravimetric method (CPCB 2012).	(10 μg/m^3 to 1000 μg/^{3})
Particulate matter as $PM_{2.5}$	Fine particulate sampler (FPS) (Envirotech APM 550 MFC)	Gravimetric method (CPCB 2012).	(5 μg/m^3 to 1000 μg/m^3)
Sulphur dioxide as SO_2	RDS with thermo-electrically cooled gaseous sampler (Envirotech APM 411 TE)	Improved West and Gaeke method (CPCB 2012).	(4 μg/m^3 to 200 μg/m^3)
Oxides of nitrogen as NO_x	RDS with thermo-electrically cooled gaseous sampler (Envirotech APM 411 TE)	Jacob and Hochheiser modified method (CPCB 2012).	(7 μg/m^3 to 200 μg/m^3)
Pollutants—trace elements	Instruments used for monitoring	Method of analysis	Below detection limit
Fe, Zn, Cu, Mn, Ni, Cd, Cr, Pb	Respirable dust sampler (RDS) (Envirotech APM 460 NL)	Samples of PM_{10} collected in EPM 2000 Filter Paper → filter papers digested through HNO_3 and HCL in microwave digester → filter the extracted fluid with Whatman Filter Paper No. 42 → analysed in AAS (GBC Avanta PM, Australia) (CPCB 2012).	(0.001 μg/m^3)

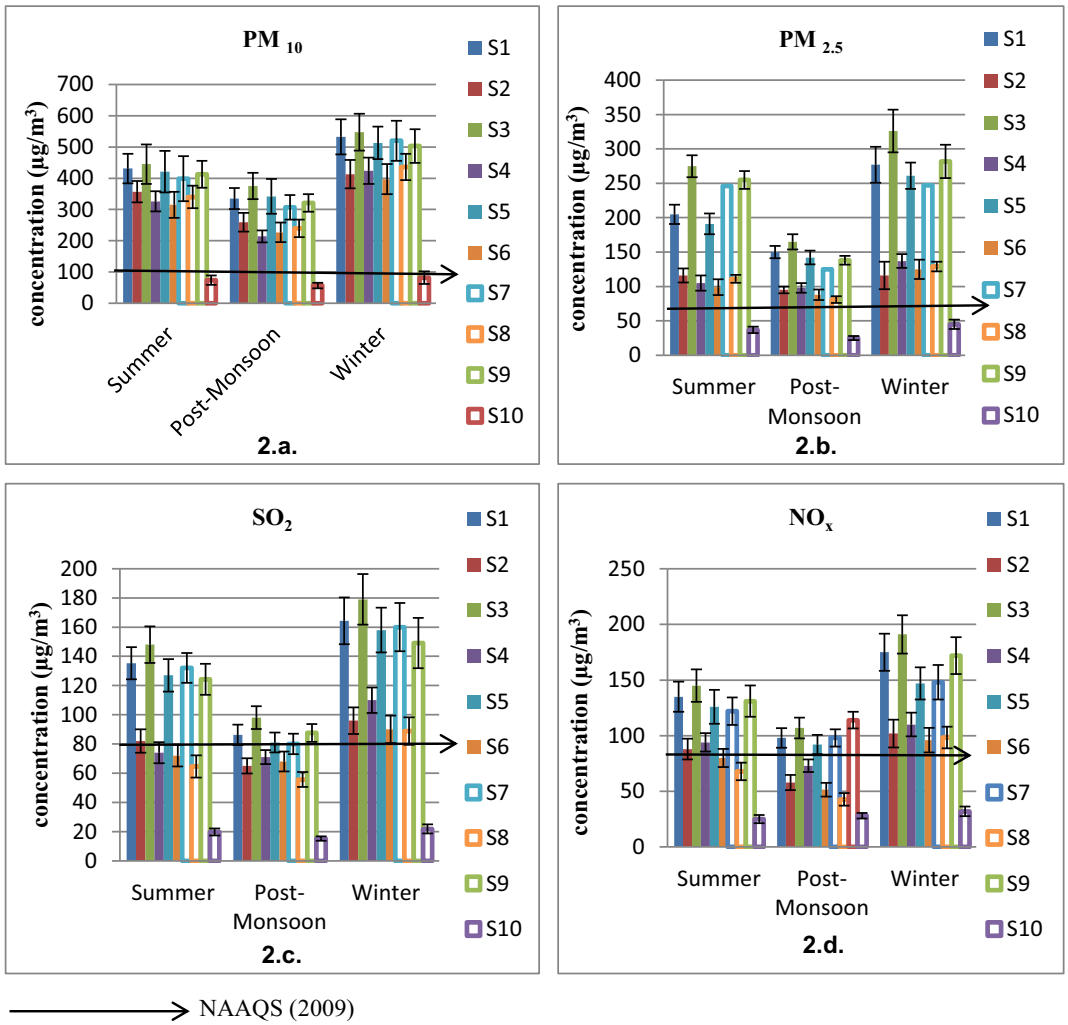

Fig. 2 Seasonal variation in concentration (µg/m^3) of PM_{10} (**a**), $PM_{2.5}$ (**b**), SO_2 (**c**) and NO_x (**d**) at ten monitoring sites

Kujama Colliery (S9) experienced higher levels of particulate matter due to the active coal mine fire and other mining activities like crushing, grinding and abrasion of surfaces and also due to evaporation of sprays and re-suspension of dusts. Spontaneous combustion and unscientific exploitation of coal and other exogenous factors lead to the self-ignition of coal, which causes active coal mine fire in the coal mining areas and ultimately leads to the emission of particulate matter to a significant level. Average concentrations of PM_{10} were found maximum in the ambient air of Lodhna PS (S3) (455.67 µg/m^3) during the whole period of monitoring, followed by Tetulmari PS (S1) (432.67 µg/m^3), Bastacolla Colliery (S5) (425.33 µg/m^3), Kujama Colliery (S9) (412.33 µg/m^3), Jogta 14 Pit (S7) (408.67 µg/m^3), Loyabad PS (S2) (343 µg/m^3), Katras (S8) (338.67 µg/m^3), Kenduadih PS (S4) (321.33 µg/m^3), Sijua Stadium (S6) (313 µg/m^3) and IIT (ISM) Dhanbad Campus (S10) (71 µg/m^3). The ambient air of Lodhna PS (S3) also exhibited maximum average concentration of $PM_{2.5}$ (255.33 µg/m^3) during the monitoring period followed by Kujama Colliery (S9) (225 µg/m^3), Tetulmari PS (S1) (210.67 µg/m^3), Jogta 14 pit (S7) (206 µg/m^3), Bastacolla Colliery (S5) (198 µg/m^3), Loyabad PS (S2) (109 µg/m^3), Katras (S8) (107 µg/m^3), Sijua Stadium (S6) (104 µg/m^3) and IIT (ISM) Campus (S10) (35.67 µg/m^3). The concentration levels of particulate matter at Loyabad PS (S2), Kenduadih PS (S4), Sijua Stadium (S6) and Katras (S8) which are coal mining areas of JCF but not affected by mine fire were comparatively lower than the coal mining areas suffering from mine fire. The concentration of $PM_{2.5}$ was

found to be very concerning when compared with the permissible limits given by the National Ambient Air Quality Standards (NAAQS 2009) (Masih et al. 2019).

On an average, the concentration of particulate matter in post-monsoon as well as in summer and winter season remained almost the same (Fig. 2 a and b) because particulate matter once generated in summer or winter remains within the atmosphere for a long time following a non-linear process, and atmospheric precipitation in the monsoon does not seem to be effective for removing those particles from the atmosphere.

All the monitoring sites except the reference site (S10) had exceeded the value of NAAQS (2009) for particulate matter by a factor of 4.33 (S1), 3.43 (S2), 4.56 (S3), 3.21 (S4), 4.25 (S5), 3.13 (S6), 4.09 (S7), 3.39 (S8) and 4.12 (S9) respectively for PM_{10} and by a factor of 3.51 (S1), 1.82 (S2), 4.26 (S3), 1.89 (S4), 3.30 (S5), 1.73 (S6), 3.43 (S7), 1.78 (S8) and 3.53 (S9) respectively for $PM_{2.5}$.

According to the mechanism of pollutant dispersion, the topography and meteorological factors of the monitoring sites, the concentration level of particulate matter gets affected (Charron and Harrison 2005). So, the particulate matter (PM) during winter remained concentrated near the emitting source of the pollutants and did not dispersed at a greater distance due to lower temperatures and lower wind speed. On the other hand, higher wind speed and higher pollution dispersion were the major reason for comparatively lower atmospheric pollutants in summer. Particulate matter during the post-monsoon season got influenced by high relative humidity and washout by atmospheric precipitation, which reduced their concentration level during this season to some extent.

Apart from the particulate pollutants, a substantial variation in the spatial distribution of gaseous pollutants was also observed in the monitoring sites. There were significant variations in the concentration level of gaseous pollutants (SO_2 and NO_x) at the selected monitoring sites of Jharia Coalfield.

The ambient air SO_2 concentrations were estimated in the range of 18.90 μg/m^3 to141.67 μg/m^3. Out of all the selected monitoring sites, the ambient air of Lodhna PS (S3) experienced the highest concentration of gaseous pollutants (SO_2 and NO_x) during the whole monitoring period (Fig. 2 c and d) (Supplementary Table A) because of the presence of surface and underground coal mines adjacent to the site which were highly affected by mine fire. Besides, four other sites like Tetulmari PS (S1), Bastacolla Colliery (S5), Jogta 14 pit (S7) and Kujama Colliery (S9) were present adjacent to coal mines affected by mine fire. Coal washeries and coke-oven plants were also present in the vicinity. These sites showed higher concentrations of gaseous pollutants (SO_2 and NO_x) which adversely contaminated the ambient air quality. In these coal mines, sulphur-rich coal releases sulphur dioxide into the atmosphere when it comes in contact with oxygen due to various mining activities or tectonic motions. At the same time, the coke-oven plants also release huge amounts of partially oxidized nitrogen by supplying oxygen to produce lesser by-products. These were the main reasons for the elevated level of gaseous pollutants in the monitoring sites like Lodhna (S3), Tetulmari PS (S1), Bastacolla Colliery (S5), Jogta 14 Pit (S7) and Kujama Colliery (S9). So, the emission of elevated levels of SO_2 and NO_x was an indicator of the higher level of pollution in the mining areas affected by mine fire. The concentration of gaseous pollutants was higher at all sites in winter in comparison with summer and post-monsoon seasons due to lower atmospheric dispersion of pollutants during winter.

Air quality of reference site IIT (ISM) Institutional Campus (S10) came under a satisfactory level (refer to Table 3) because it was devoid of any such mining or other industrial activities and is surrounded by Green Belt. Therefore, the concentration of pollutants was minimum in all three seasons monitored. All sites except the reference site (S10) showed a much higher concentration of gaseous pollutants than the NAAQS (2009) permissible limit.

Average concentration levels of SO_2 were observed highest during the monitoring period at Lodhna PS (S3) (141.67 μg/m^3), Tetulmari PS (S1) (128.63 μg/m^3), Jogta 14 Pit (S7) (124 μg/m^3), Bastacolla Colliery (S5) (122 μg/m^3), Kujama Colliery (S9) (120.33 μg/m^3), Kenduadih PS (S4) (85 μg/m^3), Loyabad PS (S2) (81 μg/m^3), Sijua Stadium (S6) (76.67 μg/m^3), Katras (S8) (69.67 μg/m^3) and IIT (ISM) Dhanbad Campus (S10) (18.90 μg/m^3). The concentration levels of NO_x in ambient air were seen highest at Lodhna PS (S3) (147.67 μg/m^3) followed by Kujama Colliery (S9) (139 μg/m^3), Tetulmari PS (S1) (136 μg/m^3), Jogta 14 Pit (S7) (122.67 μg/m^3), Bastacolla Colliery (S5) (121.67 μg/m^3), Kenduadih PS (S4) (92.33 μg/m^3), Loyabad PS (S2) (82.67 μg/m^3), Sijua Stadium (S6) (75.83 μg/m^3), Katras (S8) (69.63 μg/m^3) and IIT (ISM) Campus (S10) (28.42 μg/m^3).

Table 3 Air quality index of the studied monitoring sites

Location ID	AQI values	Predominant Pollutant	AQI Category	Colour Code
S1	401.61	PM_{10}	Severe	
S2	293.00	PM_{10}	Poor	
S3	406.91	PM_{10}	Severe	
S4	277.23	$PM_{2.5}$	Poor	
S5	394.14	PM_{10}	Very poor	
S6	263.00	PM_{10}	Poor	
S7	373.23	PM_{10}	Very poor	
S8	288.67	PM_{10}	Poor	
S9	380.81	$PM_{2.5}$	Very poor	
S10	71.00	PM_{10}	Satisfactory	

Dhanbad has a tropical climatic pattern with lowest temperature (on an average 17 °C), lower sunlight and lower wind speed (on an average 2 km/h) during winter which causes poor dispersion of pollutants. So, the concentration of NO_x was found highest in winter in comparison with summer and post-monsoon. Elevated levels of NO_x in six mining sites may also be attributed due to the occurrence of active coal mine fire, vehicular transport of coal on heavy vehicles and other mining activities like drilling and blasting.

Overall, it has been recorded that at the monitoring sites of mine fire areas, i.e. Tetulmari PS (S1), Lodhna PS (S3), Bastacolla Colliery (S5), Jogta 14 Pit (S7) and Kujama Colliery (S9), higher values of particulate matter (PM_{10} and $PM_{2.5}$) and gaseous pollutants (SO_2 and NO_x) were observed as compared with the monitoring sites of non-mine fire areas, i.e. Loyabad PS (S2), Kenduadih PS (S4), Sijua Stadium (S6) and Katras (S8). Emissions from mine fire-affected coal mines, coal washeries and coke-oven plants were the major reason for higher concentration of pollutants in the ambient air of those areas at JCF. Spatial distribution of the four major pollutants (PM_{10}, $PM_{2.5}$, SO_2 and NO_x) taking an average of all the three monitored seasons (summer, post-monsoon and winter) is depicted in Fig. 3.

Concentrations of trace elements

The seasonal variation in the concentration level of trace elements at ten selected monitoring sites is plotted in Fig. 4. The concentration of trace elements ranged from 2.88 to 8.35 μg/m^3 (iron), 0.22 to 1.09 μg/m^3 (zinc), 0.88 to 5.20 μg/m^3 (copper), 0.17 to 2.87 μg/m^3 (manganese), 0.02 to 0.04 μg/m^3 (nickel), 0.02 to 0.07 μg/m^3 (cadmium), 0.12 to 0.33 μg/m^3 (chromium) and 0.04 to 0.34 μg/m^3 (lead) (Supplementary Table B) at ten monitoring sites in the order of Fe > Cu > Mn > Zn > Pb > Cr > Cd > Ni (Supplementary Table B). The annual average concentration of trace elements was found highest in the coal mining areas of JCF, which were severely affected by coal mine fire like Lodhna (S3), Tetulmari PS (S1), Kenduadih PS (S5), Jogta 14 Pit (S7) and Kujama Colliery (S9). On an average, the concentrations of trace elements in PM_{10} were found higher in winter in comparison with summer and post-monsoon (Koukoulakis et al. 2019; Malandrino et al. 2013a, 2013b; Marcazzan et al. 2001; Prodi et al. 2009). This is due to the fact that winter in Dhanbad is characterized by low temperature, lower wind speed and thermal inversion in the stratosphere and ground-level fog. This caused poor dispersion of air pollutants and thus the particulate-borne trace elements accumulated at the source of their emission without being dispersed at a greater distance (Khare and Baruah 2010; Song et al., 2015; Padoan et al. 2016). This was the reason for the highest concentration of trace elements during winter in comparison with summer. Concentration of trace elements remained lowest in post-monsoon because the air pollutants were flushed out from the source of their emission by the atmospheric precipitation (rainfall) during post-monsoon. On the other hand, the values of Zn and Ni were found higher in summer and post-monsoon than winter which might be due to the influence of transportation and industrial activities at Dhanbad, which had lower strength during the winter season. Similar results were reported at Hisar in India and Bohai Rim in China as observed by Haritash and Kaushik (2007) and Zhang et al. (2014). Spatial distribution of the monitored trace elements (Fe, Zn, Cu, Mn, Ni, Cd, Cr, Pb) taking an average of all the

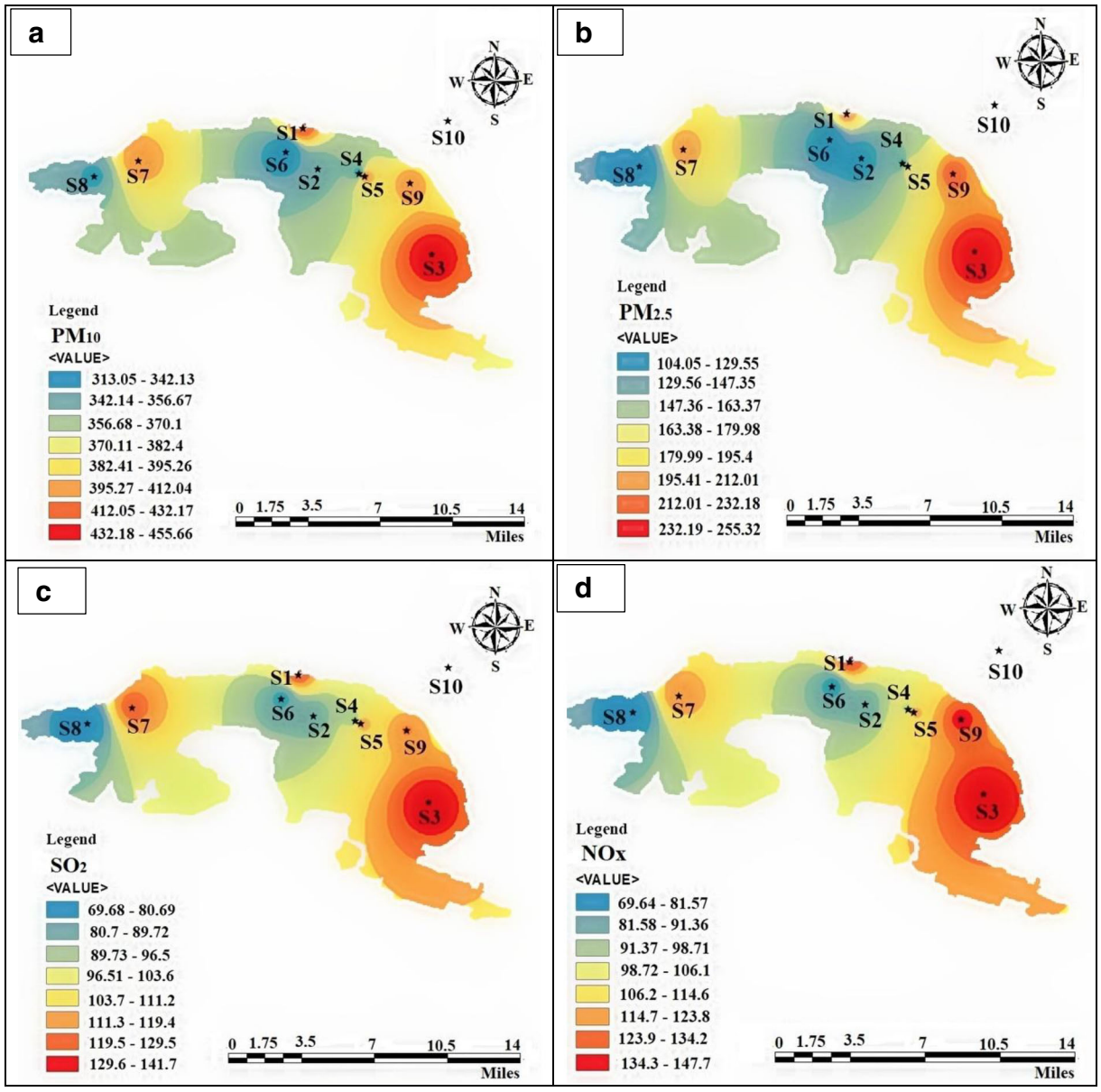

Fig. 3 Spatial distribution of PM_{10} (**a**), $PM_{2.5}$ (**b**), SO_2 (**c**) and NO_x (**d**) at the selected monitoring sites

three monitored seasons (summer, post-monsoon and winter) is depicted in Fig. 5.

Although leaded gasoline is not in use nowadays, re-suspension of lead (Pb)-rich dust due to heavy traffic load, coal mine fire and unscientific mining methods increases the concentration of Pb in the ambient air. As lead is one of the major elements present in Earth's crust, mining activities lead to emission of higher levels of Pb in the ambient air (Cheng and Hu 2010). As the residence time and transport of lead (Pb) are co-related with atmospheric aerosols (U.S. ATSDR 2005), particulate matter (PM_{10}) settles into the ambient air very quickly near the sources of their emission. This was the reason behind the higher level of emission of Pb in mining areas, and on the other hand, natural windblown dust and vehicular emission at the campus were the reason for a lower concentration of Pb at IIT (ISM) Dhanbad Campus.

Our results further specified that Fe, Cu, Mn and Zn were highest in concentration among all the trace

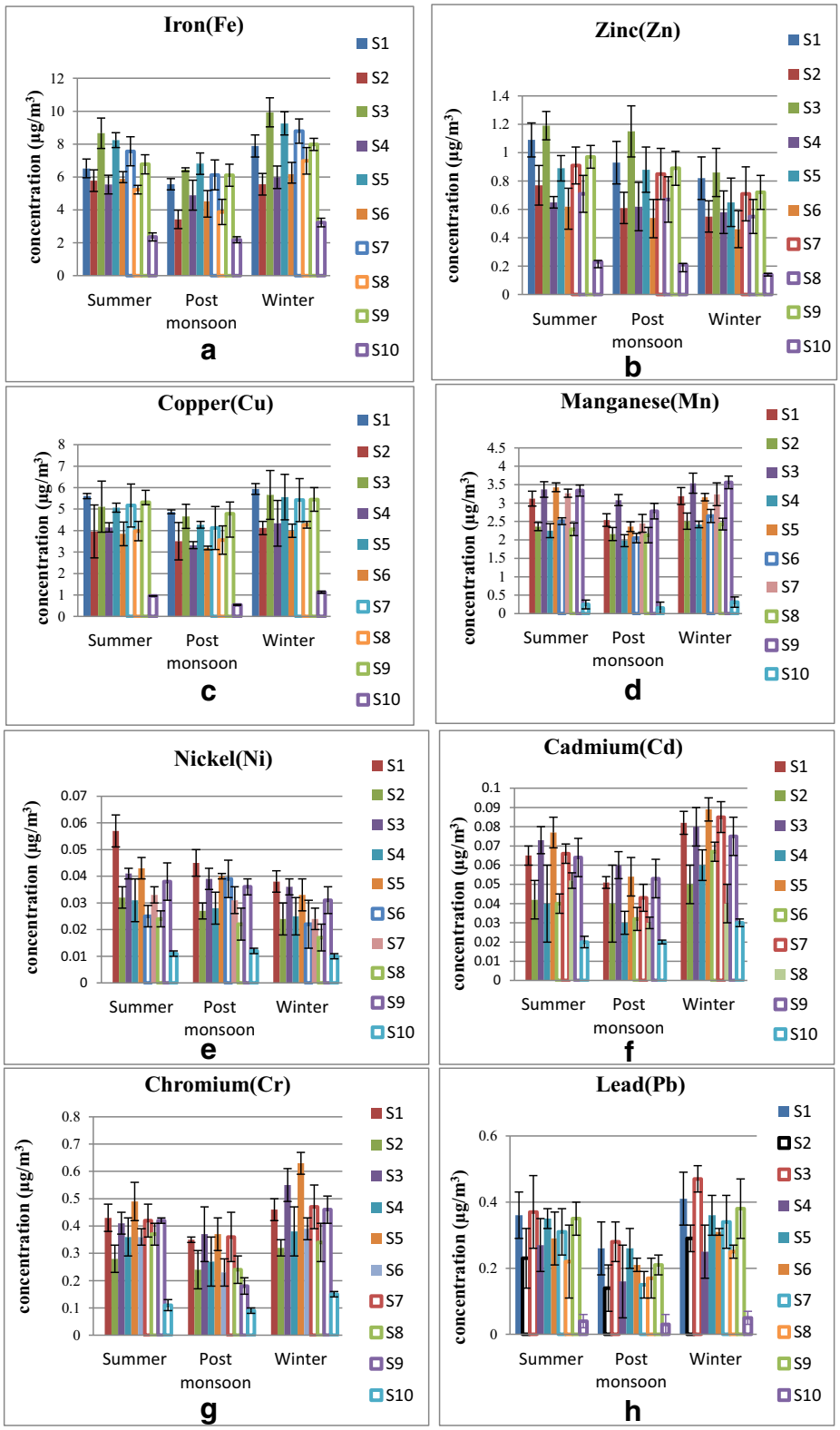

Fig. 4 Seasonal variations in concentration of trace elements like Fe (**a**), Zn (**b**), Cu (**c**), Mn (**d**), Ni (**e**), Cd (**f**), Cr (**g**) and Pb (**h**) at ten selected monitoring sites along with their standard deviation

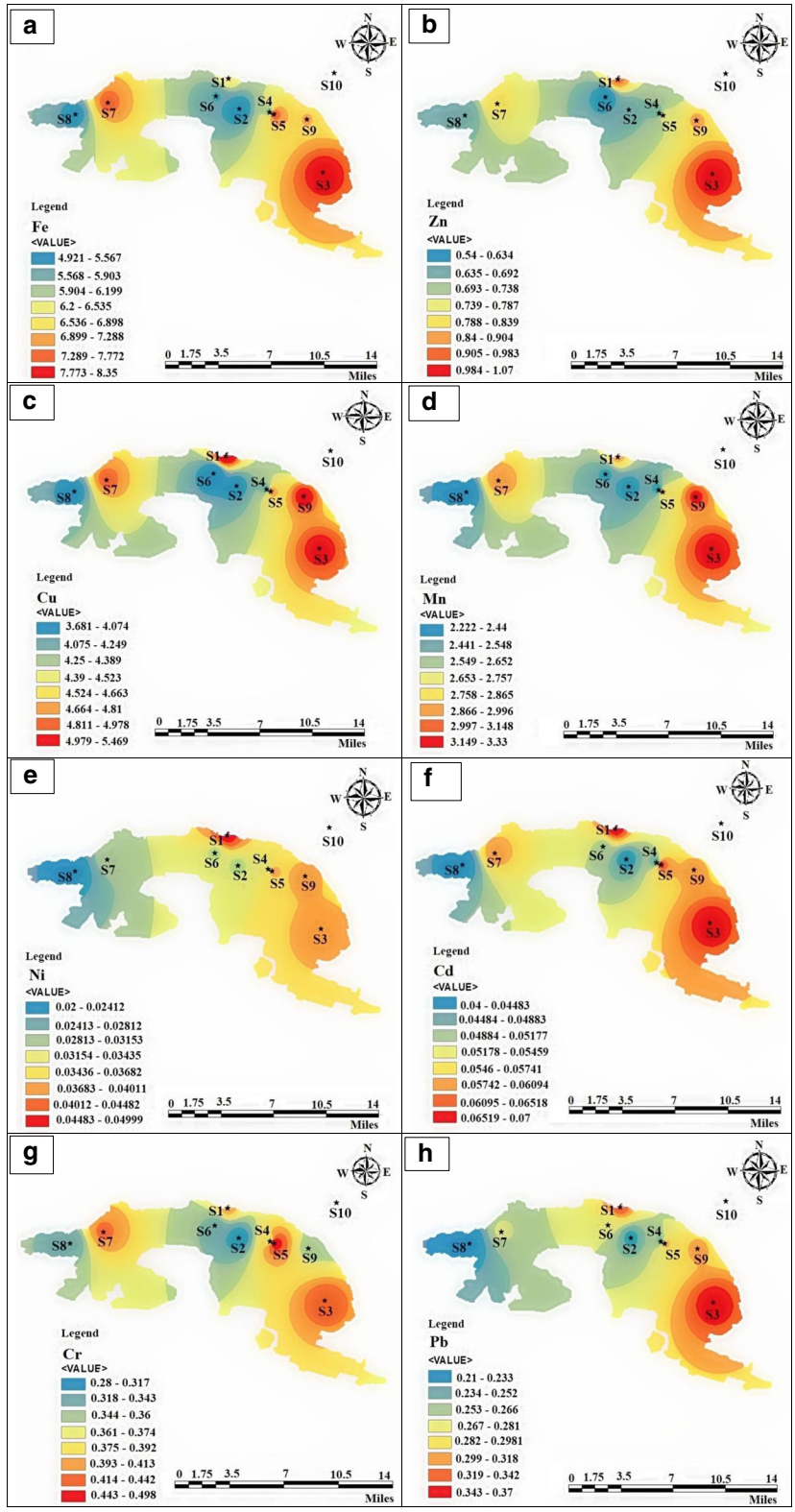

Fig. 5 Spatial distribution of trace elements like Fe (**a**), Zn (**b**), copper (**c**), Mn (**d**) Ni (**e**), Cd (**f**), Cr (**g**) and Pb (**h**) at the monitoring sites

elements in PM_{10}. Higher concentration levels of iron (Fe) may be attributed to higher levels of Fe present in crustal abundance, which was present in loosely bound granular dust of coal mining areas (Mahowald et al. 2005). Also, as Fe and Zn are inter-related, the concentration of the trace metals in the ambient air was mainly related to the emission of fossil fuel combustion, incineration and also from natural origin (Manalis et al. 2005). As the institute campus was free of heavy vehicular transport and surrounded by lush green trees, the concentration of all the analysed trace elements was lowest there. The atmospheric trace elements found in the coal mining areas were primarily due to active mine fires, various coal mining activities and heavy vehicular transport across the mining region (Dubey et al. 2012).

Air quality index determination

A huge amount of data gets generated after regular monitoring at numerous sites cannot convey the air quality status to the various concerned people such as the scientific community, government officials, policymakers and most importantly to the general public in a simple manner, that is why determination of the ambient air quality of a specific region by estimation of air quality index (AQI) is considered to be an important tool.

AQI of the study area was calculated according to the National Air Quality Index guidelines given by Central Pollution Control Board (2014). This National AQI transforms complex air quality data of the pollutants into a single number (index value), nomenclature and colour to disseminate information on air quality and its associated health impacts in an easily understandable form for the common people. The pollutant concentration (Ip) values were calculated and the maximum Ip values were considered the AQI of an area according to the formula (Table 4).

$$\mathrm{Ip} = [\{(I_{\mathrm{HI}} - I_{\mathrm{LO}})/(B_{\mathrm{HI}} - B_{\mathrm{LO}})\} \times (\mathrm{Cp} - B_{\mathrm{LO}})] + I_{\mathrm{LO}}$$

where Ip is the sub-index, B_{HI} is the breakpoint concentration greater than or equal to the concentration given, B_{LO} is the breakpoint concentration less than or equal to the concentration given, I_{HI} is the AQI value corresponding to B_{HI}, I_{LO} is the AQI value corresponding to B_{LO} and Cp is the concentration of pollutants. Finally,

$$\mathrm{AQI} = \max(\mathrm{Ip}),$$

where $p = 1, 2, \ldots, n$ denotes n pollutants.

The values of the AQI were calculated based on the method prescribed by CPCB (2014) of ten selected monitoring sites and are depicted in Fig. 6. The AQI values (as shown in Table 3) in the study area varied between a maximum of 407 and a minimum of 71. The values of AQI at Tetulmari PS (S1) and Lodhna PS (S3) were falling under severely polluted category due to their proximity to both underground and surface coal mining areas, rigorously affected by coal mine fire and heavy vehicular transportation of coal in the mines. The air quality of Bastacolla Colliery (S5), Jogta 14 Pit (S7) and Kujama Colliery (S9) were falling under very poor category due to the active mine fire and adjacent coal washeries as well as nearby coke-oven plants. The AQI values of Loyabad PS (S2), Kenduadih PS (S4), Sijua Stadium (S6) and Katras (S8) were falling under very poor category. The reason behind this is the burning of coal in the mining areas and heavy vehicular load in these regions. The air quality index of the mine fire-affected areas was nearly 1.5 times higher than the air quality index of non-mine fire areas of JCF. On the other hand, the air quality of IIT (ISM) Dhanbad (S10) falls under the category of satisfactory level because it is devoid of any such mining or industrial activities. From the AQI of all the studied sites, it was observed that the responsible air pollutants for the deterioration of ambient air quality were PM_{10} and $PM_{2.5}$. The overall AQI of the study area reflects an image of a critically polluted area with considerable pollution load in Dhanbad.

Principal component analysis

Principal component analysis (PCA) with varimax rotation and Kaiser normalization had been performed in SPSS 16 to get a valid estimation of potential sources that contributed to the emission of atmospheric pollutants in the coal mining areas. In the coal mining areas affected by mine fire (Table 4a), three PCs with eigenvalues greater than 1.0 were extracted with 83.423% of the total variance in the entire data set. High loadings of PM_{10}, $PM_{2.5}$, SO_2, NO_x, Cu, Mn, Pb and Fe in PC1 indicated active coal mine fire, unscientific exploitation of coal, nearby coke-oven plants and allied mining activities as major sources. The maximum percent variance

Table 4 Rotated principal component loadings for particulate matter, gaseous pollutants and trace elements in the mine fire areas (a) and non-mine fire areas (b) of Jharia Coalfield

Elements	Component		
	PC1	PC2	PC3
a			
PM_{10}	0.921		
$PM_{2.5}$	0.930		
SO_2	0.932		
NO_x	0.929		
Fe	0.552		
Zn			0.933
Cu	0.905		
Mn	0.879		
Ni			0.901
Cd		0.941	
Cr		0.855	
Pb	0.806		
Eigenvalues	6.022	2.138	1.850
Variance (%)	50.187	17.816	15.419
Cumulative (%)	50.187	68.003	83.423
Possible sources	Coal mine fire, nearby coke-oven plants, coal washeries and other mining activities	Heavy vehicular load in the mines	Crustal/resuspended windblown dust
b			
PM_{10}	0.906		
$PM_{2.5}$	0.896		
SO_2		0.731	
NO_x	0.915		
Fe	0.710		
Zn			0.934
Cu	0.790		0.555
Mn	0.891		
Ni			0.557
Cd		0.963	
Cr		0.958	
Pb	0.833		
Eigenvalues	5.599	2.516	1.435
Variance (%)	46.659	20.963	11.958
Cumulative (%)	46.659	67.622	79.579
Possible sources	Point sources like burning of coal in the mines	Heavy vehicular load in the mines	Crustal/resuspended windblown dust

(50.187%) for this PC indicated that these sources were the main reasons for the emission of the atmospheric pollutants. SO_2 was the indicator of active coal mine fire whereas NO_x was the major pollutant emitted from mine fires as well as nearby coke-oven plants of the mining areas. In PC2, heavy vehicular loads in the mining areas were the significant sources of Cd and Cr as these two trace elements are emitted significantly from crude oil combustion and vehicular emissions (Tasdemir et al. 2006; Pandey et al.

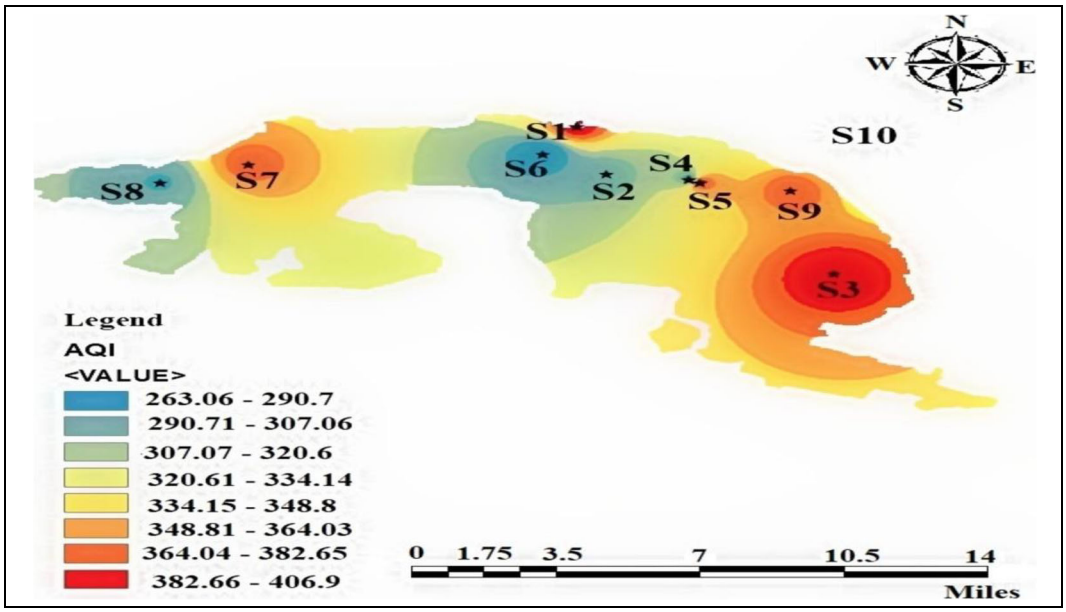

Fig. 6 Air quality index (AQI) of the ten monitoring sites

2014). The PC3 with 15.419% of variance showed loadings of Zn and Ni which indicated that these two trace elements were emitted into the atmosphere mainly due to re-suspension of Earth's crust or wind-blown dust (Quiterio et al. 2004). Three-dimensional factor loadings of the air pollutants (particulate matter, gaseous pollutants and trace elements) in mine fire areas of JCF are depicted in Fig. 7a.

Three PCs with eigenvalues greater than 1.0 were extracted with 79.579% of the overall variance of the analysed data of coal mining areas which were not affected by coal mine fire (Table 4b). High loadings of PM_{10}, $PM_{2.5}$, NO_x, Cu and Mn, Pb and Fe in PC1 indicated point sources like the burning of coal in the mining areas as major sources. The maximum percent variance (46.659%) for this PC indicates that these sources are the major reasons for the emission of the atmospheric pollutants. In PC2, heavy vehicular load in the mining areas was the significant source of SO_2, Cd and Cr as these three pollutants are emitted mainly from crude oil combustion and vehicular emissions (Äyräs and Kashulina 2000; Tasdemir et al., 2006; Pandey et al.

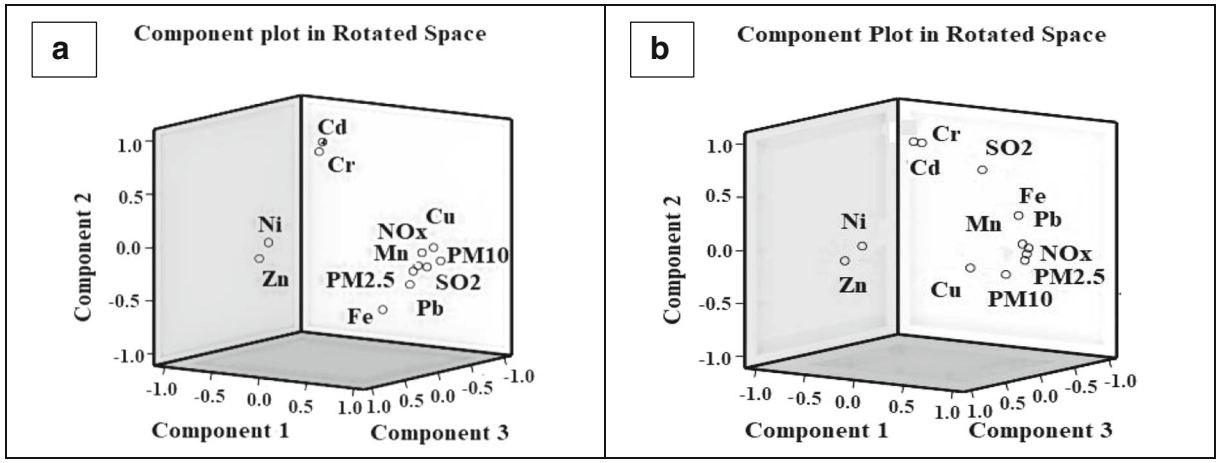

Fig. 7 Three-dimensional factor loadings of the studied air pollutants (particulate matter, gaseous pollutants and trace elements) in mine fire areas (**a**) and non-mine fire areas (**b**) of JCF

2014). SO_2 was present in between cluster 2 and cluster 1 in the three-dimensional rotated space (Fig 7b), which indicated that SO_2 had more than one significant source. The PC3 with 11.958% of variance showed loadings of Zn and Ni which indicated that these pollutants were emitted to the atmosphere mainly due to re-suspension of Earth's crust or windblown dust (Quiterio et al. 2004).

Conclusions

The present study provided an idea of the current status of air pollutants like PM_{10}, $PM_{2.5}$, SO_2, NO_x and trace elements (Fe, Zn, Cu, Mn, Ni, Cd, Cr, Pb) in the coal mining areas of Jharia Coalfield. Significant seasonal and spatial variation of the air pollutants is depicted, which showed that the concentration level of the air pollutants was much higher in winter in the monitoring sites which were severely affected by active coal mine fire. The effect was due to the lower wind speed and lower atmospheric dispersion of pollutants during winter. PCA identified that active coal mine fire, nearby coke-oven plants and allied mining activities were the significant contributors of air pollutants in the coal mining areas affected by mine fire. SO_2 was the indicator of active mine fire whereas NO_x was the major pollutant emitted from mine fire as well as nearby coke-oven plants of the mining areas. Based on the AQI of the selected monitoring sites in Jharia Coalfield, it was observed that the AQI of mine fire areas was nearly 1.5 times higher than the AQI of non-mine fire areas. The overall AQI of the study area reflected an image of a critically polluted area with considerable pollution load. Advanced mining technology should be adopted to mitigate active mine fires and reduce the emission of toxic air pollutants. The outcome of this study lays down the framework for formulating a proper scheme for necessary preventive measures.

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Compliance with ethical standards

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

Human and animal rights This article does not contain any studies with human or animal subjects performed by any of the authors. The manuscript has been prepared following the instructions provided in the Author's Guidelines of the journal.

References

Abulude, F. O., Adeyeye, E. I., & Asaolu, S. S. (2003). Assessment of some heavy metals in mushroom samples from Ondo State, Nigeria. *International Journal of Environmental Studies, 60*(6), 535–536. https://doi.org/10.1080/0020723032000130070.

Afridi, H. I., Kazi, T. G., Kazi, N., Kandhro, G. A., Baig, J. A., Shah, A. Q., Khan, S., Kolachi, N. F., Wadhwa, S. K., Shah, F., Jamali, M. K., & Arain, M. B. (2011). Evaluation of cadmium, chromium, nickel, and zinc in biological samples of psoriasis patients living in Pakistani cement factory area. *Biological Trace Element Research, 142*(3), 284–301.

ASTDR (Agency for Toxic Substances and disease Registry) (1993). Toxicological profile for lead. Update. Prepared by Clement International Corporation under Contract No. 205-88-0608 for ASTDR. U.S. Public Health Service, Atlanta, GA.

Äyräs, M., & Kashulina, G. (2000). Regional patterns of element contents in the organic horizon of podzols in the central part of the Barents region (Finland, Norway and Russia) with special reference to heavy metals (Co, Cr, Cu, Fe, Ni, Pb, V and Zn) and sulphur as indicators of airborne pollution. *Journal of Geochemical Exploration, 68*(1–2), 127–144.

Baldauf, R. W. (2001). Ambient air quality monitoring network design for assessing human health impacts from exposures to airborne contaminants. *Environmental Monitoring and Assessment, 66*(1), 63–76. https://doi.org/10.1023/A:1026428214799.

Banerjee, A. D. K. (2003). Heavy metal levels and solid phase speciation in street dusts of Delhi, India. *Environmental Pollution, 123*(1), 95–105. https://doi.org/10.1016/S0269-7491(02)00337-8.

Basha, A. M., Yasovardhan, N., Satyanarayana, S. V., Reddy, G. V. S., & Kumar, A. V. (2014). Baseline survey of trace metals in ambient PM 10 at Tummalapalle uranium mining site. *Atmospheric Pollution Research, 5*(4), 591–600. https://doi.org/10.5094/APR.2014.068.

Bharat Coking Coalfield Limited (BCCL) (1991). Mine fires in the Jharia coalfield, Bharat Coking Coal Limited, Project andPlanning Division, Dhanbad, India, pp 1–17.

Bhuyan, P. K., Samantray, P., & Rout, S. P. (2010). Ambient air quality status in Choudwar area of Cuttack District. *International journal of environmental sciences, 1*(3), 343–356.

Birmili, W., Allen, A. G., Bary, F., & Harrison, R. M. (2006). Trace metal concentrations and water solubility in size-fractionated atmospheric particles and influence of road traffic. *Environmental Science & Technology, 40*(4), 1144–1153. https://doi.org/10.1021/es0486925.

Brunekreef, B., & Holgate, S. T. (2002). Air pollution and health. The Lancet, 360(9341), 1233–1242. 10.1016/S0140-6736(02)11274-8.

Charron, A., & Harrison, R. M. (2005). Fine (PM2. 5) and coarse (PM2. 5-10) particulate matter on a heavily trafficked London highway: sources and processes. *Environmental Science & Technology, 39*(20), 7768–7776. https://doi.org/10.1021/es050462i.

Cheng, H., & Hu, Y. (2010). Lead (Pb) isotopic fingerprinting and its applications in lead pollution studies in China: a review. *Environmental Pollution, 158*(5), 1134–1146. https://doi.org/10.1016/j.envpol.2009.12.028.

CPCB. 2012. Guidelines for the measurement of ambient air pollutants, vol. I (New Delhi).

Collins, M. J., Williams, P. L., & McIntosh, D. L. (2001). Ambient air quality at the site of a former manufactured gas plant. *Environmental Monitoring and Assessment, 68*(2), 137–152. https://doi.org/10.1023/A:1010747225479.

Coal India Limited (n.d.). https://www.coalindia.in/en-us/performance/physical.aspx. Accesssed 20 March 2018.

Danielsson, B. R., Hassoun, E., & Dencker, L. (1982). Embryotoxicity of chromium: distribution in pregnant mice and effects on embryonic cells in vitro. *Archives of Toxicology, 51*(3), 233–245.

Dubey, B., Pal, A. K., & Singh, G. (2012). Trace metal composition of airborne particulate matter in the coal mining and non–mining areas of Dhanbad Region, Jharkhand, India. *Atmospheric Pollution Research, 3*(2), 238–246. https://doi.org/10.5094/APR.2012.026.

Feng, X. D., Dang, Z., Huang, W. L., & Yang, C. (2009). Chemical speciation of fine particle bound trace metals. *International Journal of Environmental Science & Technology, 6*(3), 337–346. https://doi.org/10.1007/BF03326071.

Gautam, S., Prasad, N., Patra, A. K., Prusty, B. K., Singh, P., Pipal, A. S., & Saini, R. (2016). Characterization of PM2.5 generated from opencast coal mining operations: a case study of Sonepur Bazari Opencast Project of India. *Environmental Technology & Innovation, 6*, 1–10. https://doi.org/10.1016/j.eti.2016.05.003.

Guan, H., Van Genderen, JL. (1997). Report on environment monitoring of spontaneous combustion in the coal field of North China, Aero-Photogrammetry and Remote Sensing Bureau of China and International Institute for Aerospace survey and Earth Sciences, Enscheda, The Netherland.

Gummeneni, S., Yusup, Y. B., Chavali, M., & Samadi, S. Z. (2011). Source apportionment of particulate matter in the ambient air of Hyderabad city, India. *Atmospheric Research, 101*(3), 752–764. https://doi.org/10.1016/j.atmosres.2011.05.002.

Hall, J. L. (2002). Cellular mechanisms for heavy metal detoxification and tolerance. *Journal of Experimental Botany, 53*(366), 1–11. https://doi.org/10.1093/jexbot/53.366.1.

Haritash, A. K., & Kaushik, C. P. (2007). Assessment of seasonal enrichment of heavy metals in respirable suspended particulate matter of a sub-urban Indian city. *Environmental Monitoring and Assessment*, *128*(1–3), 411–420. https://doi.org/10.1007/s10661-006-9335-1. http://www.foundryinfo-india.org/Critically_polluted_43_industrial_clusters_in.aspx (Accessed on 5th may, 2018). https://news.yale.edu/2018/01/23/2018-environmental-performance-index-air-quality-top-public-health-threat. (Accessed on 30.01.2018). https://www.greenpeace.org/southeastasia/press/679/latest-air-pollution-data-ranks-worlds-cities-worst-to-best/. (Accessed on 15.05.2018). www.indiaenvironmentportal.org.in › *files* › *file* › *Air Quality Index. (Accessed on 23.07.2018).*

IARC (2013). Outdoor air pollution a leading environmental cause of cancer deaths. IRIS (Integrated Risk Assessment System), vol. 1995. United States Environmental Protection Agency. www.epa.gov/IRIS/

Iijima, S., Matsumoto, N., & Lu, C.-C. (1983). Transfer of chromic chloride to embryonic mice and changes in the embryonic mouse neuroepithelium. *Toxicology, 26*(3–4), 257–265. https://doi.org/10.1016/0300-483X(83)90086-0.

Jena, S., & Singh, G. (2017). Human health risk assessment of airborne trace elements in Dhanbad, India. *Atmospheric Pollution Research, 8*(3), 490–502. https://doi.org/10.1016/j.apr.2016.12.003.

Karar, K., Gupta, A. K., Kumar, A., & Biswas, A. K. (2006). Characterization and identification of the sources of chromium, zinc, lead, cadmium, nickel, manganese and Iron in PM10 particulates at the two sites of Kolkata, India. *Environmental Monitoring and Assessment, 120*(1–3), 347–360. https://doi.org/10.1007/s10661-005-9067-7.

Khare, P., & Baruah, B. P. (2010). Elemental characterization and source identification of PM2.5 using multivariate analysis at the suburban site of North-East India. *Atmospheric Research, 98*(1), 148–162. https://doi.org/10.1016/j.atmosres.2010.07.001.

Koukoulakis, K. G., Chrysohou, E., Kanellopoulos, P. G., Karavoltsos, S., Katsouras, G., Dassenakis, M., Nikolelis, D., & Bakeas, E. (2019). Trace elements bound to airborne PM10 in a heavily industrialized site nearby Athens: seasonal patterns, emission sources, health implications. *Atmospheric Pollution Research, 10*(4), 1347–1356. https://doi.org/10.1016/j.apr.2019.03.007.

Kuenzer, C., & Stracher, G. B. (2012). Geomorphology of coal seam fires. *Geomorphology, 138*(1), 209–222. https://doi.org/10.1016/j.geomorph.2011.09.004.

Kuenzer, C., Zhang, J., Tetzlaff, A., van Dijk, P., Voigt, S., Mehl, H., & Wagner, W. (2007). Uncontrolled coal fires and their environmental impacts: investigating two arid mining regions in north-central China. *Applied Geography, 27*(1), 42–62. https://doi.org/10.1016/j.apgeog.2006.09.007.

Lee, B.-K., Jun, N.-Y., & Lee, H. K. (2005). Analysis of impacts on urban air quality by restricting the operation of passenger vehicles during Asian Game events in Busan, Korea. *Atmospheric Environment, 39*(12), 2323–2338. https://doi.org/10.1016/j.atmosenv.2004.11.044.

Leili, M., Naddafi, K., Nabizadeh, R., Yunesian, M., & Mesdaghinia, A. (2008). The study of TSP and PM10 concentration and their heavy metal content in central area of Tehran, Iran. *Air Quality, Atmosphere & Health, 1*(3), 159–166. https://doi.org/10.1007/s11869-008-0021-z.

Li, S., Matthews, J., & Sinha, A. (2008). Atmospheric hydroxyl radical production from electronically excited NO2 and H2O. *Science, 319*(5870), 1657–1660. https://doi.org/10.1126/science.1151443.

Limbeck, A., Handler, M., Puls, C., Zbiral, J., Bauer, H., & Puxbaum, H. (2009). Impact of mineral components and selected trace metals on ambient PM10 concentrations. *Atmospheric Environment, 43*(3), 530–538. https://doi.org/10.1016/j.atmosenv.2008.10.012.

López, J. M., Callén, M. S., Murillo, R., García, T., Navarro, M. V., de la Cruz, M. T., & Mastral, A. M. (2005). Levels of selected metals in ambient air PM10 in an urban site of Zaragoza (Spain). *Environmental Research, 99*(1), 58–67. https://doi.org/10.1016/j.envres.2005.01.007.

Mahowald, N. M., Baker, A. R., Bergametti, G., Brooks, N., Duce, R. A., Jickells, T. D., et al. (2005). Atmospheric global dust cycle and iron inputs to the ocean: atmospheric iron deposition. *Global Biogeochemical Cycles*, *19*(4), n/a-n/a. https://doi.org/10.1029/2004GB002402.

Malandrino, M., Di Martino, M., Ghiotti, G., Geobaldo, F., Grosa, M. M., Giacomino, A., & Abollino, O. (2013a). Inter-annual and seasonal variability in PM10 samples monitored in the city of Turin (Italy) from 2002 to 2005. *Microchemical Journal, 107*, 76–85. https://doi.org/10.1016/j.microc.2012.05.026.

Malandrino, M., Di Martino, M., Giacomino, A., Geobaldo, F., Berto, S., Grosa, M. M., & Abollino, O. (2013b). Temporal trends of elements in Turin (Italy) atmospheric particulate matter from 1976 to 2001. *Chemosphere, 90*(10), 2578–2588. https://doi.org/10.1016/j.chemosphere.2012.10.102.

Manalis, N., Grivas, G., Protonotarios, V., Moutsatsou, A., Samara, C., & Chaloulakou, A. (2005). Toxic metal content of particulate matter (PM10), within the Greater Area of Athens. *Chemosphere, 60*(4), 557–566. https://doi.org/10.1016/j.chemosphere.2005.01.003.

Mancuso, T. F. (1975). *Consideration of chromium as an industrial carcinogen*. Toronto, Ontario: In International Conference on Heavy Metals in the Environment, 343–56.

Marcazzan, G. M., Vaccaro, S., Valli, G., & Vecchi, R. (2001). Characterisation of PM10 and PM2.5 particulate matter in the ambient air of Milan (Italy). *Atmospheric Environment, 35*(27), 4639–4650. https://doi.org/10.1016/S1352-2310(01)00124-8.

Masih, J., Dyavarchetty, S., Nair, A., Taneja, A., & Singhvi, R. (2019). Concentration and sources of fine particulate associated polycyclic aromatic hydrocarbons at two locations in the western coast of India. *Environmental Technology & Innovation, 13*, 179–188. https://doi.org/10.1016/j.eti.2018.10.012.

Matsumoto, N., Iijima, S., & Katsunuma, H. (1976). Placental transfer of chromic chloride and its teratogenic potential in embryonic mice. *The Journal of Toxicological Sciences, 1*(2), 1–13. https://doi.org/10.2131/jts.1.2_1.

Meena, M., Meena, B. S., Chandrawat, U., & Rani, A. (2016). Seasonal variation of selected metals in particulate matter at an industrial city Kota, India. *Aerosol and Air Quality Research, 16*(4), 990–999. https://doi.org/10.4209/aaqr.2015.02.0074.

National Ambient Air Quality Standards (2009). Notification, New Delhi, the 18th November.

National Remote Sensing Agency (NRSA), Hyderabad (2006). Report on coal mine fire delineation and surface features mapping using satellite data in Jharia coal field, Dhanbad Jharkhand.

Padoan, E., Malandrino, M., Giacomino, A., Grosa, M. M., Lollobrigida, F., Martini, S., & Abollino, O. (2016). Spatial distribution and potential sources of trace elements in PM10 monitored in urban and rural sites of Piedmont Region. *Chemosphere, 145*, 495–507. https://doi.org/10.1016/j.chemosphere.2015.11.094.

Pandey, B., Agrawal, M., & Singh, S. (2014). Assessment of air pollution around coal mining area: emphasizing on spatial distributions, seasonal variations and heavy metals, using cluster and principal component analysis. *Atmospheric Pollution Research, 5*(1), 79–86. https://doi.org/10.5094/APR.2014.010.

Pandey, J., Kumar, D., Singh, V. K., & Mohalik, N. K. (2016). Environmental and socio-economic impacts of fire in Jharia Coalfield, Jharkhand, India: an appraisal. *Current Science, 110*(9), 1639. https://doi.org/10.18520/cs/v110/i9/1639-1650.

Park, R. M., Bena, J. F., Stayner, L. T., Smith, R. J., Gibb, H. J., & Lees, P. S. J. (2004). Hexavalent chromium and lung cancer in the chromate industry: a quantitative risk assessment. *Risk Analysis, 24*(5), 1099–1108. https://doi.org/10.1111/j.0272-4332.2004.00512.x.

Pathak, A. K., Yadav, S., Kumar, P., & Kumar, R. (2013). Source apportionment and spatial–temporal variations in the metal content of surface dust collected from an industrial area adjoining Delhi, India. *Science of the Total Environment, 443*, 662–672. https://doi.org/10.1016/j.scitotenv.2012.11.030.

Patra, A. K., Gautam, S., & Kumar, P. (2016). Emissions and human health impact of particulate matter from surface mining operation—a review. *Environmental Technology & Innovation, 5*, 233–249. https://doi.org/10.1016/j.eti.2016.04.002.

Pedersen, N. B. (1982). The effects of chromium on the skin. In Biological and environmental aspects of chromium, 249–275.

Prodi, F., Belosi, F., Contini, D., Santachiara, G., Di Matteo, L., Gambaro, A., et al. (2009). Aerosol fine fraction in the Venice Lagoon: particle composition and sources. *Atmospheric Research, 92*(2), 141–150. https://doi.org/10.1016/j.atmosres.2008.09.020.

Quiterio, S. L., Sousa da Silva, C. R., Arbilla, G., & Escaleira, V. (2004). Metals in airborne particulate matter in the industrial district of Santa Cruz, Rio de Janeiro, in an annual period. *Atmospheric Environment, 38*(2), 321–331. https://doi.org/10.1016/j.atmosenv.2003.09.017.

Roy, P., Kumar Sikdar, P., Singh, G., & Kumar Pal, A. (2012). Source apportionment of ambient PM10: a case study from a mining belt of Orissa. *Atmósfera, 25*(3), 311–324.

Senlin, L., Longyi, S., Minghong, W., Zheng, J., & Xiaohui, C. (2007). Chemical elements and their source apportionment of PM10 in Beijing urban atmosphere. *Environmental Monitoring and Assessment, 133*(1–3), 79–85. https://doi.org/10.1007/s10661-006-9561-6.

Shaheen, N., Shah, M. H., Khalique, A., & Jaffar, M. (2005). Metal levels in airborne particulate matter in urban Islamabad, Pakistan. *Bulletin of Environmental Contamination and Toxicology, 75*(4), 739–746. https://doi.org/10.1007/s00128-005-0813-x.

Shridhar, V., Khillare, P. S., Agarwal, T., & Ray, S. (2010). Metallic species in ambient particulate matter at rural and urban location of Delhi. *Journal of Hazardous Materials, 175*(1–3), 600–607. https://doi.org/10.1016/j.jhazmat.2009.10.047.

Singh, G., Roy, D., & Sinha, S. (2014). Ambient air quality assessment with particular reference to particulates in Jharia

Coalfield, Eastern India. *Journal of Environmental Science & Engineering, 56*(1), 19–30.

Song, Z., Zhu, H., Jia, G., & He, C. (2014). Comprehensive evaluation on self-ignition risks of coal stockpiles using fuzzy AHP approaches. *Journal of Loss Prevention in the Process Industries, 32*, 78–94. https://doi.org/10.1016/j.jlp.2014.08.002.

Tripathi, A. K., & Gautam, M. (2007). Biochemical parameters of plants as indicators of air pollution. *Journal of Environmental Biology, 28*(1), 127–132.

Tasdemir, Y., Kural, C., Cindoruk, S. S., & Vardar, N. (2006). Assessment of trace element concentrations and their estimated dry deposition fluxes in an urban atmosphere. *Atmospheric Research, 81*(1), 17–35.

U.S. ATSDR (U.S. Agency for Toxic Substances and Disease Registry). (2005). Toxicological profile for lead, U.S. Department of Health and Human Services, Public Health Service, Atlanta, U.S.A, p. 582.

USEPA (Environmental Protection Agency) (1990). Air quality criteria for lead: supplement to the 1986 Addendum. Environmental Criteria and Assessment Office, Research Triangle Park, NC. EPA-600/8e89/049F.

Weckwerth, G. (2001). Verification of traffic emitted aerosol components in the ambient air of Cologne (Germany). *Atmospheric Environment, 35*(32), 5525–5536. https://doi.org/10.1016/S1352-2310(01)00234-5.

Yadav, M., Sahu, S. P., & Singh, N. K. (2019). Multivariate statistical assessment of ambient air pollution in two coalfields having different coal transportation strategy: a comparative study in Eastern India. *Journal of Cleaner Production, 207*, 97–110. https://doi.org/10.1016/j.jclepro.2018.09.254.

Zhang, J., Wagner, W., Prakash, A., Mehl, H., & Voigt, S. (2004). Detecting coal fires using remote sensing techniques. *International Journal of Remote Sensing, 25*(16), 3193–3220. https://doi.org/10.1080/01431160310001620812.

Zhang, F., Chen, Y., Tian, C., Wang, X., Huang, G., Fang, Y., & Zong, Z. (2014). Identification and quantification of shipping emissions in Bohai Rim, China. *Science of the Total Environment, 497–498*, 570–577. https://doi.org/10.1016/j.scitotenv.2014.08.016.