Particulate matter pollution in opencast coal mining areas: a threat to human health and environment

Sneha Gautam, Aditya Kumar Patra, Satya Prakash Sahu & Michael Hitch


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ABSTRACT
With the increase in depth of mines, the movement and dispersion of particulate matter (PM) are very difficult to predict due to improper ventilation. Insufficient open pit ventilation remains the principal driver for the lack of dispersion and evacuation from mines and ultimately increases the time and amount of exposure to miners. Studies suggest that there is a direct and dependent relationship between the composition and exposure time to PM in mining operations. Furthermore, this paper helps the reader appreciate the need of carrying out studies to understand the nature of the dispersion of PM inside the mines.

1. Introduction
Air pollution, especially due to particulate matter (PM) is receiving importance worldwide [1]. The atmospheric pollution due to airborne PM alone and in association with gaseous pollutants have been responsible for several global, regional and local impacts that include modification of cloud property, the global climate change [2], acid rain [3,4], stratospheric ozone depletion [5], reduction in visibility and soiling of monuments [6]. While chemical and mineralogical composition, number, surface area and mass of PM influence adverse health effects, the size of a particle determines its penetrability into deeper parts of the lungs and therefore is considered to be the most important parameter in determining different diseases or health hazards which include chronic pulmonary diseases like cancer, bronchial asthma and chronic bronchitis [7,8].

PMs are the solid particles or a mixture of solid particles and liquid droplets in the air consisting of several components such as organic compounds, metals, acids, soil and dust [9–11]. Poschl [12] defined PM as a type of air pollutant which vary in mass and composition, consisting of complex and varying mixtures of particles suspended in the breathing air and are produced by a wide variety of natural and anthropogenic activities. PM is considered to be one of six criteria pollutants designated by the US Clean Air Act of 1971 [13]. In addition to the natural sources like sea salts, long range transport from desert storm and wind induced re-suspension of crustal matter, the PM in the air is produced from a variety of anthropogenic sources that include industrial activity, transportation and burning of biomass [14].
### 1.1. Classification of PM

The parameters that play an important role in eliciting health effects are size, shape, density mass/number and composition of particles [1]. Particle size is expressed by their aerodynamic properties because they govern the transport and removal of particles from the air, their deposition within the respiratory system and they are associated with the chemical composition and sources of particles. These properties are conveniently summarised by the aerodynamic diameter, which is defined as the diameter of a hypothetical sphere of density 1 g cm$^{-3}$ having the same terminal velocity in calm air as the particle in question, regardless of its geometric size, shape and true density [15]. PM is also classified with respect to its environmental, occupational health and physiological effects [16]. A summary of classification is presented in Figure 1.

Smokes are fine, solid particles consisting mainly of carbon and other combustible materials generating due to incomplete combustion of coal, wood or tobacco. Fumes are fine, solid particles formed as a result of condensation of vapours of solid particles. Fly ash arising from combustion of coal consists of finely divided, noncombustible particles that are present in flue gases. Mist basically consists of liquid particles and droplets that are formed by the condensation of a vapour, the dispersion of a liquid or the enactment of a chemical reaction. Lastly, spray consists of liquid particles formed by the atomisation of parent liquids, such as pesticides and herbicides. Size ranges of these above mentioned PMs are summarised in Table 1.

Total suspended PM is the PM that is contained in the air. Nuisance PM mostly consists of coarse particles that may lead to the reduction of environmental amenity or may damage machinery, lessen visibility or become an irritant substance in the atmosphere. Fugitive PM refers to PM whose source can’t be defined easily or derived from more than one source [16].

The size of PM determines the sites in the respiratory tract that they will deposit. PM$_{10}$ particles deposit mainly in the upper respiratory tract while fine and ultrafine particles are able to reach lung alveoli. The total inhalable dust is the fraction of airborne material, which after entering the nose and mouth during breathing, gets deposited anywhere in the respiratory tract [17]. Thoracic dust is defined as the fraction of inhaled particles that penetrate beyond the larynx. Respirable dust represents the fraction that penetrates to the gas exchange region of the lung. Toxic dusts may cause chemical reactions with the respiratory system or may allow toxic compounds to be absorbed into the bloodstream through the alveolar walls. Examples of such hazardous dusts are lead, arsenic, uranium and other radioactive minerals, tungsten, mercury, cadmium, manganese, silver and nickel [18]. Carcinogenic dusts that cause cancer are uranium, asbestos, arsenic or quartz dust. Silica, asbestos, mica, talc are some of the most hazardous fibrogenic dusts and may also produce toxic and carcinogenic reactions [18].

Health Effects Institute (HEI) [19] stated that ultrafine particles present in greater numbers do not last long in the atmosphere and they generally form fine particles either by coagulating (two or more small particles combining) or condensing (gas molecules condensing onto a solid particle). Fine and ultrafine particles also may carry toxic components into the deep lung. As smaller particles have greater total surface area than larger particles of the same mass; the toxic materials carried by ultrafine particles, may be more likely to interact with cells in the lung than those carried by larger particles [19]. USEPA [20] presented a typical distribution of different sizes or modes of particles in urban air and how several particles of different sizes relate to these modes as shown in Figure 2. From Figure 2, it is evident that the distribution of particles measured in urban air falls into three main modes based on their aerodynamic diameter: nuclei mode (smaller than about 0.1 μm), accumulation mode (between approximately 0.1 and 1 μm) and coarse mode (larger than 1 μm).

### 1.2. Air quality standards and composition for PM

Epidemiological studies have indicated the relationship between adverse health effects and PM$_{2.5}$ and have also shown a correlation between elevated levels of airborne particle and increased rate of
morbidity and mortality [21–24]. Some studies suggested PM$_{2.5}$ to be more harmful to health than PM$_{10}$ [16, 25–27]. Therefore, ambient air quality standard across the globe has been set in terms of PM$_{10}$ and PM$_{2.5}$ (Table 2).

**Table 1.** Size ranges PM classified on the basis of mode of formation.

<table>
<thead>
<tr>
<th>PM type</th>
<th>Size ranges (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dust</td>
<td>1.0 to 10,000</td>
</tr>
<tr>
<td>Smoke</td>
<td>0.5 to 1.0</td>
</tr>
<tr>
<td>Fumes</td>
<td>0.03 to 0.3</td>
</tr>
<tr>
<td>Fly ash</td>
<td>1.0 to 1000</td>
</tr>
<tr>
<td>Mist</td>
<td>Less than 10</td>
</tr>
<tr>
<td>Spray</td>
<td>10 to 1000</td>
</tr>
</tbody>
</table>

**Figure 1.** Classification of PM based on (a) state in air, (b) size, (c) mode of formation and (d) significance.
The composition of PM also varies as they absorb and transfer a multitude of pollutants. When humans are exposed to pollutant mixtures than to single substances, the different composition of air pollutants, dose and time of exposure can lead to adverse impacts on human health. The PM may include a wide range of chemical species ranging from metals to organic and inorganic compounds. Trace metals, which are the most important ones among the inorganic compounds, are generally emitted by several natural and anthropogenic sources. These sources may include crustal materials, road dust, construction activities, motor vehicles, coal and oil combustion and other industrial activities [36,37]. Toxicity of particles mainly arise out of the chemical composition of the PM (Figure 3).

The trace metals, which are associated with PM, have been linked with both acute and chronic adverse health effects such as respiratory diseases, lung cancer, heart diseases and damage to other organs [38,39]. Harrison and Yin [39] introduced a term ‘bulk chemical composition’ which refers to the relative abundance of the major components such as sulphate, nitrate, ammonium, chloride, elemental and organic carbon, crustal materials, biological materials etc. Harrison and Jones [40] also stated that the PM may be consisted of major components, each of which represents a certain per cent of the total mass of a particle along with trace elements. These trace elements usually represent less than 1% of total particle mass. Aneja et al. [41] after elemental analysis for PM$_{10}$ samples, related to surface coal mining operations in Appalachia, revealed the presence of antimony, arsenic, beryllium, cadmium, chromium, cobalt, lead, manganese, mercury, nickel, selenium. Dubey et al. [42] carried out trace metal analysis through Atomic Absorption Spectrophotometer (AAS) and mean concentrations are found in the order of iron $>$ copper $>$ zinc $>$ manganese $>$ chromium $>$ cadmium $>$ lead $>$ nickel. Huertas et al. [43] characterised airborne particle sample collected from the opencast coal region located in northern Colombia through X-ray photoelectron spectroscopy (XPS) and reported that the main elements present in the particles with an equivalent aerodynamic diameter less than 10 $\mu$m (PM$_{10}$) are carbon, oxygen, potassium and silicon with average mass concentrations of 41.5, 34.7, 11.6 and 5.7%, respectively. Pandey et al. [44] stated that the highest mean concentration of heavy metal is for Fe followed by copper, zinc, manganese, lead, chromium, cadmium and nickel in PM$_{10}$ obtained from ambient air from different sites in Jharia Coal Field, Dhanbad, Jharkhand, India. Iron, copper, zinc, manganese, lead, chromium, cadmium and nickel contributions in PM$_{10}$ are 70.6, 14.6, 6.7, 5.6, 1.1, 1.1, 0.3 and 0.1%, respectively.

Figure 2. Typical distribution of three sizes or modes of particles in urban air.
1.3. World Energy scenario

Now-a-days the link between environmental issues and the development is one of the foremost issues and it is evident that development, progression has been accompanied by quick increases in energy demand [45]. These days energy is primarily produced by burning of fossil fuels such as coal, oil, natural gas, which in turn contaminates the environment significantly in different ways and at different levels [46,47]. Among all these abovementioned energy sources, coal is a principal resource, most abundantly present, and is also the cheapest source of energy [48]. It has been found that over the decade to 2010, coal accounted for nearly half the global increase in fuel use (World Energy Outlook 2011) as shown in Figure 4.

In percentage terms, growth in coal use over the decade also overtook growth in renewable. According to preliminary estimates, coal use accounted for 28% of global primary energy use in 2010,

<table>
<thead>
<tr>
<th>Country</th>
<th>PM size</th>
<th>Concentration in ambient air (µg m⁻³)</th>
<th>Time weighted average</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>India</td>
<td>PM₁₀</td>
<td>100</td>
<td>24 h</td>
<td>CPCB [28]</td>
</tr>
<tr>
<td></td>
<td>PM₂.₅</td>
<td>60</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>PM₁₀</td>
<td>60</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>PM₂.₅</td>
<td>40</td>
<td></td>
<td></td>
</tr>
<tr>
<td>US</td>
<td>PM₁₀</td>
<td>150</td>
<td>24 h</td>
<td>NAAQS [29]</td>
</tr>
<tr>
<td></td>
<td>PM₂.₅</td>
<td>35</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>PM₁₀</td>
<td>–</td>
<td>Annual</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PM₂.₅</td>
<td>12</td>
<td>Annual</td>
<td></td>
</tr>
<tr>
<td>European Union</td>
<td>PM₁₀</td>
<td>50</td>
<td>24 h</td>
<td>EU [30]</td>
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<tr>
<td></td>
<td>PM₂.₅</td>
<td>–</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>PM₁₀</td>
<td>40</td>
<td>Annual</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PM₂.₅</td>
<td>25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Canada</td>
<td>PM₁₀</td>
<td>–</td>
<td>24 h</td>
<td>CAAQS [31]</td>
</tr>
<tr>
<td></td>
<td>PM₂.₅</td>
<td>28</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>PM₁₀</td>
<td>–</td>
<td>Annual</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PM₂.₅</td>
<td>10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Australia</td>
<td>PM₁₀</td>
<td>50</td>
<td>24 h</td>
<td>Air NEPM [32]</td>
</tr>
<tr>
<td></td>
<td>PM₂.₅</td>
<td>25</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>PM₁₀</td>
<td>–</td>
<td>Annual</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PM₂.₅</td>
<td>8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>South Africa</td>
<td>PM₁₀</td>
<td>75</td>
<td>24 h</td>
<td>SAAQIS [33]</td>
</tr>
<tr>
<td></td>
<td>PM₂.₅</td>
<td>65</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>PM₁₀</td>
<td>20</td>
<td>Annual</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PM₂.₅</td>
<td>12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mexico</td>
<td>PM₁₀</td>
<td>120</td>
<td>24 h</td>
<td>NOM-025-SSA1-[34]</td>
</tr>
<tr>
<td></td>
<td>PM₂.₅</td>
<td>65</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>PM₁₀</td>
<td>50</td>
<td>Annual</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PM₂.₅</td>
<td>15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Japan</td>
<td>PM₁₀</td>
<td>–</td>
<td>24 h</td>
<td>EQS [35]</td>
</tr>
<tr>
<td></td>
<td>PM₂.₅</td>
<td>35</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>PM₁₀</td>
<td>–</td>
<td>Annual</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PM₂.₅</td>
<td>15</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 3. Factors affecting the toxicity of airborne PM.

Table 2. Ambient air quality standards for PM.
compared with 23% in 2000 (World Energy Outlook 2011). Coal provides 30.1% of global primary energy needs and generates over 40% of the world's electricity. In the present scenario, China and India together account about 45% of the increase in energy sector (World Energy Outlook 2012). A complete world coal generation came to a record level of 7822.8 Mt in 2013, expanding by 0.4% in comparison to the earlier year, 2012 (World Coal Association-Coal facts 2014). It is also used in the production of over 70% of the world's steel. So, it can be said that development is driven by energy and energy is driven by coal and opencast coal mining.

1.4. Energy scenario in India

In recent years, India's energy consumption has been increasing at one of the fastest rates in the world due to population growth and economic development. In order to meet the rapidly growing demand for electricity, power sector has grown at an exceptional rate during last few decades in India. Thermal power plants and hydro sectors are two major power producers in India. It is obvious that due to availability of fossil fuels, the power demand is met by power plants in India. As India has better coal reserves than other fossil fuels, power generation is totally dependent on the coal. Apart from coal, India is also abundantly endowed with renewable energy in the form of solar, wind, hydro and bio-energy and has very small hydrocarbon reserves of about 0.4% of the World’s reserve as stated by Roy and Singh [49].

1.5. Coal mining in India

The overall coal production and coal mining have tremendously increased in India in order to meet the energy requirement. Coal mining is one of the prominent core industries in India, which ranks third among top 10 coal producing countries (World Coal Association-Coal facts 2014) and plays a vital role in changing economic aspect of the country. The largest coal producing countries are not confined to one region. The top five hard coal producers are China, the USA, India, Australia and Indonesia as shown in Table 3 (IEA Coal Information 2015).

Table 4 shows the three major coal producing states in India in 2013–14 (Provisional Coal Statistics (Government of India, Ministry of Coal 2013–14). It has been found that the three major contributors are Chhattisgarh (22.46%), Jharkhand (19.97%) and Odisha (19.95%) which together accounted for about 62.38% of the total coal production in the country. Mandal et al. [50] reported that most of the coal production in India comes from opencast mines which contribute over 90% of the total production and remaining 10% from underground mines.
The main objective of the review paper is to assess the possible source, generation and dispersion of PM pollution from opencast coal mining and its adverse health effect. In this paper source of PM pollution due to coal mining, its adverse health effect and dispersion in mine are discussed.

2. Air pollution in coal mining areas

Air pollution from coal mines is mainly due to the fugitive emission of PM and gases, including methane, sulphur dioxide and oxides of nitrogen. In comparison to underground mines, opencast coal mines give higher production due to the large-scale operations and use of high capacity and heavy machines. These machines sometimes generate huge quantities of PM leading to enhanced pollution levels in and around opencast coal mines. This PM includes the raw material mined and particles types in the nearby haul road that is carried by the wind and some transportation movement in the working mine environment. The activities which are associated with coal mining are the main sources of PM in coal mining areas. Different types of mining activities (e.g., drilling, blasting, loading, unloading and transport of material) generate PM in various size ranges. With the increase in depth of mines the movement and dispersion of particulate matter is very difficult due to improper ventilation. Less amount of dispersion directly increases the time and exposure of PM on worker. Naidoo et al. [51] studied that workers at various places are exposed to different levels of PM, depending on their location and association with a particular mining activity.

Keeping in view the aforementioned issues that have been raised due to generation and dispersion of PM during several activities in opencast coal mining areas, efforts have been made to focus on certain adverse effects of PM (especially PM$_{10}$ and PM$_{2.5}$) on human health and environment starting with a brief introduction to PM along with its classification and composition. Apart from these aspects mentioned issues ambient air quality standards across the globe in terms of PM$_{10}$ and PM$_{2.5}$ are summarised along with some relevant findings of past coal mine exposure studies. The major aspects of this review which are described above are depicted in Figure 5.

2.1. Activities responsible for PM emission during opencast coal mining

The degradation of air quality is a major concern in the opencast mining [40,43]. It is of more concern in case of coal mines where different operations in opencast mining contribute huge amounts of PM to the surrounding atmosphere that are very harmful to human health and environment [52–55]. As impacts of PM from mining operations on human health and environment got widely reported, studies on generation and dispersion of PM during mining operations were carried out [56]. Several studies focused on estimation of PM generated by a mining activity whereas some studies measured the contribution of a surface mine to the PM level in atmosphere near the mine, which is discussed below. Most
of the studies reported that mining operations generate more inhalable coarse PM (PM$_{2.5-10}$) than fines (PM$_{2.5}$) [41,56]. The activities responsible for generation of PM of different sizes with different concentrations in and around opencast coal mining areas which are the sources of PM emission [57–60] are described below. Figure 6 shows certain activities responsible for generation of PM along with some vital locations, which are the sources of PM emission. The operations and their corresponding contributions to the generation of PM are shown in Figure 7 [61].

2.2. Top soil removal

The first step in an opencast coal mining operation is to remove the topsoil from the area that is to be mined. After the removal, it is stored in a location away from the mine area to be used for reclamation of the mine area later. Once the topsoil is removed the overburden, which is generally a waste material overlying the coal, is exposed. The overburden normally consists of rock and must be loosened or broken by drilling and blasting the material. This is done by creating a pattern of blast holes. This operation is therefore the first stage of PM generation for an opencast coal mine [62]. Ghose and Majee [61] calculated that 660 kg d$^{-1}$ dust is generated due to overburden removal in Indian coal mines.

2.3. Drilling and blasting

After the blast pattern is loaded with explosives, the area is cleared and the explosives are set off. Removal of the overburden begins, once the explosives are set off. Removal of the coal sometimes may require drilling and blasting. If so, then the steps in the drilling and blasting section are repeated. A loader removes the overburden by loading it into trucks that haul it to a waste dump for storage. The overburden is then dumped and the material is spread out over the waste dump by bulldozers. Drilling which is the second unit operation, leads to generation of significant amount of PM [46].
Ghose and Majee [61] estimated the dust concentration levels during drilling and reported that in overburden benches it may be between 20 and 25 mg m$^{-3}$, and in coal benches it may be between 15 and 30 mg m$^{-3}$. Blasting which is the third unit operation, results in short term exposure of particulate pollutant, but the concentration of pollutant remains very high. Dust emission mechanism of drilling and blasting operation is air flush from drilling and from force of the blast.

2.4. Loading, unloading and transport of overburden and coal

A loader removes the coal by loading it into trucks that haul it to a processing plant where the coal is processed to its final stage and ultimately sold to the public. The pollution remains very high at the point of loading and unloading. Gautamet al. [63] stated that during transport, haul road becomes a major source of airborne particle due to road-type interaction and for friable material, if unpaved, direct emissions during transport also contribute to air pollution. Mandal et al. [50] reported that
80.2% of total dust emission is from transport road of Indian mines. Dropping materials from heights is the emission mechanism for loading and dumping.

### 2.5. Processing of coal

Process of the ore consists of extracting the final product from the rock and emission mechanism involves impact, abrasion and also dropping from heights.

Apart from these aforementioned activities, the presence of fire also tends to increase in concentrations of PM pollutants in the atmosphere finally leading to severe air pollution around coal mining areas [64]. It has been observed out of total PM generated, the PM$_{10}$ constitute one-third to half [61,65]. Hence, it can be concluded that highly mechanised opencast coal mining generates huge amount of air borne dust that may cause safety and health hazards. These may ultimately reduce working efficiency through poor visibility, failure of equipment, increase in maintenance cost and lowering of labour productivity.

### 3. Factors influencing dispersion of PM in opencast mine

Size, shape, density, nature of particles as well as meteorology and locality are the prominent parameters that are influencing the movement and spread of PM in surrounding [66,67]. Factors those are influencing dispersion of PM may be categorised into following classes as shown in Figure 8.

- **Meteorological factors**
  - Wind speed & direction
  - Atmospheric stability
  - Thermal effects

- **Topographical factors**
  - Slopes and benches
  - Depth of the open pit
  - Length and width of the open pit
  - Aspect ratio

![Factors influencing dispersion of PM in opencast mine](image)

**Figure 8.** Factors influencing dispersion of PM in opencast mine.

Wind flow is considered to be the prime mover of the particulate pollution from one place to another. Several studies were carried out to simulate wind flow pattern with the assumption that particulate matter dispersion will follow it. The flow in the mine could be turbulent at one place, whereas at other places it could be laminar [68]. Recirculation also takes place at different locations inside the mine [69]. Wind speed and wind flow path inside the pit are largely influenced by the pit geometry i.e. length of the pit (L), depth of the pit (D) and width of the pit (W). Larchevéque et al. [70] classified the pit geometry on the basis of aspect ratio (ratio of length (L) to depth of the mine (D)) as shown in Table 5. Depending upon the aspect ratio, Chowdhary [71] reported that wind velocity will be more in shallow mines than in deep mines.

Previous researchers stated that the atmospheric stability also affects the flow in the mine by influencing the vertical motion. They also reported that pollutants get deposited as the stable atmosphere suppresses the vertical motion of the pollutants whereas in case of unstable and neutral conditions it has been found that the escape fraction of particulates is more [71–73]. Particle travel time may be defined as the time taken by PM to any other location of interest under different meteorological conditions [66]. Fast removal from work place due to short travel time causes early return of PM concentration to the ambient level at the work place.
As the opencast mines go deeper dispersion of PM from mines become more complex due to improper ventilation in deeper parts of the mine. The complexity of PM dispersion further increases due to multiple sources located at deeper parts of the mine.

### 4. Variation in PM exposure in an opencast mine

As discussed earlier, workers working at different places inside a mine are exposed to different levels of PM depending on their location and association with the mining operation. Gautam and Patra [66] reported that PM generated at the lower benches of a mine travel across all other higher benches before it escapes the mine. Time taken by the PM generated at a certain depth to escape the mine is therefore important. If the time taken for the PM to escape the mine is very long, it indicates that workers inside the mine are exposed to elevated concentration for a longer duration. On the other hand, if the PM escapes the mine in a short time, its adverse effect on health will be less due to less exposure duration [65]. Further, as the PM travel from lower part of the mine to upper horizons, not all the particles travel at the same speed and proportion. A coarse particle with higher settling velocity settles on mine floor faster than a fine particle.

Past literature on adverse health effects of PM showed associations between higher PM concentration and exposure such as ‘Black lung’ diseases are observed in higher number in coal mine workers due to PM exposure from coal dust [74], because accumulation of PM in dipper part of lung, several sample of identified in coal mining area [75], higher exposure (1.5 per person year) to PM from opencast coal mining is reported near the opencast coal mines [76] and different type of diseases like black lung, hypertension and kidney diseases are reported due to coal dust [77].

Exposure of mine workers to PM in opencast coal mines is of greater importance because of associated adverse health effects. As dispersion of PM in such mines, depends on their design and local meteorological conditions as stated before, with increase in depth of mines efficient vertical movement and the dispersion of PM away from mine working area become more difficult. For example, an operator who is engaged in drilling blast holes works in both overburden and ore benches may not expose to same PM level because the dispersion from these two operations at different locations will not be the same because of variation in pit geometry and micro-meteorology (mainly wind direction and wind speed) inside the mine.

### 5. Impact of PM generated due to opencast coal on human health and surrounding environment

The significant adverse impact of PM on health is of greater importance than all air pollutants [78–80]. Size of a particle determines its penetrability into deeper parts of the lungs and therefore it is considered to be the most important parameter in assessing different diseases or health hazards. As inhaled particulates pass through the different stages of the respiratory system of a human being they are named according to their sizes as shown in Figure 9. Some studies indicated increased level of disease in the human body due to exposure of PM emission from opencast mines [74, 75, 77, 81].

<table>
<thead>
<tr>
<th>Pit geometry</th>
<th>Aspect ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shallow pit</td>
<td>L/D &gt; 1</td>
</tr>
<tr>
<td>Deep pit</td>
<td>L/D &lt; 1</td>
</tr>
<tr>
<td>Open pit</td>
<td>L/D &lt; 10</td>
</tr>
<tr>
<td>Closed pit</td>
<td>L/D &gt; 13</td>
</tr>
<tr>
<td>Two dimensional</td>
<td>L/W &gt; 1</td>
</tr>
<tr>
<td>Three dimensional</td>
<td>L/W &gt; 1</td>
</tr>
</tbody>
</table>
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Adverse health effects of PM generated during coal mining showed association of increased PM concentration with several diseases, which are summarised in Figure 10 [82–86]. Harrison and Yin [39] identified several factors that may influence the toxicity of airborne PM as depicted in Figure 10.

6. Evidences of adverse effects of PM generated during coal mining on health as well as environment

It has been reported that the quantity of arsenic is high in atmosphere in some coal mining areas [74, 81]. According to Huang et al. [83], the pyrite content of coal is associated with the occurrence of coal workers’ pneumoconiosis. Inhalation of silica laden particle leads to a carcinogenic disease known as silicosis [87,88]. Long-term exposure of silica, which is often associated with coal seam as sandstone bands, can cause pulmonary diseases [39]. One of the most damaging to the health is the silicate based respirable fraction of mine dust. Inhalation of crystalline silica can result in silicosis [89, 90] and can ultimately result in tuberculosis [82]. Increased level of silica in mining area is a major problem in the surrounding area of mines and this has attracted considerable investigations [91]. From some research works conducted earlier it is evident that rank of coal is more responsible for coal workers’ pneumoconiosis [92,93]. A summary of relevant past coal mines exposure studies is presented in Table 6.

From this point of view, a focus on the occupational hazards and overall condition of surrounding atmosphere in Indian opencast coal mines are felt to be important. Simple Coal Workers’
Pneumoconiosis (SCWP) and Progressive Massive Fibrosis (PMF) are the chief occupational respiratory diseases that are caused by exposure to respirable particles generated during various opencast coal mining operations. Donoghue [96] also described coal dust as one of the chemical hazards causing coal workers’ pneumoconiosis or ‘black lung’ and chronic obstructive pulmonary disease. Numerous studies suggest that health effects are not only restricted to occasional episodes when pollutants are particularly at high levels but also at particulate levels that are at or below the permitted levels set under national and international air quality standards. There are other adverse impacts from PM10 exposure in addition to health effects. It is known that even small particles in the air hinder visibility, as the small particles generally scatter and absorb light when it travels to the observer from a source. USEPA [97] conducted numerous studies which show the association of PM pollution with acute change in lung function and respiratory illness. Ultimately these lead to increased hospital admissions for respiratory disease and heart disease, school and job absences from respiratory infections, or augmentation of prolonged conditions such as asthma and bronchitis USEPA [97]. Recently, many demonstrative and sometimes controversial evidences are shown from a number of epidemiological studies [98, 99] which have linked short-term increase in particulate level, such as those occur during major pollution events, with immediate (within 24 h) increase in mortality. This pollution-induced spike in the death

<table>
<thead>
<tr>
<th>Study area</th>
<th>Key findings</th>
<th>Author (year)</th>
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<tbody>
<tr>
<td>Spain</td>
<td>Mining operations may be releasing toxic substances which may lead to a health problem to populations. Detection of excess mortality of colorectal cancer, lung cancer specifically related to opencast coal mining</td>
<td>Frenandez-Navarro et al. [94]</td>
</tr>
<tr>
<td>Coal mining areas of Appalachia</td>
<td>Environmental exposure to PM or toxic agents present in coal and released in its mining and processing may lead to higher chronic heart, respiratory and kidney disease mortality in coal mining areas</td>
<td>Hendryx [77]</td>
</tr>
<tr>
<td>West Virginia</td>
<td>High levels of coal production are associated with high rates of cardiovascular disease, hypertension, lung disease, kidney disease, etc.</td>
<td>Hendryx and Ahern [75]</td>
</tr>
<tr>
<td>China</td>
<td>Human disease associated with coal mining mainly results from inhalation of PM during the mining process. The disease is black lung disease (Coal Worker’s Pneumoconiosis) characterised by coal dust-induced lesions in the gas exchange regions of the lung</td>
<td>Finkelman et al. [74]</td>
</tr>
<tr>
<td>England</td>
<td>Children in opencast communities are exposed to a small but significant amount of additional PM10, to which the opencast sites are a measurable contributor. Evidences are also found for associations between living near an opencast site and an increased frequency of respiratory illness, asthma severity, etc.</td>
<td>Pless-Mulloli et al. [76]</td>
</tr>
<tr>
<td>UK</td>
<td>Identified the evidences of pneumoconiosis and other respiratory health effects associated with exposure to respirable mixed dust and quartz</td>
<td>Love et al. [95]</td>
</tr>
</tbody>
</table>
ranges from 2 to 8% for every 50 \mu g m^{-3} increase in particulate levels as stated by Roy et al. [100]. Climate change may also occur from PM\textsubscript{10} exposure as the small particles in the atmosphere absorb and reflect the radiation from the sun USEPA [20].

7. Discussion and conclusion

It can be said, the future demand of coal will be very high with the rapid growth of industries. But the utilisation of coal would be associated with environmental disruption which includes air quality deterioration due to the generation and dispersion of PM from various mining operations. Increasing level of PM is considered to be the most serious problem in opencast coal mining areas. Further, certain aspects of air pollution issues due to PM generation and dispersion in case of opencast coal mines need to be addressed as shown in Figure 11.

In this paper, attempts have focused on the contribution of air pollution of an opencast coal mining areas. This paper starts with the brief introduction to PM where classification, composition of PMs and their emission of different sizes from several opencast coal mining activities are discussed.

It is evident that several studies have focused on the contribution of an opencast coal mine to PM level. It has been studied that the degree of impact is also dependent on the size of the PM. Thoracic particles are generally larger than respirable particles which can reach deeper parts of the lungs causing more serious lung damage. The above review shows the adverse effects on health as well as environment due to inhalation of PM in opencast coal mining areas. Most of the studies have also reported that mining operations generate more inhalable coarse PM than fines. Determination of the respirable dust exposure of opencast coal mines through proper monitoring techniques will help to investigate relationships between such exposures and respiratory diseases.

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