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Screening potential plant species for arresting particulates in Jharia coalfield, India

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Abstract

Mining and related activities cause severe degradation of ambient air quality. A study of particulate matter (PM) across transportation, mining and control (C) sites for dust attenuation capacity (DAC) in selected tree species were carried out in Jharia coalfield (JCF) to estimate the menace of dust pollution and also to measure air pollution tolerance index (APTI). Results indicated that the maximum value of PM_{10} and $PM_{2.5}$ ranged from 54 to 174 and 29 to 78 μg m^{-3} respectively across all the sites. The maximum values occurred in transportation and the minimum at C for both the particulates. Mining and transportation resulted in an increase in PM_{10} values by 161 and 200% and $PM_{2.5}$ values by 100 and 136% respectively as compared to those in C. The mean concentration of PM_{10} and $PM_{2.5}$ across the sites exceeded the permissible limit of 100 and 60 μg m^{-3} respectively. Transportation was worse than mining due to the high proportion of hazardous fine ($PM_{2.5}$) particulates. DAC indicated that *Tectona grandis* (*TG*) captured maximum dust (2.15 mg cm^{-2}) with 85% and *Peltophorum inerme (PI)* the minimum (0.15 mg cm^{-2}) with 5% efficiency. The trend for DAC showed *TG* > *Ficus glomerata (FG)* > *Psidium guajava (PG)* > *Ficus benghalensis (FB)* > *Ficus religiosa (FR)* > *Alstonia scholaris (AS)* > *Aegle marmelos (AM)* > *Gmelina arborea (GA)* > *Dalbergia sissoo (DS)* > *Syzyzium cumini (SC)* > *Azadirachta indica (AI)* > *Terminalia arjuna (TA)* > *Mangifera indica (MI)* > *Albizia lebbeck (AL)* > *PI* in descending order. APTI based on pH, total chlorophyll, ascorbic acid and relative water content indicated maximum values for *TG* (17) with 90% and minimum for *PI* (10) with 57% of the total and is a measure of the sustainability of plants in JCF. The descending order for APTI was *TG* > *PG* > *FG* > *FR* > *FB* > *AI* > *MI* > *SC* > *DS* > *GA* > *AM* > *AS* > *AL* > *TA* > *PI*. Thus, *TG* is the most suitable and *PI* the least. Stomatal density is negatively related to DAC and positively related to APTI. DAC therefore, cannot be attributed to a single factor but a mix of complex factors such as morphological and anatomical characteristics of the leaf, particle size, species type, metabolism, location, meteorology and stress conditions. Based on the findings a greenbelt design was proposed to improve the air quality of the mining and transportation areas.

Keywords: JCF, PM, DAC, Green Belt, Biofilter, APTI

Introduction

India is the world's fastest-growing economy with a population of 1.3 billion and is the fourth-largest producer of coal. High-grade coking coal in India is mainly located in Jharia and Raniganj coalfield and is the most prolific coal mining area in our country. Traditionally, coal mining was considered one of the most polluting industries having a significant environmental impact if proper management strategies are not adopted. Historically, mining was executed with the main object of mineral beneficiation with little or no consideration towards the environment, local community or holistic development. Mining activity is the major contributor to air pollution apart from other industrial activities of this region along with transportation activity, poor road condition, coke oven plants and other industries.

The coal-burning releases harmful gases as well as particulate matter and its transportation with mine wastes

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has been recognized as the prime source of suspended particulate matter (SPM) with the dominance of < 10 μ size. Hazardous level of air pollution has been found in coal-burning areas. Mining depletes vegetation causing extended soil erosion altering the microbial ecosystem. Coal mining also affects the local, regional and global environment through the release of coalbed methane, which is twenty-three times as powerful as carbon dioxide as a greenhouse gas [1]. Coal mining thus badly impacts air quality and is one of the most potent sources of multi-faceted environmental pollution, hence requires efficient mine planning, design and an equally effective scientific environmental management with the mine closure plan. The best practice will always set the limits on the procedure to be followed keeping cost-benefit in mind.

The capacity of plants to check air pollution is well recognized and cited in the standard literature on numerous occasions [2–5]. Foliar uptake [5–7] of metal and metalloid particulates is reported by many authors [8–11]. Several studies have attempted on the arrest of air pollutants by avenue plants [6, 12–15]. Plantation of evergreen and deciduous trees with high tolerance capacities for effectively mitigating the air quality by abrasion, sedimentation, adsorption and absorption of pollutants is the desired option. Screening of plant species with proper spacing for controlling fine (< 2.5 μ) dust [5, 6, 15, 16] in vulnerable areas can thus be selected. Dust attenuation capacity (DAC) is attributed to its outer morphology and inner metabolism [17]. A greenbelt development with the screened plant species would arrest and reduce the pollutant dispersion.

Catalysts with suitable metal combinations can also be used to arrest air-borne particulates through adsorption and absorption. The catalyst made from 75% waste aluminum foil was reported by Osman et al. [18, 19] having enhanced gas burning efficiency leading to reduction of vehicle pollutant emission. Photocatalytic layer coating in the form of titanium dioxide (TiO_2) has been known to reduce particulate matter of < 10 μ (PM_{10}) and < 2.5 μ ($PM_{2.5}$) size by 30% [18] due to UV irradiation of carbonaceous compounds present in ambient particulates with the release of CO_2 resulting in 92% reduction in total carbon [19]. More recent research with other catalysts is targeted in this area with a wide application scenario in the future.

The present study emphasizes on the vegetative remediation of ambient particulates having a sustainable approach keeping long term accruing benefits for people's health of Jharia coalfield (JCF) region. Current task is an attempt to estimate the dust emission due to coal mining activities, road transportation and its impact on ambient air quality along with DAC and tolerance index of selected plant species to put forth a cost-effective management plan in the form of a greenbelt designed to improve the air quality of JCF region. Previous studies [20, 21] made in JCF have pointed to the development of a green belt but no one elaborated screening of plant species for sustainability based on DAC and air pollution tolerance index (APTI) based on principles of ecological engineering. This study will bridge such gap and will make way for effective air pollution control of the region.

Materials and methods

The ambient air monitoring stations were selected following guidelines of the Central Pollution Control Board [22], India, based on the micrometeorological conditions of the area and the mining practices, methods of working, locality, openness and especially resource availability. Location sites are shown in Table 1. Method and instruments used are shown in Table 2. The approach was to see that mining activities and locations covered loading, drilling, blasting, transport and haul road, barren overburden dumps, stockyard, coal handling plant, workshop and open mine face.

Study site

The study sites are situated in Dhanbad district, the Jharkhand state of India between 23° 04′ to 23° 5′ N longitude 86° 2′ to 86° 3′ E latitude (Fig. 1 and Table 1). The selected sites comprised of coal mines dominated by opencast operations [Jeenagora (MA), Amjhar (MB) and Aamtal (MC)], transportation [Barwa Road (BR)] and a control site [CSIR-CIMFR (C)]. The drainage pattern of the area is controlled by Damodar river flowing west to east along the southern periphery and its tributaries viz. Jamunia, Khudia, Katri, Ekra, Tisra, Chatkari rivers. Soil cover is the alluvial type with low organic matter and impoverished nutrients. A coal-bearing Gondwana superstratum lies beneath this soil cover. The area is mostly surrounded by the Archean rocks with fine to medium-grained buff-colored sandstone, greyish to greenish micaceous shale, coal seams and siltstones.

The selection of the different study sites was based on contribution to the dust load such as transportation and mining in particular and to devise effective control measures to curtail finer dust. These sites represent their respective categories in perfect measure so that the methodology adopted to estimate and devise dust control mechanism takes all relevant variables in mind. The steps taken and procedure adopted are based on the Environmental Protection Agency (USA) guidelines followed by the Government of India [22, 23] and are reproducible. However, variations may occur based on mining methods and climatic factors.

Table 1 Details of air sampling locations in Jharia coalfield

Code	Location	Latitude-longitude	Source of air pollution
C	CSIR-CIMFR	23°49′5″ N 86°25′41″ E	A mixed-forest of planted trees, herbs, and shrubs, official premises, minimum traffic (light and medium vehicle), paved road, encircling residential complexes, the highway at 1 km distance.
BR	Barwa road	23°48′39″ N 86°25′56″ E	Heavy public traffic on the highway, paved road, commercial activities, residential colonies on both sides, least avenue trees.
MA	Jeenagora	23°42′8″ N 86°26′25″ E	Mining activities surrounding the site, poor roads, and low public traffic, coke oven plants, of coal-burning and allied industries, sparse trees.
MB	Amjhar	23°43′34″ N 86°29′36″ E	Mining activities surrounding the site, paved road, low traffic, coal burning, coke-oven plants, a forest of *Tectona grandis* surrounding the site.
MC	Aamtal	23°45′2″ N 86°26′42″ E	Mining and allied activities at 1 km distance, paved road, low traffic, coal burning, sparse plantations.

The area is having a tropical climate and is characterized by a very hot summer and cold winter. The temperature in the summer months (March to June) varies from the lowest minimum of 15 °C (March) to the highest maximum of 46 °C (June), in the colder months (November to February) from the lowest minimum of 8 °C to the highest maximum of 35 °C and in the rainy season (July to October), the temperature varies from 16 to 36 °C. Relative humidity (RH) is high on rainy days (94%) in July and low in October (36%). Thunderstorms usually occur in June and July accompanied by a temporary fall in temperature. The area receives annual precipitation of about 1000–1200 mm, out of which 75–80% occurs from June to September with a smaller amount during winter.

Vegetation

The vegetation is tropical dry deciduous dominated by woody savanna with high biodiversity mainly due to topographic and edaphic factors. Soil is usually red loam to lateritic. Rainfall occurs from June to October with a maximum of 1200 mm during July–August. *Shorea robusta* is the dominating tree of JCF region. Other major trees are *Butea monosperma, Aegle marmelos (AM), Azadirachta indica (AI), Dalbergia sissoo (DS), Ficus benghalensis (FB), Ficus glomerata (FG), Ficus religiosa (FR), Mangifera indica (MI), Psidium guajava (PG), Cassia fistula, Syzygium cumini (SC), Alstonia scholaris (AS), Tectona grandis (TG), Albizia lebbeck (AL), Gmelina arborea (GA), Peltophorum inerme (PI), Terminalia arjuna (TA), Tamarindus indica, Holarrhena antidysenterica, Madhuca indica* and *Anthocephalus cadamba. Heteropogon contortus, Saccharum spontaneum, Cynodon dactylon, Cymbopogon* and *Bothrichloa* are the frequently occurring grass species. Fifteen species were selected for dust attenuation studies. An additional file shows morphological and anatomical characteristics of the selected tree species [see Additional file 1].

Table 2 Methodology and instrument used for air quality analysis

Parameter	Method	Instrument
$PM_{2.5}$	Gravimetric and Beta attenuation Method	APM550 as per USEPA guidelines
PM_{10}	Gravimetric and Beta attenuation Method	APM550 as per USEPA guidelines
pH	Conductivity	pH meter
Total chlorophyll and ascorbic acid	Machlachlan and Zalik, 1963 and Keller and Schwager, 1977 respectively	Centrifuge, Spectrophotometer
Relative water content	Weatherly, 1965	Oven

Sampling

The study sites were selected and divided into three categories based on pollution load, e.g., transportation and mining with a control site for PM_{10} and $PM_{2.5}$ sampling. Monitoring was undertaken at different study sites during pre-monsoon (March–June) and post-monsoon (Nov-Feb) seasons, due to intensive excavation activities at coal mines.

Air monitoring for PM_{10} and $PM_{2.5}$ was done for 24 h on 15-d intervals at each site and concentration were expressed as $\mu g\ m^{-3}$. The mean value for dust was calculated for 24 h based on the National Ambient Air Quality Standard [23], India. The PM_{10} and $PM_{2.5}$ were sampled by ambient air sampler (model APM550, Envirotech Instruments, India). The concentration of particulates was determined gravimetrically [23] (Table 2). The concentration of SPM ($\mu g\ m^{-3}$) is computed by measuring the mass of collected particles and the volume of air sampled.

Dust deposition

Ten replicates of the fully-grown leaf of the selected plants were collected randomly in the early morning

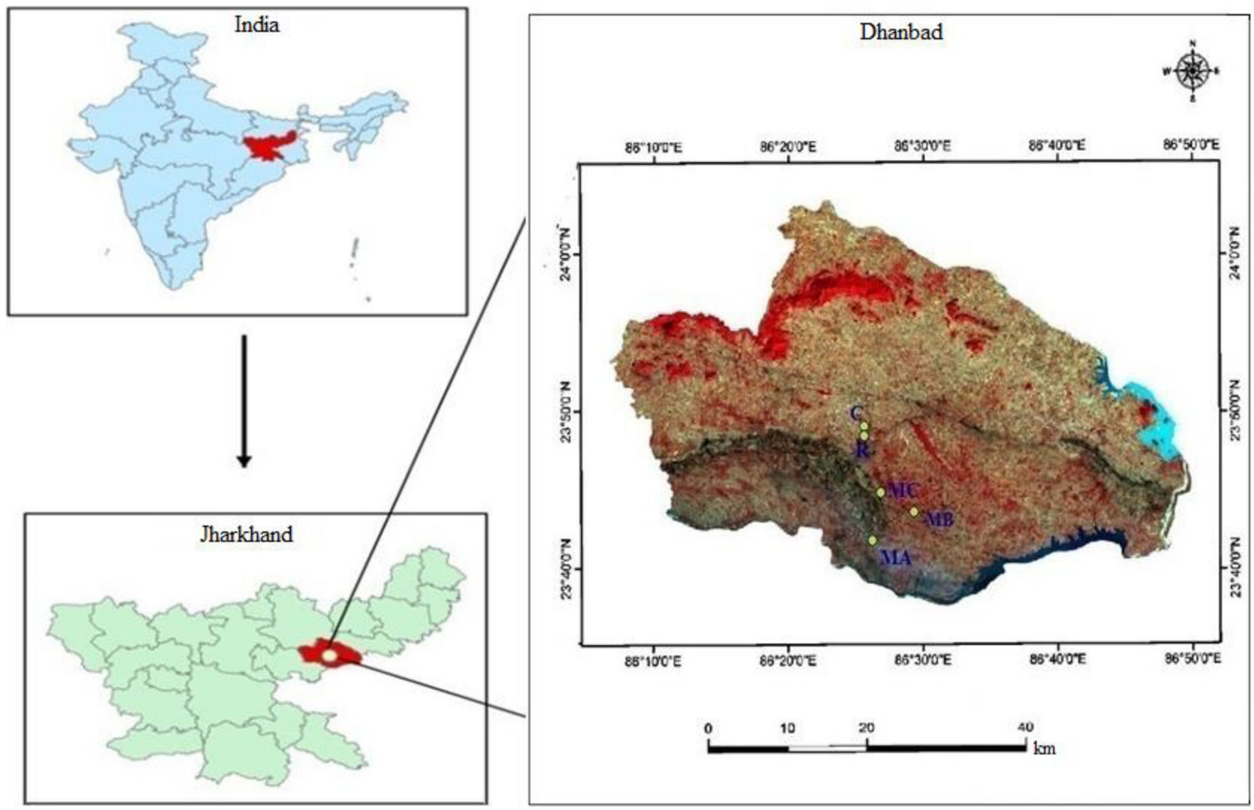

Fig. 1 Location map of the study area

from branches at a height of 2–4 m and were transferred quickly to the laboratory in polythene bag within 24 h and kept in the ice-box for further analysis. The amount of dust was calculated by taking the initial and final weight of the beaker in which unwashed and washed leaf samples were kept. It was calculated by using the Eq. (1) [14].

$$W = \frac{W2 - W1}{A} \tag{1}$$

where, W = Dust deposition ($g\ cm^{-2}$), W1 = Weight of beaker without dust in g, W2 = Weight of the beaker with dust in g, A = Total leaf area in cm^2.

Dust deposition was calculated yearly for attenuation capacity estimation under natural conditions.

Leaf area

Conventional graphical methods were used for calculating the leaf area. Fresh leaf was placed on the graph paper and the outer boundary was drawn with a sharp pencil. The blocks were counted to calculate the surface area of the leaf. Utmost care was taken to count smaller blocks.

pH, total chlorophyll, ascorbic acid and relative water content

A total of 100 g of the fresh leaf was crushed to paste, mixed with 10 mL of distilled water and centrifuged for 15 min. The supernatant was taken out and shaken well to measure pH by Orion meter. To estimate the chlorophyll, 0.1 g of the fresh leaf of the desired species was taken in 10 mL of 80% acetone and kept for 24 h at 4 °C. It was mixed uniformly and centrifuged at 6000 *g* for 15 min. Optical density was measured at 480, 510, 645 and 663 nm. Chlorophyll a and b were calculated using the formula described by Maclachlan and Zalik [24]. To estimate the ascorbic acid, 0.5 g of a fresh leaf was homogenized in a 20 mL extracting solution (5 g oxalic acid + 0.75 EDTA-Na_2 in 1000 mL of deionized water) in an ice bath for 30 s. The homogenate samples were centrifuged at 6000 *g* for 15 min. 5 mL of 2,6-dichlorophenol-indophenol was poured into 1 mL of leaf extract, shaken vigorously. Optical density was measured at 520 nm by Spectronic*20D* spectrophotometer. 1 mL of 1% ascorbic acid was added to discolor the solution and absorbance taken again at 540 nm. 1% ascorbic acid (aqueous) was used to obtain the calibration curve [25]. For determination of Relative Water Content (RWC), fresh weight (Wf) of the leaf sample was taken and kept in water for 24 h for saturation. The turgid weight (Wt) was also taken. The leaf sample was again put into the oven at sufficient temperature to get dried completely. The dried leaf was again reweighed (Wd). The RWC was determined using Eq. (2) [26].

$$RWC = \frac{\mathrm{Wf}-\mathrm{Wd}}{\mathrm{Wt}-\mathrm{Wd}} \tag{2}$$

Stomatal density

The study was performed by an optical microscope (Leica DM300) with eyepiece and objective lens (OL) having a magnification of 10x and 40x respectively with a field view of 0.045 mm diameter. The stomatal count was performed manually corresponding to the 40x OL area (πr^2) for stomatal density (SD) calculation.

APTI

Determination of APTI was done based on the formula given by Singh and Rao [27].

$$APTI = \frac{\mathrm{AA}\ (\mathrm{TC}+\mathrm{P})+\mathrm{RWC}}{10} \tag{3}$$

where, AA = Ascorbic acid; TC = Total chlorophyll; P = pH; and RWC = Relative water content.

Statistical analysis

SPSS (Ver 16.0) was used to generate dendrograms and Pearson correlation for LA, P, TC, RWC, DAC and APTI.

Results and discussion

PM_{10} and $PM_{2.5}$

Analytical data for PM_{10} and $PM_{2.5}$ are shown in Table 3. The maximum value of PM_{10} and $PM_{2.5}$ ranged from 54 to 174 and 29 to 78 μg m^{-3} respectively across all the sites. The maximum values occurred in BR and the minimum was at C for both the particulates. Mining and transportation resulted in an increase in PM_{10} values by 161 and 200% and $PM_{2.5}$ values by 100 and 136%, respectively, as compared to those in C. The mean concentration of PM_{10} and $PM_{2.5}$ across the sites exceeded the permissible limit of 100 and 60 μg m^{-3} [23]. Higher concentrations of PM_{10} in mining areas can be attributed to operational strip-mining activities, up and downwind direction. The mean values of $PM_{2.5}$ revealed that transportation sites had a higher percentage of finer particulates and were worse than mining due to heavy automobile exhaust emission and adjacent burning of coal for fuel use. Therefore, mining cannot be blamed singularly for fine particulate emission. Mean value below the permissible limit for MC (52 μg m^{-3}) can be attributed to downwind location from the mine and plantations of native dust arresting trees near the site. Air Quality Index remains largely unhealthy (151 to 200) to severe (201 to 300) categories with a minimum in summer and highest in winter months [28].

Table 3 PM_{10} and $PM_{2.5}$ across different study sites

		PM_{10} (μg m^{-3})				$PM_{2.5}$ (μg m^{-3})				
Location	Code	Max	Min	Ave	Std.	Max	Min	Ave	Std.	AQI*
CSIR-CIMFR	C	60	54	57	100	33	29	31	60	185
Barwa road	BR	174	162	168	100	78	69	74	60	
Jeenagora	MA	148	135	142	100	70	62	66	60	
Amjhar	MB	173	157	165	100	76	64	70	60	
Aamtal	MC	146	129	138	100	58	46	52	60	

*yearly average of all-season [28]

The air quality highly depends on meteorology such as wind velocity and direction. The predominant wind direction during sampling was S to N in winter, SE to NW in the summer season, respectively. The area is characterized by small to large mine voids, dumps, rivulets, tributaries and small hillocks with the average wind speed of 4–5 m s^{-1} and the wind circulating within the area. These characteristics do not allow dust-laden wind to escape and the particulate deposition occurs within the area. However, few sites do not have such obstructions leading to smooth wind flow taking particulates away. Temperature and moisture greatly impact the process of inversion. It is highest (> 80%) during Dec-Jan. and lowest (< 17%) during May–June due to low (7–20 °C) and high (34–43 °C) temperature, respectively. Rainfall impact is negligible on the particulate deposition during winter and summer months due to minimal rainfall (100–400 mm). The sky is clear and thunderstorms are occasional during both the seasons. The concentration of dispersed particulates of an area declines with the increasing distance from the mining area towards the NE, the annual predominant wind direction. The SPM concentrations decreased with increasing distance from the emission source. Wind direction alters from time to time and accountable for the scattering of air pollutants to an unidentified location. The trend of PM_{10} and $PM_{2.5}$ are indicated in Fig. 2a and b across study sites.

Screening plant species for dust attenuation

Mechanism

The characteristics of the ambient particulate and plant leaf form an important criterion of DAC evaluation [29]. These include both solid and liquid such

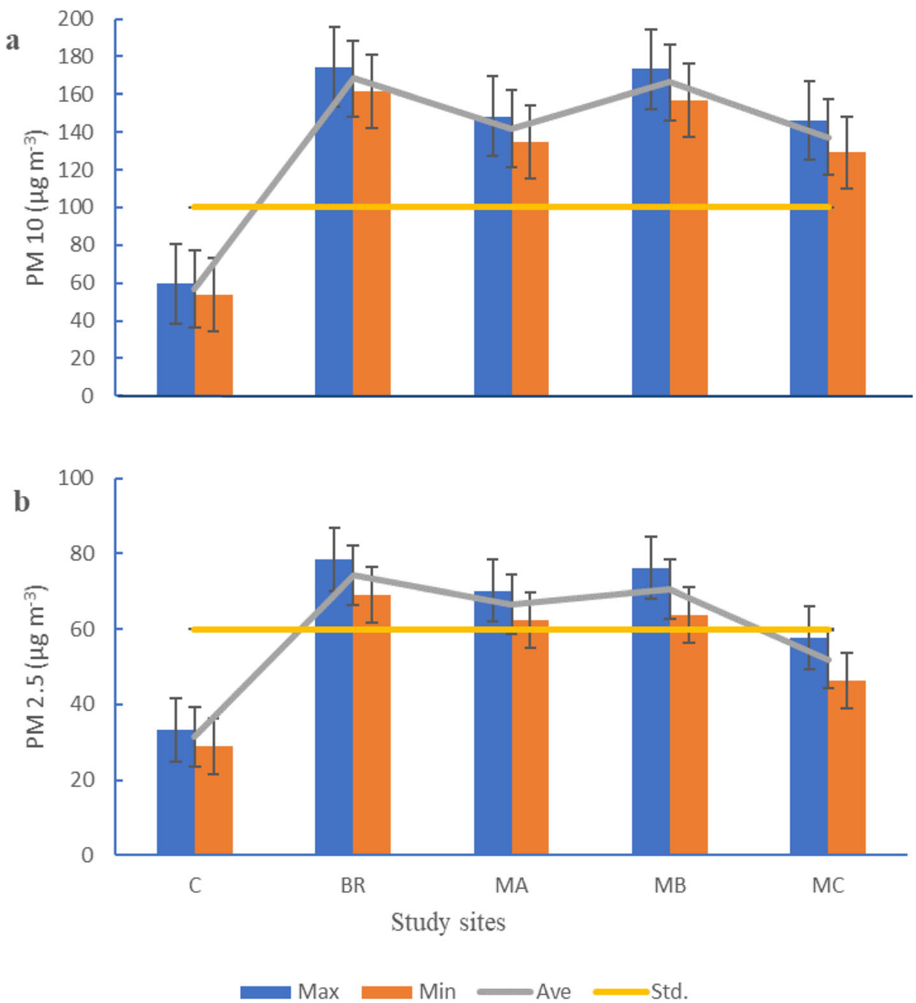

Fig. 2 Particulate matter across different study sites (**a**) PM_{10} (**b**) $PM_{2.5}$

as mist, soot, dust, salt particles, spores, microbes which are very minute (< 10 µm) and forms a significant part [8] of airborne dust. Their morphology and chemical properties depend on their origin. They consist of secondary aerosol (gas to particle), combustion products and settled metal and organic vapors [8]. These tiny particulates interact with polycyclic aromatic hydrocarbons, toxic metals, persistent free radicals to form tertiary aerosols. Gravimetric process of wet and dry nature is followed to remove particulates from the environment. They settle within a week. Thus, their time effects are varied and site-specific. The entry point of an air pollutant is the leaf cuticle and stomata [8, 9]. Further reactions within the plant cell are interrelated depending on particle properties, plant metabolism and external environment. They can either be sequestered, detoxified or yield CO_2 and H_2O after metabolic processes.

Leaf morphology and anatomy

Plants can play a significant role in mitigating airborne particulates and their removal capacities vary with the plant traits [3, 16, 17] (see Additional file 1). Tree crown morphology is one of the most important factors in arresting particulates along with crown density, leaf type and pattern. Venation pattern plays an important role in arresting the particulate matter. Thus, particulate deposition cannot be attributed to a single factor but is a complex mix of factors such as leaf characteristics [2–5, 16, 17, 29–35] such as hair, wax, foliage, leaf area, venation patterns, grooves and trichomes (see Additional file 1), particle size [12, 32, 34, 35], among others. Large trees are considered to arrest fewer particulates as compared to shrubs with foliar leaves close to the source [12]. Similarly, dense plantation with porous and large leaf surface area arrests a greater number of particulates [12]. Thus, the

Fig. 3 Leaf characteristics of plant species (**a**) *T. grandis* (**b**) *P. inerme*

choice of vegetation (tall, short, dense, sparse etc.) affects dust deposition. Emphasizing on $PM_{2.5}$ being most hazardous [11] due to toxicity [10, 11] and fineness, reports indicate conical leaves with 60% DAC compared to expanded leaves of only 47% [8, 17]. Broad-leaved, foliar [36] structures such as grooves, glands and trichomes when exposed captured $PM_{2.5}$ the most during foliar growth [11, 16]. Complex factors were contributing to particle arrest but are significantly plant-specific [16].

Thus, phenology and biodiversity would increase $PM_{2.5}$ capture [16]. Further, it is estimated that a single mature plant of these species will yield timber worth millions. Particulates cause a decrease in stomatal

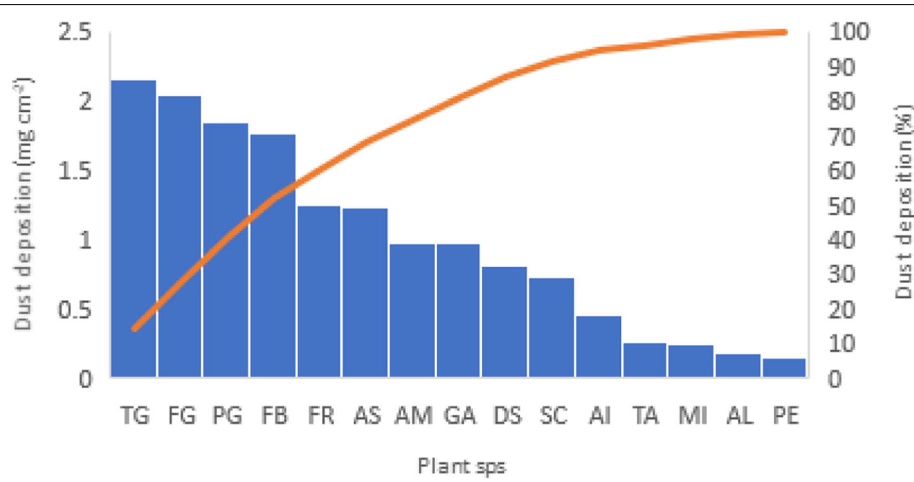

Fig. 4 DAC of trees in JCF, India

activity [7, 37] and chlorophyll content [37] and thus photosynthetic rate [7, 37]. Fully matured plant ecosystem sequesters atmospheric carbon and increases biodiversity to harvest valuable woody trees.

DAC and APTI

The removal of ambient dust can be successfully performed based on plant behavior, particle properties and climate. All the selected plant species (evergreen or deciduous) belonging to different plant families were evaluated for DAC yearly. The highest efficiency of 85% was observed for *TG* with DAC of 2.15 mg cm^{-2} and the lowest for *PI* with 5% and DAC of 0.15 mg cm^{-2}. This can be attributed to the rough, hairy trichomes with glandular deposits at the adaxial surface of the leaf and shorter petiole suitable for particulate capture in *TG* while the leaf of *PI* is compound, glabrous with no prominent hair and glandular wax. Moreover, there is a minimum abrasive mechanism to check wind speed helping gravity settling because of biparipinnate leaf which is smaller and divided (Fig. 3). It is to be noted that broad hairy leaf with a slight sticky wax can retain fine particulates for a long time [2, 30, 36]. A similar observation was seen in *AM* and all the species of *Ficus* due to waxy-glabrous leaf. DAC of *PG, AS, GA* and *TA* can be attributed to medium-size leaf with a hairy and rough surface with a significant wax deposit. DAC of *DS, AL* and *MI* is lower due to the small size and smooth leaf surface. Leaf of *SC* and *AL* arrested fewer particulates due to the glabrous surface with minimum roughness. The exposed upper surface of the leaf obstructs wind flow creating abrasion helping sedimentation and precipitation for particulate deposit. The trend of plant DAC followed the descending order: *TG* > *FG* > *PG* > *FB* > *FR* > *AS* > *AM* > *GA* > *DS* > *SC* > *AI* > *TA* > *MI* > *AL* > *PI*. Details have been described and depicted in Fig. 4, Table 4 and Additional file 1.

Table 4 List of DAC of plant species for greenbelt development in JCF

S.N.	Plant species	Family	DAC (mg cm^{-2})	E/D
1	*AM*	Rubiaceae	0.98	D
2	*AL*	Fabaceae	0.17	E
3	*AS*	Apocynaceae	1.23	E
4	*AI*	Meliaceae	0.45	D
5	*DS*	Fabaceae	0.81	D
6	*FB*	Moraceae	1.77	E
7	*FG*	Moraceae	2.05	D
8	*FR*	Moraceae	1.25	D
9	*GA*	Lamiaceae	0.97	E
10	*MI*	Anacardiaceae	0.25	E
11	*PI*	Fabaceae	0.15	D
12	*PG*	Myrtaceae	1.84	E
13	*SC*	Myrtaceae	0.72	E
14	*TG*	Verbenaceae	2.15	D
15	*TA*	Rubiaceae	0.27	E

E Evergreen, *D* Deciduous

Out of *fifteen* species selected for the study in JCF, eleven species showed a declining trend in SD while four species showed an increasing trend (Fig. 5). The highest decline of 59% in SD (number cm^{-2}) was observed in *AM* and the lowest in *TA* with 4% with respect to C. Some species showed an increase in SD from 17% in *FB* to 125% in *SC* with respect to C. This variation in the SD can be attributed to frequent rainfall occurring in the region during sampling which lowers dust deposition on the leaf surface along with the negligible ionic activity of fine particulates responsible for dissolution of the cell-wall. The SD of *TG* is much higher (1.51×10^6 cm^{-2}) than *PI* (0.69×10^6 cm^{-2}) in JCF (Table 5). Thus, higher SD indicates the sustainability due to high metabolic pliability [38] of the species which can be

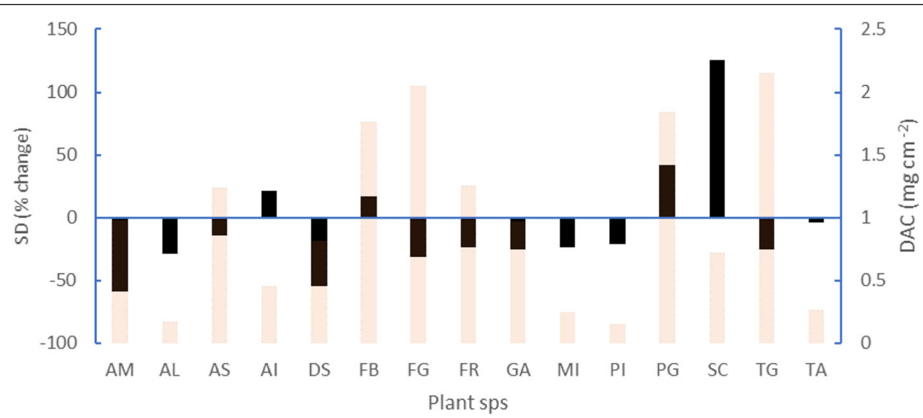

Fig. 5 Variation of SD with DAC

Table 5 SD (10^6) and DAC in JCF

S.N.	Plant species	SD (number cm^{-2}) (C)	SD (number cm^{-2}) (JCF)	SD* (% change)	+/−	DAC (mg cm^{-2})
1	*AM*	2.77	1.13	59	–	0.98
2	*AL*	0.88	0.63	29	–	0.17
3	*AS*	0.88	0.75	14	–	1.23
4	*AI*	1.20	1.45	21	+	0.45
5	*DS*	1.38	0.63	55	–	0.81
6	*FB*	1.45	1.70	17	+	1.77
7	*FG*	1.64	1.13	31	–	2.05
8	*FR*	1.32	1.01	24	–	1.25
9	*GA*	1.51	1.13	25	–	0.97
10	*MI*	1.32	1.01	24	–	0.27
11	*PI*	0.88	0.69	21	–	0.15
12	*PG*	1.95	2.77	42	+	1.84
13	*SC*	1.01	2.26	125	+	0.72
14	*TG*	2.01	1.51	25	–	2.15
15	*TA*	1.45	1.38	4	–	0.27

+/− positive/negative change in SD *Rainy season data

seen by relatively lower DAC and higher APTI values (Figs. 5 and 6).

The screening process for calculating APTI is depicted in the flow chart (Fig. 7). APTI of various plant species (Fig. 8) was calculated based on P, TC, AA and RWC [39].

LA is highest for *TG* with 690.5 and lowest for *AL* with 5.5 cm^2 respectively. The plant leaf is known for its important contribution in regulatory processes such as photosynthesis and transpiration. It acts as a receptor for particulate and gaseous pollutants. Fine and coarse air particulates along with the gaseous pollutants such as SOx, NOx, SO_2, CO and O_3 enter epidermis and stomata of the leaf to reach plant cell altering metabolic process affecting flowering, reproduction leading to a reduction in leaf size and number with enhanced senescence. Observed P is negatively related to the DAC in JCF as the P of coal dust particles is mostly acidic [21]. Highest P was found for *PI* (7.0) and lowest for *TG* (5.4) having DAC of 0.15 and 2.15 mg cm^{-2} respectively. This can be attributed to dissolution of deposited particulates into the cell sap of the plant leaf which is acidic [21] and gases such as SOx and NOx [14]. TC shows a positive relationship with the DAC and APTI. The maximum value of 2.9 mg g^{-1} was found in *TG* having DAC of 2.15 mg cm^{-2} and APTI of 16.8 and minimum in *PI* with

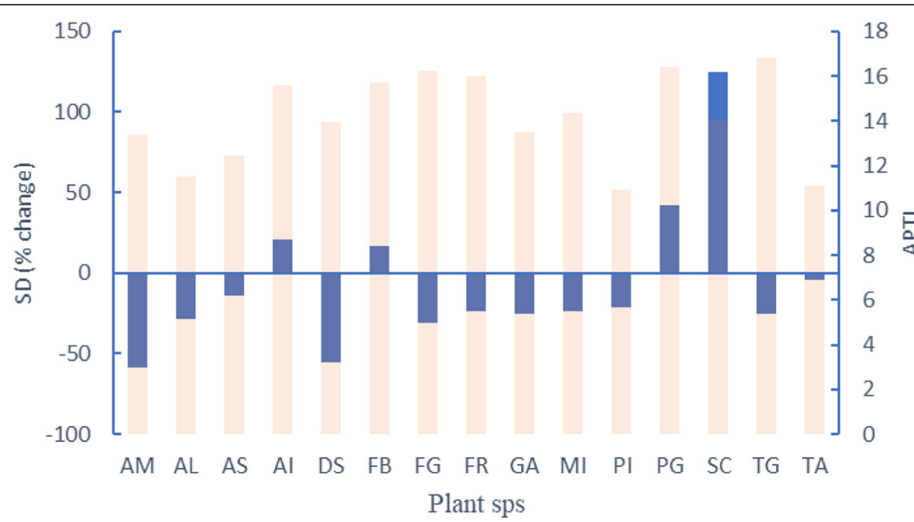

Fig. 6 Variation of SD with APTI

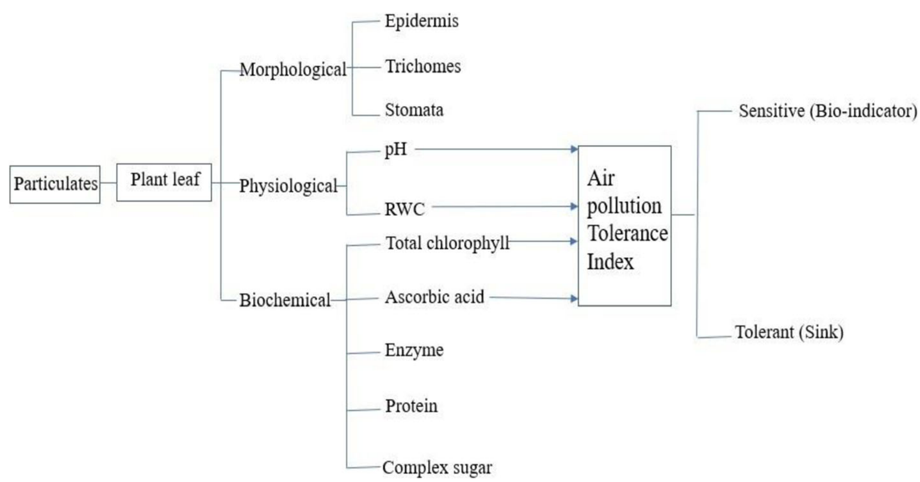

Fig. 7 Screening of plant species for assessing APTI

1.7 mg g^{-1} having DAC of 0.15 mg cm^{-2} and APTI of 10.1. Ascorbic acid (also known as citric acid) has been known to inhibit the formation of toxic elements due to its antioxidant properties. It is present in higher amount in growing plants and substitutes requirement of water in stress conditions regulating biological and physiological processes such as cell division [14]. Formation of H_2O_2, O_2 and OH radicals due to atmospheric SO_2 is effectively checked by ascorbic acid present in chloroplast. It also protects cell wall damage due to oxidation O_2 to O_3 [40]. A positive relationship is seen between the level of ascorbic acid with DAC and APTI as reported by many authors [13, 14]. Highest AA of 8.4 mg g^{-1} was found in *TG* having DAC of 2.15 mg cm^{-2} and APTI of 16.8 and lowest of 4.0 mg g^{-1} in *PI* having DAC of 0.15 mg cm^{-2} and APTI of 10.1. Water is essential for all the metabolic activities of the plant. RWC maintains balance during high-stress conditions created due to increased transpiration rate. Higher levels of RWC indicates plant survivability to meet adverse climatic conditions. A positive relation is seen between RWC, DAC and APTI. It varies from a minimum of 67.4% in *AS* with DAC of 1.23 mg cm^{-2} and APTI of 12.5 to maximum of 99.6% in *TG* with DAC of 2.15 mg cm^{-2} and APTI of 16.8. Detailed interactions between all the components are shown in Table 6 and Figs. 7, 9 and 10.

The APTI was calculated based on Singh et al. [39]. Highest tolerance index was found for *TG* (16.8) with 90% and the lowest for *PI* (10.1) with 57% and is a measure of sustainability in JCF. The sequence in descending order was *TG* > *PG* > *FG* > *FR* > *FB* > *AI* > *MI* > *SC* > *DS* > *GA* > *AM* > *AS* > *AL* > *TA* > *PI*. The species can be a labeled indicator by their tolerance or sensitivity. It can either act as a storehouse for the air pollutants or may die [13, 14].

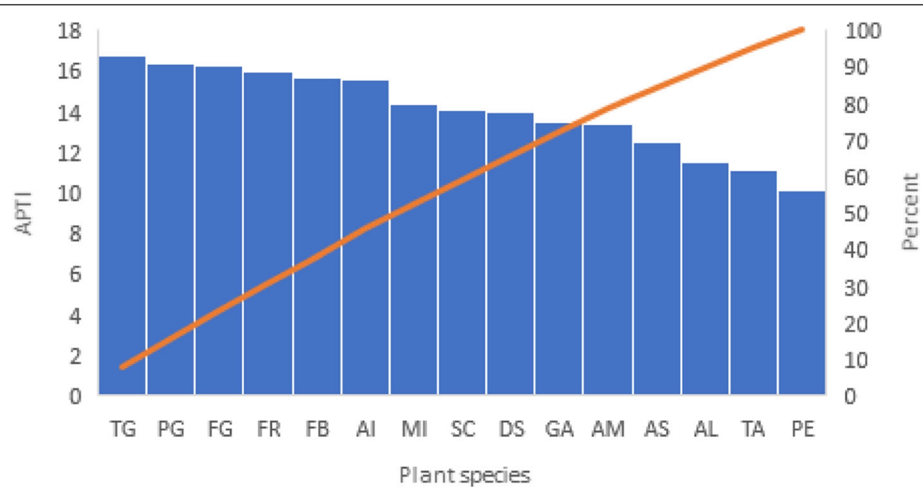

Fig. 8 APTI of selected plant species

Table 6 APTI of selected plant species in JCF

S. N.	Plant species	LA (cm^2)	P	TC ($mg\ g^{-1}$)	AA ($mg\ g^{-1}$)	RWC (%)	DAC ($mg\ cm^{-2}$)	APTI
1	*AM*	188.5	6.5	2.3	5.1	88.2	0.98	13.4
2	*AL*	5.5	6.9	1.9	4.4	76.5	0.17	11.5
3	*AS*	160	6.5	1.8	6.9	67.4	1.23	12.5
4	*AI*	45	6.7	2.9	6.2	99.4	0.45	15.6
5	*DS*	32	6.1	2.4	5.1	96.1	0.81	14.0
6	*FB*	142.5	6.7	1.9	6.8	98.8	1.77	15.7
7	*FG*	252.5	5.4	2.8	8.2	95.3	2.05	16.3
8	*FR*	157	6.2	2.8	7.1	95.8	1.25	16.0
9	*GA*	156.5	6.6	2.6	4.9	89.4	0.97	13.5
10	*MI*	185	6.8	1.9	5.2	98.4	0.27	14.4
11	*PI*	9	7.0	1.7	4.0	74.2	0.15	10.1
12	*PG*	262	5.6	2.6	7.9	99.5	1.84	16.4
13	*SC*	160.5	6.4	1.9	5.1	98.6	0.72	14.1
14	*TG*	690.5	5.4	2.9	8.4	99.6	2.15	16.8
15	*TA*	90	6.9	1.7	4.2	75.1	0.27	11.1

Hierarchical dendrogram analysis amongst plant species indicates the development of three clusters with first group consisting of *FR, GA, AS, MI, AM, FB, AL, PI, DS, AI, TA, FG* and *PG.* The second group consists of a single species of *SC* which is closely related to the first group. The third group consists of *TG* which is distantly related to both the above groups (Fig. 10a).

Hierarchical dendrogram analysis amongst plant characteristics indicates the development of four clusters with first group consisting of TC, DAC, P, AA and APTI which is more closely related with SD. Both groups are closely related to RWC. All the above three groups are more distantly related to LA (Fig. 10b). Thus, DAC and APTI may vary distantly with LA (Table 6 and Fig. 10).

Greenbelt design

The study area showed the massive dispersion of air dust pollutant by coal mining and transportation activities in the form of PM_{10} and $PM_{2.5}$ which can be reduced significantly by the above plants to enhance the air quality of the mining areas. A green belt development around the mining sites and transportation with suitable plant species would reduce the pollutant dispersion to a greater extent [5]. Particulate attenuation by the trees can easily be estimated by using various mathematical

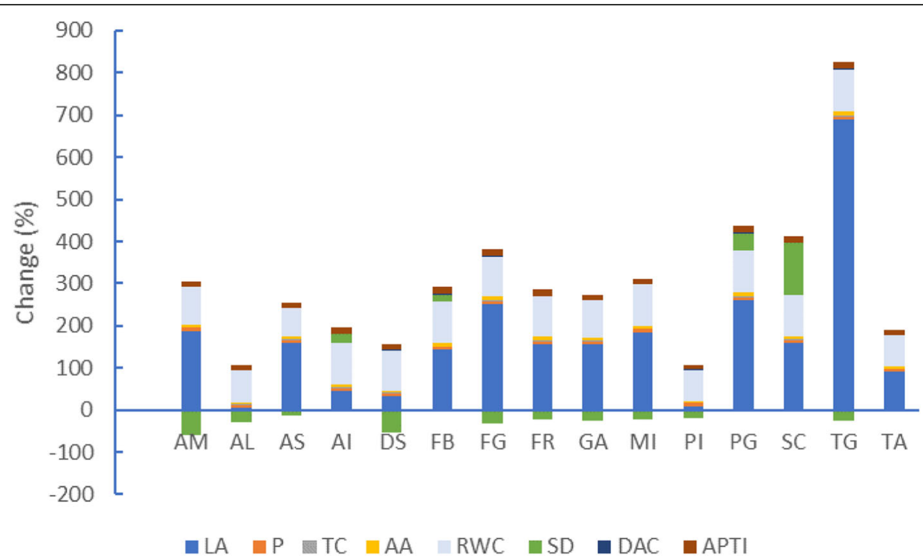

Fig. 9 Relative changes in LA, P, TC, AA, RWC, SD, DAC and APTI of selected plants

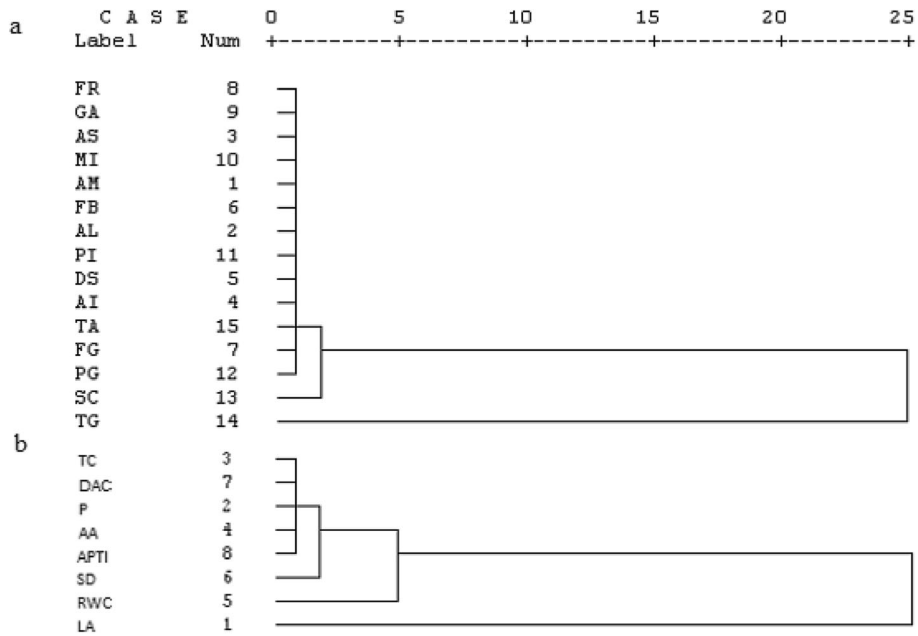

Fig. 10 Hierarchical dendrogram cluster for (**a**) Selected trees and (**b**) LA, P, TC, AA, RWC, DAC and APTI

models [6]. Transpiration is a valuable physiological process for assimilation and removal of fine particulates from the ambient environment.

To reduce the impact of air pollution, systematic and scientific plantation has to be done on both sides of the haul road and approach road of mining and transportation road with vegetation cover comprising of herbs (grasses), shrubs and trees of 6 to 40 m in height at a distance of 5–6 m (from the edge) on both sides of the transporting road (Fig. 11). The accurate size of the plantation depends on road width, number of moving vehicles, lane numbers and the speed limits of the plying vehicles. Huge quantities of CO_2 are also sequestered by the afforested plants, thus improving the air quality both in terms of dust and gaseous pollutants. Green belt development attenuates environmental pollution and provides fruits, nuts, timber, fuel-wood and fodder. It also helps to achieve the targeted 33% forest cover in the long run. Further, it provides ecosystem services like nutrient cycling, dwelling for the wildlife, browse for animals and sustainable tourism. It also replenishes groundwater raising water table. The planted trees in large area help in raising rainfall.

Statistical analysis

Pearson correlation (two-tailed) was studied at $p < 0.05$ level of significance for all the characteristics (Table 7).

Fig. 11 Green belt design along the mine road

Table 7 Pearson correlation* amongst different plant characteristics

	LA	P	TC	AA	RWC	DAC	APTI	SD
LA	1							
P	−0.733	1						
TC	0.470	−0.695	1					
AA	0.694	−0.834	0.625	1				
RWC	0.393	−0.493	0.614	0.469	1			
DAC	0.718	−0.833	0.536	0.905	0.442	1		
APTI	0.602	−0.738	0.754	0.847	0.860	0.764	1	
SD	0.003	−0.149	−0.007	−0.125	0.352	−0.016	0.1	1

*Significant $p < 0.05$ (two-tailed)

It indicats that TC, AA, RWC, DAC, APTI and SD are negatively related with P. TC and DAC is not significantly related to SD at this level. All other parameters are positively related.

Conclusions

The results of the present study indicate that opencast coal mining emits a huge amount of particulate matter into the atmospheric environment due to various operations such as drilling, blasting, loading, excavation, transportation and coal washing activities. The study showed that all the sampling sites were polluted with respect to the standard limit of PM_{10} and $PM_{2.5}$ except C. DAC was highest for *TG* (2.15 $mg\,cm^{-2}$) and lowest for *PI* (0.15 $mg\,cm^{-2}$). The decreasing order for DAC was $TG > FG > PG > FB > FR > AS > AM > GA > DS > SC > AI > TA > MI > AL > PI$. APTI based on pH, TC, AA and RWC was highest for *TG* (16.8) and lowest for *PI* (10.1) amongst the selected tree species. The descending order for APTI was $TG > PG > FG > FR > FB > AI > MI > SC > DS > GA > AM > AS > AL > TA > PI$. The SD behaved negatively to DAC and positively to APTI. Thus, *TG* is best suitable and *PI* the least in JCF. Attributes of particulate attenuation, therefore, is a function of many factors such as particle size, species type, metabolism, location, meteorology, nutrient stress, micromorphological and anatomical properties of the leaf and cannot be assigned to a single factor. The plant can act as a very efficient biofilter to arrest particulates. Based on the results, a greenbelt has been designed to improve the air quality of the mining and transportation areas.

Supplementary information

Supplementary information accompanies this paper at https://doi.org/10.1186/s42834-019-0039-y.

Additional file 1: Table S1. Morphological and anatomical characteristics of the leaf.

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Authors' contributions
Mr. RK Singh helped acquire field and laboratory data, Dr. RS Singh and Dr. D Pal in preparing the manuscript, Dr. KKK Singh and Dr. PK Singh in editing the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials
All data generated or analyzed during this study are included in the article and its Additional file 1.

Competing interests
The authors declare they have no competing interests.

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