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Nature Environment & Pollution Technology

This is a peer-reviewed prepublished version of the paper to be published in Vol. 25, No. 4, December 2026 issue

Eco-Physiological Assessment of Native Plant Species for Mitigating Airborne Pollutants and Greenbelt Development in a Coal Mining Region

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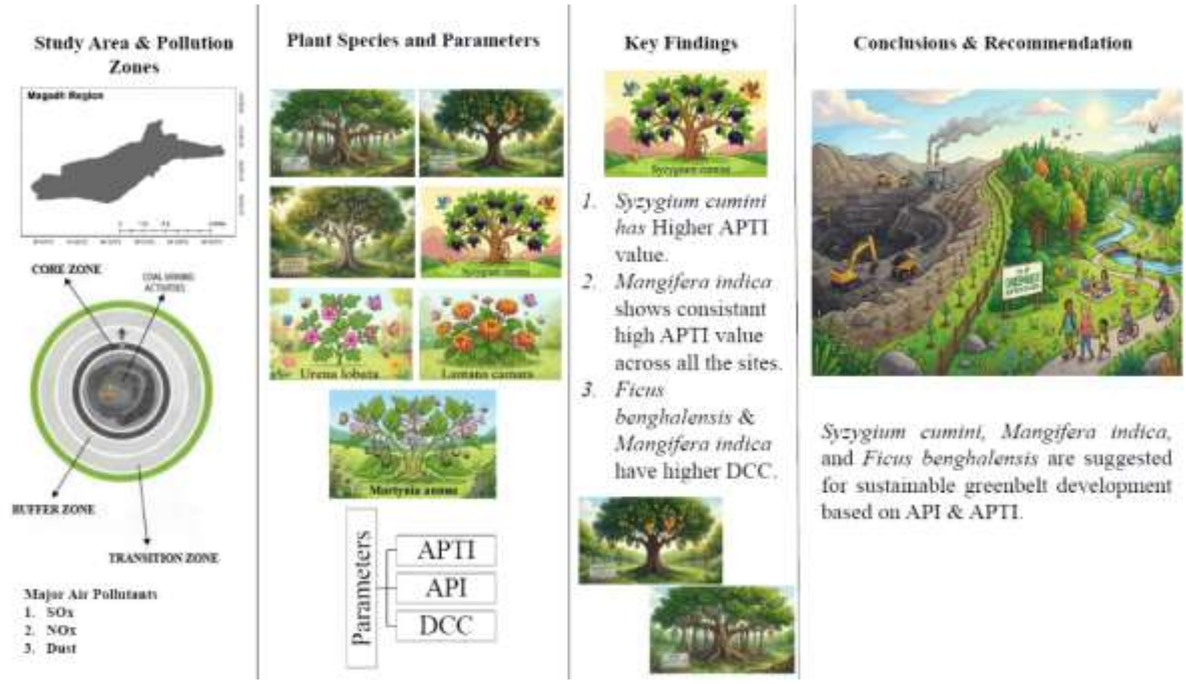
Key Words	Air Pollution Tolerance Index (APTI), Phytoremediation, Dust capturing capacity, Environmental monitoring
DOI	https://doi.org/10.46488/NEPT.2026.v25i04.B4441 (DOI will be active only after the final publication of the paper)
Citation for the Paper	Polavarapua, M.P., Kumara, M., Goswamib, S., Mishraa, S., Singha, A.K. and Shuklaa, S.K., 2026. Eco-physiological assessment of native plant species for mitigating airborne pollutants and greenbelt development in a coal mining region. 25(4), B4441. https://doi.org/10.46488/NEPT.2026.v25i04.B4441

Abstract: Coal mining operations are major sources of atmospheric pollution, substantially degrading ambient air quality and imposing physiological stress on surrounding vegetation. This study aims to evaluates the pollution tolerant capacity of seven native plant species across Core, Buffer, and Transition zones within the specific range Magadh coal mining region, Jharkhand, India. To identify suitable pollution tolerant species for sustainable greenbelt development, the Air Pollution Tolerance Index (APTI), Anticipated Performance Index (API) and Dust Capturing Capacity (DCC) were assessed. The results revealed significant species-specific variation in pollution tolerance and particulate interception across the pollution gradient. *Syzygium cumini* recorded the highest APTI value (16.35) in the highly polluted Core zone, primarily associated with elevated ascorbic acid concentration (12.61 mg g^{-1}), indicating a strong antioxidative defense mechanism against oxidative stress. In contrast, *Ficus benghalensis* and *Mangifera indica* exhibited superior particulate retention capacity, with maximum DCC values of 2.50 mg cm^{-2} and 2.91 mg cm^{-2}, respectively. The native climax species *Shorea robusta* maintained relatively stable physiological attributes across pollution zones; however, its morphological characteristics resulted in a lower API classification ("Poor", 50%). Integrating biochemical, morphological, and socio-economic attributes, API analysis identified *Ficus benghalensis* (Grade IV, 68.75%) and *Syzygium cumini* (Grade IV, 62.5%) as effective candidates for pollution mitigation. Conversely, *Urena lobata* and *Lantana camara* exhibited high sensitivity to mining-induced air pollution. The integration of biochemical, physiological, and morphological parameters provides a comprehensive framework for species selection. The study highlights the importance of utilizing pollution-tolerant and high dust-retaining species for designing sustainable greenbelts in coal mining areas.

Graphical Abstract



1. INTRODUCTION

Air pollution remains one of the most serious and sensitive anthropogenic threats to the global environment. Among various anthropogenic activities, coal mining represents a major environmental challenge, as it acts both as a significant source of pollutants and a large-scale environmental contaminator (Ghosh et al., 2025). The deterioration of ambient air quality not only poses severe risks to human health but also adversely affects terrestrial vegetation, which serves as a primary sink for atmospheric pollutants (Anand et al., 2022). Plants growing in industrial and coal mining regions are continuously exposed to gaseous and particulate pollutants, which can induce alterations in their physiological structure, biological behavior, and metabolic mechanisms (Natividad et al., 2024). Therefore, the identification and selection of pollution tolerant plant species have become vital for the development of green belts and sustainable air quality management strategies (Sawarkar et al., 2023).

"*The APTI is a quantitative method used to evaluate the inherent resistance of plant species to atmospheric pollution*" (Singh et al., 1991). To quantify the air pollution tolerance level of plants species, the APTI is one of the widely used method (Paul et al., 2023). APTI integrates four major biochemical and physiological parameters such as total chlorophyll content (TCH), ascorbic acid content (AA), leaf extract pH (pH), and relative water content (RWC) (Mehmood et al., 2023). This approach helps in a wholesome evaluation of plants defence mechanisms against air pollution induced stress. Recent studies have validated APTI as a holistic tool for categorizing plants into sensitive, intermediate, and tolerant groups, therefore it helps in the selection of species for phytoremediation (Asif & Ma, 2024).

APTI consists of two major components, one is physiological components and the other one is biochemical components. Further the physiological components are composed up of leaf-extract pH and RWC. These physiological parameters indicate the plant's ability to maintain homeostasis (Goswami et al., 2023). A higher pH plays a crucial role in detoxification of acidic pollutants (e.g. SO_2 & NO_x) while RWC ensures the turgidity and physiological function despite pollutant-induced transpiration stress (Timilsina et al., 2022). The biochemical components of APTI mainly describe about the AA and TCH. It indicates the metabolic proficiency of plants in stressed condition. AA, is a potential antioxidant, serves as a reactive oxygen species (ROS) scavenger generated by pollutant exposure, so it maintains cell membrane integrity (Najafi Zilaie et al., 2023). Higher the level of ascorbic acid, higher the ability of pollution tolerance (S. Chauhan et al., 2022). The chlorophyll content is mostly reduced in the plants growing in stressed condition due to the deformation of photosynthetic pigments. Although tolerant plant species commonly maintain stable chlorophyll levels to sustain productivity (Bui et al., 2021).

Beyond these biochemical properties, the APTI of most of the plant species is highly influenced by spatiotemporal variations including seasonal changes and microclimatic conditions (Bui et al., 2023). APTI values often vary according to the seasonal variations, such as during the post-monsoon period with comparison with winter or summer seasons shows optimal metabolic activity (Bui et al., 2023). Spatial factors like elevation and pollution sources plays a significant role, such as, plants located in industrial region or high traffic zones shows higher APTI value than the plants located in residential sites, e.g. recent study indicates that the *M. indica* showed a high pollution tolerance potential with its best APTI score across all the mining sites in the Khalari region, Jharkhand (Singh & Shukla, 2025). This suggests adaptive physiological response to regular and long-term pollutant exposure (Chauhan et al., 2025). Getting the knowledge of these seasonal and spatial variations is important for accurate categorisation as sensitive in one season may shows intermediate tolerance in other seasons (Kaur, 2021).

The relationship between APTI and Dust Capturing Capacity (DCC) describes the dual role of the plants as biological monitor and physical barrier. There is a positive correlation between higher APTI values and dust accumulation in species with rough leaf structures or waxy cuticles indicating that plants tolerating higher physiological stress are often acts as an effective scrub for the particulate matter (PM) from the atmosphere (Antil et al., 2025). Evaluating both APTI and PM accumulation gives a holistic assessment of plant's scrubbing potential than individual parameter (Mehmood et al., 2023).

The present study was conducted to evaluate the biochemical and physiological characteristics of selected plant species growing in mining-affected regions. Parameters including total chlorophyll content, ascorbic acid content, relative water content, and leaf extract pH were analyzed to estimate the APTI for identifying comparatively tolerant and sensitive species under mining-induced environmental stress. In addition, the API was assessed by integrating APTI with morphological and socioeconomic attributes to evaluate the overall adaptability and suitability of plant species for greenbelt development in polluted environments. Furthermore, DCC was determined to assess the particulate interception potential of the selected species and their possible role in mitigating airborne dust pollution in mining landscapes.

2. MATERIALS AND METHODS

2.1. Study Area

The study was conducted in the Magadh open-cast mining region, located across the Tandwa block of Chatra district and the Balumath Community Development (CD) block of Latehar district, Jharkhand, India. The area represents one of the major operational coal mining regions within the North Karanpura Coalfield operated by Central Coalfields Limited (CCL). Geographically, the study area is situated at 23.8442° N latitude and 84.9885° E longitude. The nearest settlement to the mining area is Bachra, which is located approximately 20 km from Khalari and about 50 km from Hazaribagh.

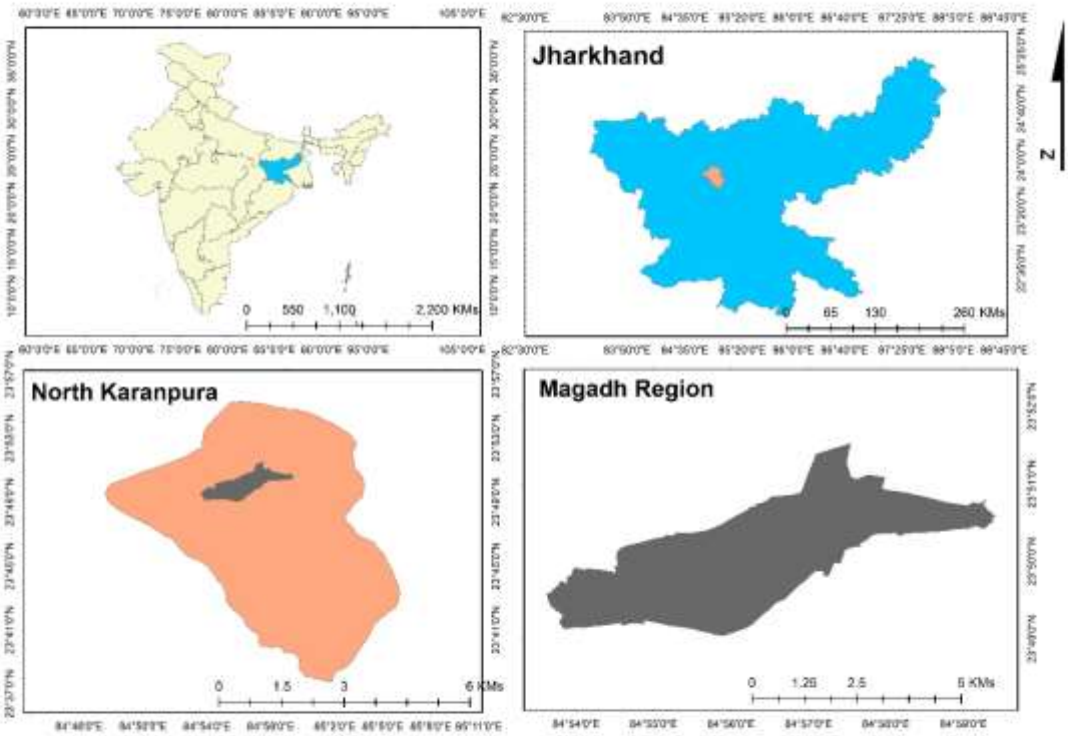


Fig 1: Domain of the study area

2.2. Sampling

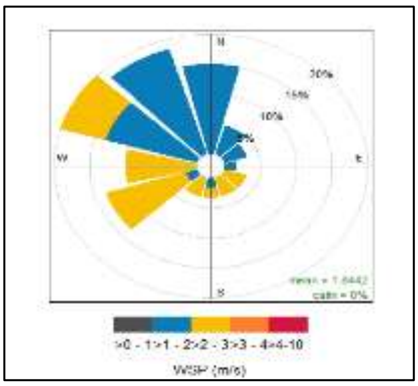


Fig 2: Windrose diagram of study region

The study area was divided into three zones based on the distance from the mining area in order to assess the air pollution tolerance of roadside vegetation under varying pollution loads. The zones were categorized as follows: Core Zone – within 500 m proximity of the mining area, Buffer Zone – located 3–5 km away from the core zone and Transition Zone – beyond the buffer zone. The ambient air quality assessment of the study region revealed that the concentrations of particulate pollutants in both the buffer and core zones were marginally above the permissible limits prescribed under the National Ambient Air Quality Standards (NAAQS; GSR 826 and 742(E)), indicating considerable environmental stress in the mining-influenced areas. The recorded SPM concentrations were 588.9 $\mu g/m^3$ in the buffer zone and 601.4 $\mu g/m^3$ in the core zone against the prescribed limit of 600 $\mu g/m^3$. Similarly, PM_{10} concentrations were observed at 99.2 $\mu g/m^3$ and 104.2 $\mu g/m^3$, while $PM_{2.5}$ concentrations were 59.1 $\mu g/m^3$ and 63.7 $\mu g/m^3$ in the buffer and core zones, respectively, compared to the standard limits of 100 $\mu g/m^3$ for PM_{10} and 60 $\mu g/m^3$ for $PM_{2.5}$ (Table 1). To identify representative vegetation and assess species distribution, an ecological survey was conducted using the quadrat method. A total of three quadrats were laid at each sampling site for vegetation analysis and species enumeration. The survey revealed the occurrence of 7 tree species and 6 shrub species in the core zone, whereas 13 tree species and 9 shrub species were recorded in the buffer zone. Based on species commonality, abundance, and occurrence across the study zones, seven plant species were selected for detailed investigation. These included four tree species: *Mangifera indica, Ficus benghalensis, Shorea robusta*, and *Syzygium cumini*; and three shrub species: *Lantana camara, Urena lobata*, and *Martynia annua*. The selection of sampling sites was further supported by the Windrose diagram (Fig. 1), which represented the direction and dispersion pattern of pollutants emitted from the open-cast mining activities. This helped in identifying the most pollution-affected regions for vegetation sampling. Leaf sampling was conducted during the months of November and December under clear atmospheric conditions. Sampling was carried out only when no rainfall had occurred for at least one week prior to collection in order to minimize the influence of precipitation on leaf surface characteristics and biochemical parameters. A random sampling method was adopted for leaf collection. Fully matured and healthy leaves were collected from all sides of each selected plant species to ensure uniform representation. From each direction, 15 leaves were collected and pooled together to form a composite sample for laboratory analysis. The sampling was performed during the morning hours between 6:00 AM and 8:00 AM to minimize physiological disturbances caused by high temperature and solar radiation. All analyses were carried out in triplicate to ensure analytical reliability and reproducibility.

Table 1: Average Air quality of Magadh Region

Sampling Location	Buffer Zone	Core Zone	Limits as per NAAQ GSR 826 & 742 (E)	Unit
Parameters				

SPM	588.9	601.4	600	ug/m³
PM10	99.2	104.2	100	ug/m³
PM2.5	59.1	63.7	60	ug/m³

3. EXPERIMENTAL ANALYSIS

3.1. Total Chlorophyll Content (TCH)

The TCH of leaves was determined by (Arnon, 1949) method. The formula for determining the TCH were given below:

$$TCH\ (\frac{mg}{g}) = \frac{(20.2*A645+8.02*A663)*V}{1000*W\ (g)} \qquad (1)$$

where,

A_{645} , A_{663} are absorbance at 663 nm and 654 nm respectively, V and W are total extract volume (ml) and leaf weight (g) respectively (Jain et al., 2019).

3.2. Ascorbic Acid (AA)

AA was determined by the volumetric method as given by (Sadasivam & Balasubramanian, 1987). The formula for calculating AA were given below

$$A(\frac{mg}{g}) = \frac{0.5(mg)*V2\ (ml)*10\ (ml)}{V1\ (ml)*5\ (ml)*weight\ of\ the\ sample\ (g)} \qquad (1)$$

Where, V1 and V2 are the volumes of the dye titrated against the stock standard and the sample, respectively.

3.3. pH

The pH of leaf were determined using the method (Singh et al., 1991).

3.4. Relative water content (RWC)

RWC was determined using the (Singh et al., 1991).

$$RWC\ (\%) = \frac{(FW-DW)g}{(TW-DW)g} * 100 \qquad (2)$$

3.5. Air pollution tolerance index (APTI)

The APTI was estimated by using the given formula (Singh et al., 1991). The classification of APTI score were given in Table

$$APTI = [A * (T + P) + R] \div 10 \qquad (3)$$

Where, A is ascorbic acid, T is chlorophyll, P is pH and R is water content.

<1: - Very Sensitive (VS), 1–14: - Sensitive (S), 14–19: -Intermediate Tolerant (IT), 20-24: - Moderately Tolerant (MT) and >24: - Tolerant (T). (Singh et al., 2025).

3.6. Anticipated Performance Index (API)

The API of the tree species were assessed based on the method given by (Mondal et al., 2011). The API is expressed as its scoring percentage which can be calculated as follows:

$$\text{API}\ (\%) = \frac{(\text{Total positives})}{16} * 100 \qquad (4)$$

Gradation of plant species on the basis of the APTI and other biological and socio-economic characters for determination of the API of plants under study based on the given table 2 and 3.

Table 2: API grading scale and assessment pattern (Mondal et al., 2011).

Grading	Characters	Assessment Pattern	Grading Scale
Tolerance	APTI	< 9	+
		9 -12	++
		12 -15	+++
		15 -18	++++
		18 -21	+++++
		>21	++++++
Biological Characters	Plant height	Small (less then 9ft)	-
		Medium (9ft to 45 ft)	+
		Large (More then 45ft)	++
	Canopy Structure	Sparsh/irregular/globular	-
		Spreading/crown/open/semidense	+
		Spreading dense	++
	Plant height	Deciduous	-
		Evergreen	+
Laminar Structure	Leaf Size	Small	-
		Medium	+
		Large	++
	Texture	Smooth	-
		Rough	+
	Hardness	Delineate	-
		Hard	+
Economic value	Frequency	<3 uses	-
		3 or 4 uses	+
		5 or more uses	++

Table 3. Evaluation criteria for assigning anticipated performance index (API) values and categories of plants on the basis of percentage score (Mondal et al., 2011).

% score	API value	Category
≤30	0	Not recommended (NR)

31–40	1	Very poor (VP)
41–50	2	Poor (P)
51–60	3	Moderate (M)
61–70	4	Good (G)
71–80	5	Very good (VG)
81–90	6	Excellent (E)
91–100	7	Best (B)

3.7. Dust Capturing Capacity (DCC)

Six leaves from each selected species were measured for their leaf surface area and the amount of deposited dust. The DCC of each tree species was determined gravimetrically to evaluate species with high foliar dust deposition. The leaves with dust particles were weighed using a weighing balance labelled W_1 for each species. Next, dust clinging to the leaf's surface was meticulously removed by gently brushing it with distilled water. The leaves were subsequently dried and reweighed, with this updated weight recorded as W_2. The leaf area was measured using a graphical approach and recorded as A (Das & Prasad, 2012).

Finally, dust capturing potential (mg/ cm^2) for each species was calculated using the formula

$$W\left(\frac{mg}{cm^2}\right) = \frac{W2-W1}{A} \quad (5)$$

3.8. Statistical Analysis

The two-way ANOVA was performed to observe the significant difference between sites and species. The Pearsons's correlation coefficient was done to observe the relation between parameters and APTI score of tree species. The differences were observed at a significant level ($p<0.05$).

4. RESULTS AND DISCUSSIONS

4.1. Total Chlorophyll Content (TCH)

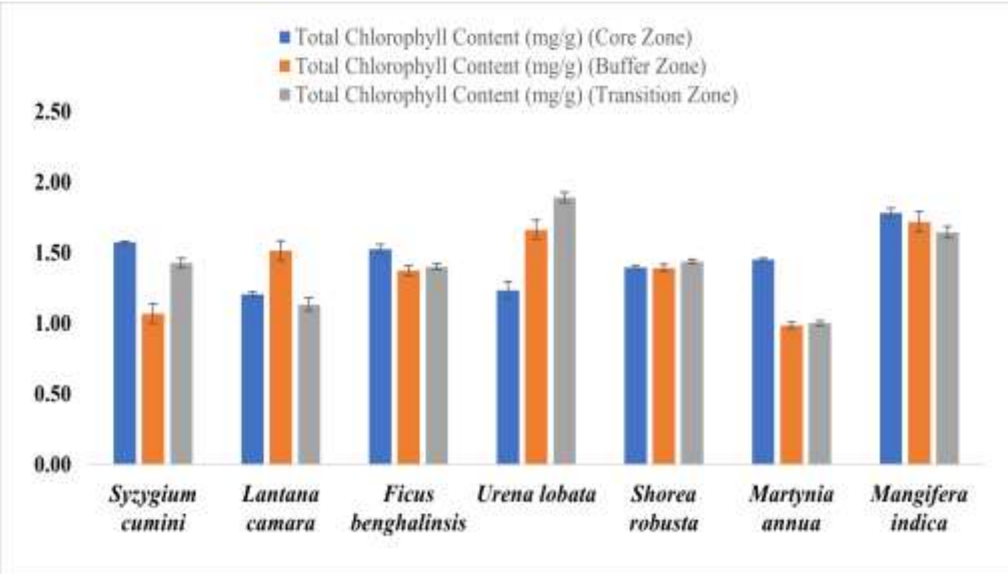


Fig 3: Graph showing the total chlorophyll content of leaf extract of plant species found in core, buffer & transition zones of Magadh open-cast coal mining region

Table 4: Total chlorophyll content of leaf extract of plant species found in core, buffer & transition zones of Magadh open-cast coal mining region

Plant Species	Core	Buffer	Transition
Syzygium cumini	1.57±0	1.07±0.06	1.42±0.03
Lantana camara	1.2±0.01	1.51±0.07	1.13±0.04
Ficus bengalinsis	1.52±0.03	1.37±0.03	1.4±0.02
Urena lobata	1.23±0.06	1.66±0.06	1.89±0.03
Shorea robusta	1.39±0.01	1.39±0.02	1.43±0.01
Martynia annua	1.45±0.01	0.98±0.02	1±0.01
Mangifera indica	1.78±0.03	1.72±0.07	1.64±0.04

The spatial variation in the TCH of the local flora across the core, buffer, and transition zones acts as a crucial physiological indicator of changing atmospheric stress condition induced by mining activities. Based on the observation, among the studied species, *Mangifera indica* have been exhibiting the highest overall pigment concentration, which demonstrate a relative stability with values of 1.78 mg/g in the core zone, 1.72 mg/g in the buffer, and 1.64mg/g in the transition zone as shown in Fig 3 and Table 4 . It suggests a higher adaptive mechanism by which the plant synthesizing compensatory chlorophyll to counteract the shading effect resulting by the heavy deposition of the coal dust on the leaf surface. In contrast, *Urena lobata* showing a linear recovery trend with the lowest TCH in the core (1.23 mg/g) and significant increase in the transition zone with TCH of 1.89 mg/g. This pigment degradation may be a result of the process called as phaeophytinization, where the acidic pollutants like oxides of sulphur (mostly SO_2) displaces the central magnesium ion from the chlorophyll molecule (Li et al., 2015). *Shorea robusta*, one of the dominant native climax species of the Jharkhand region, maintained relatively stable physiological characteristics across all study zones, with chlorophyll content values of 1.40, 1.39, and 1.44 mg g^{-1} in the core, buffer, and transition zones, respectively. This stability may indicate a comparatively higher tolerance to mining-associated environmental stress. The maintenance of chlorophyll content under high-dust conditions could possibly be associated with physiological defense mechanisms that help minimize oxidative stress caused by reactive oxygen species (ROS), which have been reported to affect thylakoid membrane stability under polluted environments (Rai, 2016), although these mechanisms were not directly investigated in the present study. In *Syzygium cumini* and *Martynia annua*, the fluctuations in total chlorophyll content from the core to buffer zones (1.57 to 1.07 mg g^{-1} and 1.45 to 0.98 mg g^{-1}, respectively) may reflect the influence of mining-associated particulate deposition on leaf physiological functioning. Previous studies have suggested that excessive accumulation of particulates on leaf surfaces can potentially interfere with stomatal functioning, alter leaf temperature, and affect chlorophyll metabolism, including chlorophyllase activity (Lin et al., 2021). Additionally, the alkaline nature of coal dust may influence cellular pH balance, which could contribute to alterations in the photosynthetic apparatus under prolonged stress conditions (Chaturvedi et al., 2013). The Two-way Anova (TwA) signifies the significant variation (SV) in TCH in the observed plant species studied in the core, buffer and transition zones at $p < 0.05$ as shown in Table 11.

4.2. Ascorbic Acid (AA)

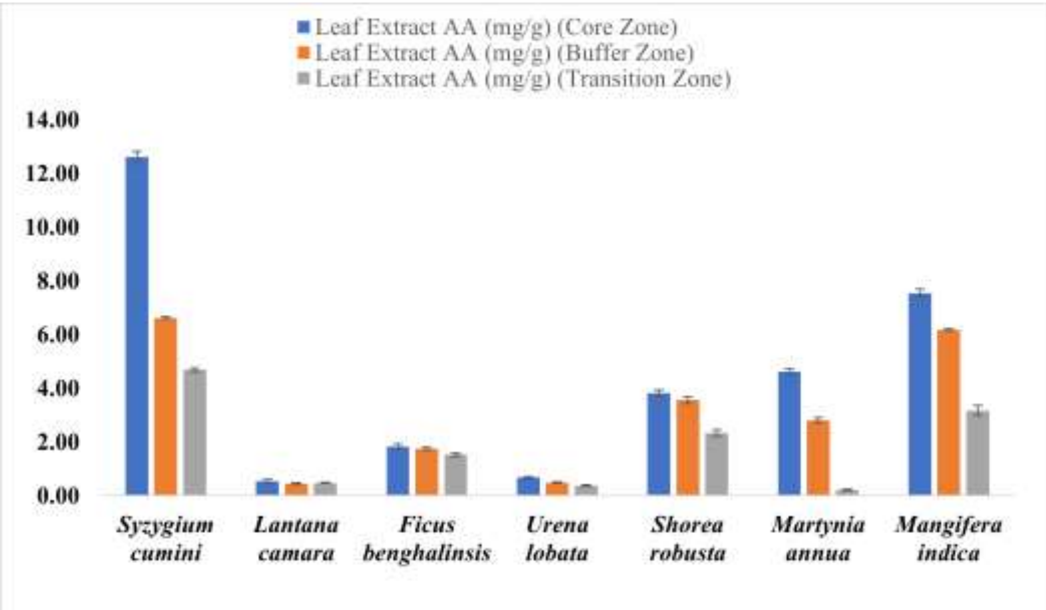


Fig 4: Graph showing the Ascorbic acid content of leaf extract of plant species found in core, buffer & transition zones of Magadh open-cast coal mining region

Table 5: Ascorbic acid content of leaf extract of plant species found in core, buffer & transition zones of Magadh open-cast coal mining region

Plant Species	Core	Buffer	Transition
Syzygium cumini	12.61±0.22	6.61±0.04	4.68±0.06
Lantana camara	0.54±0.05	0.45±0.02	0.47±0.02
Ficus bengalinsis	1.83±0.09	1.75±0.05	1.53±0.07
Urena lobata	0.68±0.03	0.48±0.02	0.37±0.03
Shorea robusta	3.81±0.13	3.56±0.13	2.33±0.11
Martynia annua	4.62±0.09	2.81±0.09	0.21±0.03
Mangifera indica	7.54±0.15	6.17±0.05	3.17±0.18

The AA content in the native flora across the Magadh coal-mines region can play a vital role of biochemical indicator of the scavenging capacity against the mine induced oxidative stress and heavy-metal laden coal dust. The *Syzygium cumini* displays the most fluctuating physiological response with highest AA level in the core region (12.61 mg/g) and declining through buffer (6.61 mg/g) to the transition zone (4.69 mg/g) as shown in Fig 4 and Table 5. This may indicate an enhanced antioxidant defense response under highly polluted conditions, which has been associated in previous studies with the up-regulation of the ascorbate–glutathione cycle involved in mitigating oxidative cellular damage (Caverzan et al., 2016).

Similarly, the *Mangifera indica* shows significant antioxidant mobilization by maintaining high values in the core (7.54 mg/g) and reducing toward buffer (6.17 mg/g) and transition zone (3.17 mg/g), again proving its ability to maintain homeostasis toward the coal induced pollution (Singh & Shukla, 2025). *Martynia annua* has been observed that the AA concentration dropping from 4.62 mg/g (Core) to 0.21 mg/g (Transition), while *Shorea robusta* demonstrated a stable and gradual lowering of the AA content (3.81 mg/g Core to 2.33 mg/g Transition). Consequently, *Lantana camara* (0.54 mg/g Core to 0.47 mg/g Transition) and *Urena lobata* (0.68 mg/g Core to 0.38 mg/g Transition) maintain consistently lower AA level. The TwA results shown the SV in the AA in the leaf of examined plant among the different sites in the Magadh region at $p < 0.05$. The higher AA level in the core zone is a defensive adaptation by the plants. As AA is an electron donor, it potentially attributes to stabilizes the photosynthetic apparatus by maintaining the reduced state of Cu & Fe cations and may also protects the phaeophytinization (Bačkor et al., 2023).

4.3. pH

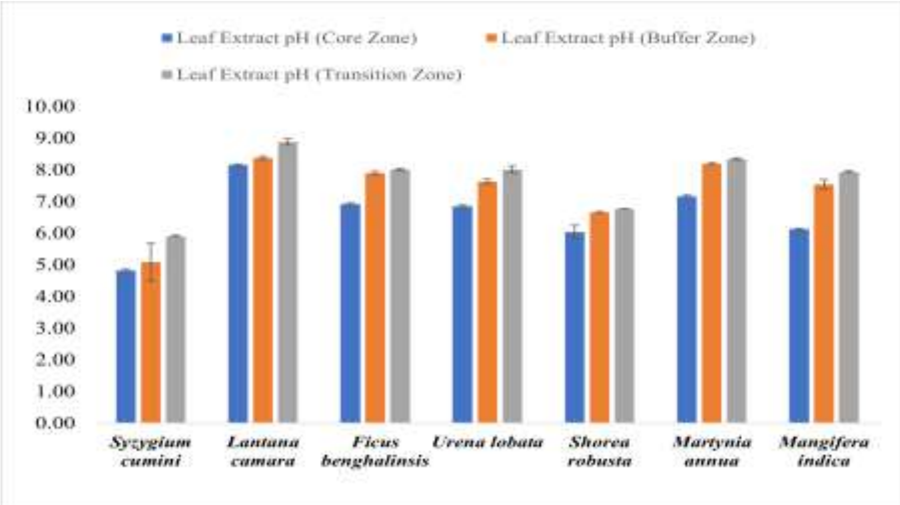


Fig 5: Graph showing the pH of leaf extract of plant species found in core, buffer & transition zones of Magadh open-cast coal mining region

Table 6: pH of leaf extract of plant species found in core, buffer & transition zones of Magadh open-cast coal mining region

Plant Species	Core	Buffer	Transition
Syzygium cumini	4.81±0.05	5.08±0.59	5.9±0.02
Lantana camara	8.15±0.02	8.37±0.06	8.87±0.1
Ficus bengalinsis	6.91±0.04	7.89±0.04	8.01±0.02
Urena lobata	6.84±0.04	7.62±0.07	8±0.11
Shorea robusta	6.03±0.2	6.66±0	6.76±0
Martynia annua	7.15±0.05	8.18±0.04	8.34±0.02
Mangifera indica	6.12±0.02	7.53±0.15	7.93±0.04

The leaf extract pH analysis across the core, buffer, and transition zones of Magadh opencast coal mining site indicates a spatial gradient of bio-physiological stress by shifting towards acidic in highly impacted zones. The pH value of *Syzygium cumini* shows the most significant acidification in the Core zone (4.81) relative to the buffer (5.08) and the transition zone (5.90) as shown in Fig 5 and Table 6. This variation primarily driven by the absorption of gaseous pollutants (SO_2 and NO_x) (Anand et al., 2022), which reacts with the water present in the cellular space inside the leaf matrix to form acidic radicals like sulphite and nitrite ions, decreasing the leaf pH (Dept. of Environmental Science, Abeda Inamdar Senior College, Pune, India et al., 2021). In contrast, the invasive species, *Lantana camara* is having alkaline pH across all the zones i.e. 8.15 (Core) to 8.87 (Transition), which indicates that the plant species is resistance towards the acidic pollutants. *Mangifera indica* and *Ficus benghalensis* both exhibit significant variation in the core zone (6.12 & 6.91 respectively) compared to the transition zone (7.93 & 8.01 respectively). It indicates that these two species act as a bio-accumulators where the dissolution of coal dust and gaseous oxides directly lowers the cytoplasmic pH, at a later time, it may impair the stomatal conductance and possibly linked with the enzymatic efficiency of the hexose sugar to ascorbate conversion pathway (Mehmood et al., 2024; Qadir et al., 2019). *Shorea robusta* shows a moderate but consistent shift of pH (6.03 in core zone to 6.76 in the transition zone), indicating its moderately tolerant plant status with a capacity to maintain a near neutral pH which is the optimum condition for protecting the magnesium content of the chlorophyll molecule from phaephytinization (Mehmood et al., 2024). The result of TwA observed SV in the pH values of leaf extract among the different sites at $p < 0.05$. The reduction in the leaf pH at the core zone is an indicator for the acid mine stress, transmitted through the atmosphere, where the presence of acidic molecules reduces the efficiency of the antioxidant scavenging system of the plant species, ultimately leading to the degradation of the photosynthetic apparatus and lowering the primary productivity (Kumar et al., 2021; Mehmood et al., 2024; Najafi Zilaie et al., 2023; Zandi & Schnug, 2022).

4.4. Relative Water Content (RWC)

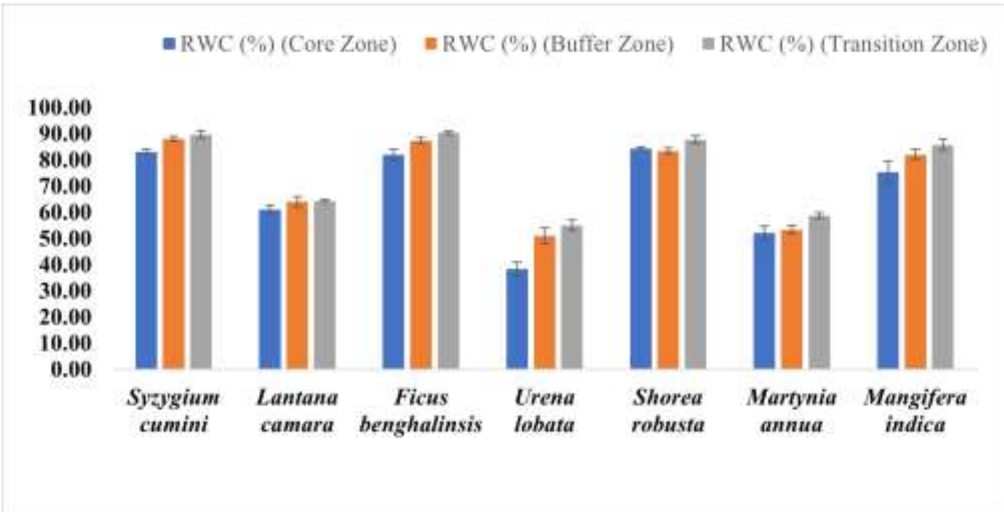


Fig 6: Graph showing the Relative water content of leaf of plant species found in core, buffer & transition zones of Magadh open-cast coal mining region

Table 7: Relative water content of leaf of plant species found in core, buffer & transition zones of Magadh open-cast coal mining region

Plant Species	Core	Buffer	Transition
Syzygium cumini	83±1	88±1	89.66±1.52
Lantana camara	61±1.73	64±2	64.33±0.57
Ficus bengalinsis	82±2	87.33±1.15	90.33±0.57
Urena lobata	38.33±2.51	51±3	55±2
Shorea robusta	84.33±0.57	83.33±1.15	87.66±1.52
Martynia annua	52±2.64	53.33±1.52	58.66±1.15
Mangifera indica	75.33±4.04	82±2	85.66±2.08

The distribution of RWC across the study area reflects a distinct physiological hierarchy in the capacity of the flora to mining induced dehydration. *Syzygium cumini* and *Urena lobata* exhibit significant hydric stress in the Core and Buffer zones, where RWC values are as low as 71.6% and 70.68% as shown in Fig 6 and Table 7. It may be the inhibitory effects of coal dust on stomatal conductance and the subsequent disruption of the transpiration process . In contrast, the higher and stable RWC maintained by *Lantana camara* (80.54%) and *Mangifera indica* (77.54%) in the Core zone highlights their good osmotic stress adjustment capabilities and membrane integrity, which allows these species to preserve their cellular turgidity, which is necessary for the maintenance of the active metabolic processes like ascorbate-glutathione cycle under highly dust contaminated environments (Hasanuzzaman et al., 2022). The depression of RWC in highly impacted zones is a consequence of increased protoplasmic permeability. It is caused due to gaseous pollutants like SO_2, leads to facilitates the leakage of intracellular water from the plant cell (Anand et al., 2022; H. Singh et al., 2023). The results performed by TwA, SV is observed among the different sites at $p < 0.05$.The ability of certain species to maintain higher RWC despite the heavy particulate loading serves as a primary determinant of their APTI, as the higher water content provides a crucial buffer against the acidification of leaf sap and the thermal degradation of chlorophyll (Goswami et al., 2023; H. Singh et al., 2023).

4.5. Air Pollution Tolerance Index (APTI)

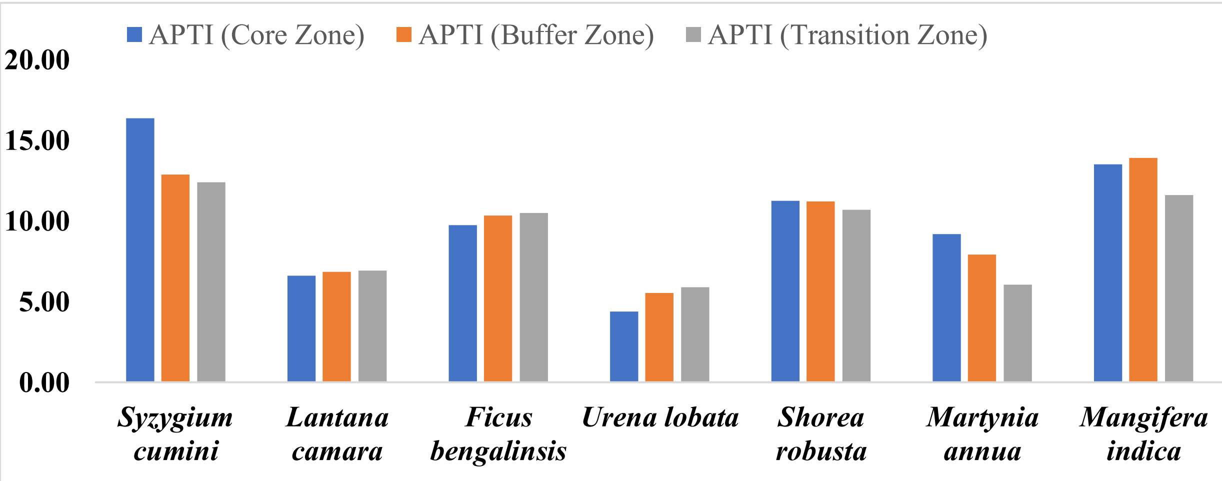


Fig 7: Graph showing the APTI of plant species found in core, buffer & transition zones of Magadh open-cast coal mining region

Table 8: APTI of plant species found in core, buffer & transition zones of Magadh open-cast coal mining region

Plant Species	Core	Buffer	Transition
Syzygium cumini	16.35	12.87	12.40
Lantana camara	6.61	6.85	6.91
Ficus bengalinsis	9.74	10.36	10.48
Urena lobata	4.39	5.55	5.87

Shorea robusta	11.27	11.20	10.68
Martynia annua	9.18	7.91	6.06
Mangifera indica	13.50	13.91	11.60

The APTI across the core, buffer, and transition zones provides a comprehensive physiological adaptation of native flora due to the coal mining-induced stress like particulate matter and the gaseous pollutants. *Syzygium cumini* and *Mangifera indica* are the two species in the study area, emerge as highly tolerant species as shown in Fig 7 and Table 8. *S. cumini* exhibiting a remarkable peak APTI of 16.35 in the high stress core zone, driven by a huge biochemical mobilization of ascorbic acid to nullify the effects induced due to the ROS. *M. indica* maintains a strong index of 13.5 in the Core to 13.91 in the buffer zone, indicating a robust structural capacity to maintain its cellular turgidity and integrity of the chloroplast despite the heavy loading of mine-induced dust. *Shorea robusta* demonstrates a remarkable stability with intermediate APTI score (11.27, 11.20, and 10.68 in the core, buffer, and transition zones respectively), which confirms its ecological resilience and its capability of maintaining the physiological homeostasis across all the region studied. On the other hand, *Urena lobata* and *Lantana camara* are observed to be having the lowest APTI values. This lower APTI value helps in categorizing these species as sensitive bio-indicators for the air pollution resulting by the mining activities. The APTI value of *U. lobata* i.e. 4.39 in the core zone reflects a failure of this species to buffer the acidic pollutants like oxides of sulphur or nitrogen, which may lead to rapid phaeophytinization and osmotic collapse (Timilsina et al., 2022). *Ficus benghalensis* have an intermediate APTI value ranging from 9.47 to 10.48, indicating the moderate sensitivity and a gradual recovery in its bio-physiological behaviours away from the core zone. Whereas *Martynia annua* displays a hyper stress-responsive gradient which is dropping from 9.18 in the core to 6.06 in the transition zone. It is most likely due to a localized, acute spike in its antioxidant defence response that rapidly depletes once it is removed from the immediate pollution source. The TwA results confirmed SV in the APTI values among the plants observed in different zones of study area at $p < 0.05$. These variations highlights that a plant's tolerance in this coalfield is highly connected to its combined ability to optimize the pH of the leaf sap against the acidic radicals, sustaining high RWC to prevent the thermal degradation of stomata, and deploy ascorbic acid to protect the photosynthetic apparatus, giving the species with high APTI invaluable for the pollution sink strategies and the species having the low APTI value, crucial for determining the active environmental bio-monitoring (Mehmood et al., 2024; A. K. Singh & Shukla, 2025).

4.6. Anticipated Performance Index (API)

The API analysis of native flora provides a critical and multidirectional evaluation which advocates about the biochemical tolerance of a plant species by integrating the APTI with fundamental, morphological, and socio-economic direction to determine the species suitability for the sustainable development of greenbelt in the highly polluted peripheries of the Magadh coalfield. Among all the studied species, *Ficus benghalensis* consistently indicates as the most robust species by securing a "Good" assessment category with the highest API scoring of 68.75% (Grade 4) constantly across the core, buffer, and transition zones. Although, its APTI value is moderate, its massive canopy structure, large leaf size, and hardy texture provide the superior aerodynamic resistance toward the pollution, allowing it to acts as a highly efficient sink for intercepting and trapping the coal particulates (PM_{10} and $PM_{2.5}$) carried by wind. *Syzygium cumini* also demonstrates a highly API performance, achieving a "Good" rating (62.5%) in the heavily polluted core zone but shifted to a "Moderate" classification (56.25%) in the buffer and transition zones. This variation shows its stress responsive biochemical profile where extreme atmospheric toxicity in the core zone triggers its peak antioxidant synthesis, which results in temporarily elevating its functional utility as a bio-shield for the pollutants. *Mangifera indica* maintains a stable "Moderate" categorization (56.25%, Grade 3) throughout all the studied zones, serving as a reliable biological barrier due to its dense canopy structure, favourable tree habit, and high economic value. Though its overall performance is slightly less compared to *Ficus benghalensis*. *Shorea robusta* demonstrated relatively stable APTI values across the core, buffer, and transition zones, indicating its ability to maintain physiological and biochemical homeostasis under mining-induced oxidative stress. However, despite this ecological resilience, the species was categorized as “Poor” under the API assessment (50%, Grade 2). This distinction arises because APTI primarily reflects physiological tolerance to air pollutants, whereas API additionally incorporates morphological and socioeconomic characteristics such as canopy architecture, leaf structure, plant habit, and foliage density that determine overall suitability for greenbelt development. Therefore, although *Shorea robusta* exhibits moderate pollution tolerance, its comparatively less dense canopy and structural attributes may limit its effectiveness in providing rapid and extensive pollutant interception in active mining areas. In the shrub category, *Lantana camara* (18.75%), Urena lobata (12.5%), and *Martynia annua* (scoring 6.25% in the Buffer and Transition zones) are universally classified as "Not recommended" (Grade 0) as the shrubs or herbaceous plants. They inherently lack the spatial canopy volume, structural hardness, and socio-economic utility required to modify the microclimates. An architectural inadequacy which is directly integrated by their extreme biochemical vulnerabilities to the acidic pollutant dissolution of the coal dust, estimating them as entirely unsuitable for the phytoremediation strategies but these species are highly effective as a sensitive bio-indicators of ecosystem degradation in such region.

4.7. Dust Capturing Capacity (DCC)

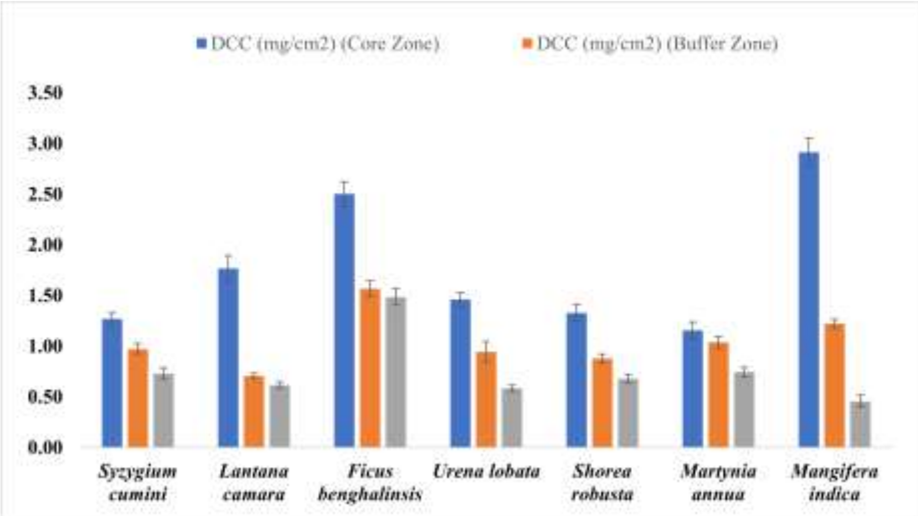


Fig 8: Graph showing the DCC of leaf surface of plant species found in core, buffer & transition zones of Magadh open-cast coal mining region

Table 9: DCC of leaf surface of plant species found in core, buffer & transition zones of Magadh open-cast coal mining region

Plant Species	Core	Buffer	Transition
Syzygium cumini	1.27±0.05	0.97±0.05	0.73±0.05
Lantana camara	1.76±0.12	0.7±0.02	0.61±0.03
Ficus bengalinsis	2.5±0.12	1.56±0.07	1.48±0.08
Urena lobata	1.46±0.06	0.94±0.1	0.58±0.03
Shorea robusta	1.33±0.08	0.87±0.04	0.67±0.04
Martynia annua	1.15±0.08	1.03±0.05	0.74±0.04
Mangifera indica	2.91±0.13	1.22±0.04	0.45±0.06

The DCC presents a clear decline from the core zone to the transition zone, which is directly indicating the atmospheric settling of the PM generated during the mining activities, and also the vehicular movement. *Mangifera indica* and *Ficus benghalensis* acts as the most favourable physical sinks for suspended atmospheric pollutants, recording the peak DCC values of 2.91 mg/cm^2 and 2.50 mg/cm^2 respectively in the heavily impacted core zone, before attenuating to 0.46 mg/cm^2 and 1.49 mg/cm^2 in the transition zone respectively as shown in Fig 8 and Table 9. This exceptional interception capacity is carried out by their leaf surface areas, dense evergreen canopies, and leathery epidermal textures of leaf along with complex epicuticular wax layers which further act as traps for the wind-blown dust. By considering the understory and pioneer ecological niches, *Lantana camara* (dropping from 1.77 mg/cm^2 in the core to 0.62 mg/cm^2 in the transition zone) and *Urena lobata* (1.46 mg/cm^2 to 0.58 mg/cm^2)

demonstrate significant particulate retention with respect to their smaller leaf area index. This phenomenon is facilitated by high foliar surface roughness and the dense proliferation of glandular trichomes or leaf hairs, that physically traps the wind-blown coal dust. *Shorea robusta*, exhibits a moderate dust capturing efficiency (declining from 1.33 mg/cm^2 to 0.68mg/cm^2 from core to transition zone respectively), while *Syzygium cumini* (1.27 mg/cm^2 to 0.73mg/cm^2 from core to transition zone respectively) and the herbaceous *Martynia annua* (1.16 mg/cm^2 to 0.74mg/cm^2 from core to transition zone respectively) record the lowest overall dust accumulations. It reflects the smoother surface of the leaf sap, arrangements of the leaf in an orientation of opposing angles for the dust retention, or canopy architectures less optimal for intercepting the dust particles. This shows the spatial variation of DCC across all species highlights a fundamental environmental principle which states that the heaviest particulate fractions (such as PM_{10} and larger coal fragments) are subject to undergo rapid gravitational settling upon the nearest vegetative barriers possessing high structural resistance, thereby validating the integration of hyper efficient dust accumulators like *M. indica* and *F. benghalensis* into the primary defensive tiers of sustainable greenbelt designs to reduce the ambient toxicity.

5. STATISTICAL ANALYSIS

Table 10: PCC between biochemical and physiological parameters, dust load and APTI

	pH	**AA**	**RWC**	**TCh**	**APTI**	**DCC**
pH	1					
AA	-0.779**	1				
RWC	-0.425**	0.437**	1			
Tch	-0.135	0.235	0.158	1		
APTI	-0.678**	0.874**	0.800**	0.278*	1	
DCC	-0.251*	0.230	0.085	0.168	0.215**	1

The provided Pearson Correlation Coefficient (PCC) matrix indicates that the APTI is positively corelated with the AA (r = 0.874) and the RWC (r = 0.800) of a plant, that means the APTI of a plant species is highly determined by the AA and RWC as shown in Table 10. As AA is found to be elevated in the highly polluted regions in the plant leaves, the APTI value for the plant will be higher in such region. The RWC is also observed to be higher in such area, so, it can be generalized that the plants having higher RWC value will must be having a greater APTI value in the polluted regions. Conversely, the leaf extract pH is demonstrating negative correlation with both APTI, the r value equal to -0.678 and AA (r = -0.779), which indicates that the lower pH levels in the leaf i.e. higher acidity is closely related to the elevated AA production and, greater pollution tolerance. TCH exerts a weaker positive influence on APTI (r = 0.278), which indicates that although the TCH is having a weaker co-relation with APTI, it slightly drives its value directly. The dust deposition characteristic exhibited a weak positive correlation with APTI (r = 0.215) and a weak negative correlation with leaf extract pH (r = –0.251), suggesting that external dust accumulation may have only a limited association with the physiological responses of the studied plant species. Although statistically significant, these relatively low correlation coefficients indicate that dust load was not a major determinant of APTI variation in the present study.

Table 11: TwA of biochemical and physiological parameters, APTI and DCC to observe significant difference among different sites and species

Elements	Source	SS	df	MS	F	Sig.
APTI	Species	562.083	6	93.680	2121.982	.000
	Sites	10.936	2	5.468	123.857	.000
	Species * Sites	46.276	12	3.856	87.351	.000
AA	Species	412.752	6	68.792	7059.617	.000
	Sites	76.205	2	38.103	3910.186	.000
	Species * Sites	89.820	12	7.485	768.132	.000
RWC	Species	14726.540	6	2454.423	678.196	.000
	Sites	664.222	2	332.111	91.768	.000
	Species * Sites	259.556	12	21.630	5.977	.000
pH	Species	59.223	6	9.870	438.936	.000
	Sites	13.582	2	6.791	301.993	.000
	Species * Sites	2.236	12	.186	8.287	.000
TCH	Species	1.951	6	.325	194.556	.000
	Sites	.044	2	.022	13.189	.000
	Species * Sites	1.763	12	.147	87.903	.000
DCC	Species	6.793	6	1.132	207.171	.000
	Sites	11.483	2	5.741	1050.538	.000
	Species * Sites	4.916	12	.410	74.955	.000

6. CONCLUSIONS

The eco-physiological evaluation of native flora across the core, buffer, and transition zones of the Magadh open-cast mining region provides a data-driven framework for identifying suitable species for sustainable greenbelt development. By integrating biochemical attributes with APTI, API, and DCC, the study highlights the differential adaptive responses of plant species under mining-induced environmental stress conditions. Among the evaluated species, *Ficus benghalensis* emerged as the most structurally suitable species for greenbelt development, achieving the highest API score (68.75%; “Good” category) consistently across all zones, along with high dust interception capacity (DCC = 2.50 mg cm^{-2} in the core zone). *Mangifera indica* also demonstrated strong suitability due to its comparatively stable physiological characteristics, elevated ascorbic acid content, and the highest dust retention capacity (DCC = 2.91 mg cm^{-2} in the core zone), indicating its potential role as an effective biological barrier against particulate pollution. *Syzygium cumini* exhibited high biochemical responsiveness under polluted conditions, with elevated ascorbic acid content (12.61 mg g^{-1}) and the highest APTI value (16.35) in the core zone, suggesting comparatively greater physiological tolerance to mining-associated stress. In contrast, species such as *Lantana camara*, *Urena lobata*, and *Martynia annua* were categorized as "Not Recommended" (Grade 0) because of their lower API scores and comparatively weaker structural and physiological suitability for greenbelt applications. Based on the combined assessment of APTI, API, and DCC, a mixed plantation strategy incorporating *Ficus benghalensis*, *Mangifera indica*, and *Syzygium cumini* may provide enhanced ecological benefits for greenbelt development in mining-affected landscapes through improved particulate interception and greater pollution tolerance capacity. However, the findings of the present study should be interpreted considering certain limitations. Direct monitoring of atmospheric pollutants accumulation was not conducted, seasonal observations were limited, and long-term field performance of the recommended species under continuous mining stress was not evaluated. Therefore, future studies integrating direct pollutant measurements, year-round monitoring, and long-term ecological performance assessments are necessary to further validate the suitability of these species for sustainable mine-site restoration and greenbelt planning.

Author contribution: MPP: Analysis, Ideation and drafting MK: Quality enhancement and Supervision, SG: Value addition and supervision, SM: Analysis and writing, AKS: Value addition and improvisation, SKS: Expert opinion and quality enhancement.

Availability of Data and Material: The data that supports the study are available from the corresponding author upon reasonable request.

Funding: Not applicable

Ethical Approval: This article does not contain any studies involving human participants performed by any of the authors.

Competing Interests: There are no competing interests.

Consent to Participate: Not applicable

Consent to publish: Not applicable

Declaration of generative AI and AI-assisted technologies in the writing process: During the preparation of this work the authors used to refine their self-written content using Grammarly writing assistant to improve writing skills and readability. After using this tool/service, the authors reviewed and edited the content as needed and took full responsibility for the content of the published article.

ACKNOWLEDGEMENT

The author gratefully acknowledges the Department of Environmental Sciences, Central University of Jharkhand, for providing the necessary research facilities and academic support to carry out this study. The author also sincerely thanks Central Coalfields Limited (CCL), Ranchi for granting permission and facilitating the conduct of the study in the coal mining region.

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