

RESEARCH ARTICLE

<https://doi.org/10.46488/NEPT.2026.v25i04.B4441>

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

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ARTICLE HISTORY

Received: 24-03-2026

Revised: 13-05-2026

Accepted: 21-05-2026

KEYWORDS

Air Pollution Tolerance Index (APTI)
Phytoremediation
Dust capturing capacity
Environmental monitoring

CITE THIS ARTICLE

Polavarapu, M.P., Kumar, M., Goswami, S., Mishra, S., Singh, A.K. and Shukla, S.K., 2026. Eco-physiological assessment of native plant species for mitigating airborne pollutants and greenbelt development in a coal mining region. *Nature Environment and Pollution Technology*, 25(4), B4441. <https://doi.org/10.46488/NEPT.2026.v25i04.B4441>

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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 evaluate the pollution tolerance capacity of seven native plant species across the core, buffer, and transition zones within the 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 an 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 socioeconomic attributes, API analysis identified *Ficus benghalensis* (Grade 4, 68.75%) and *Syzygium cumini* (Grade 4, 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 using pollution-tolerant and high dust-retaining species to design sustainable greenbelts in coal mining areas.

1. INTRODUCTION

Air pollution remains one of the most serious 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 contaminant (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 greenbelts 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 of plant species, APTI is one of the most widely used methods (Paul et al. 2023). APTI integrates four major biochemical and physiological parameters: total chlorophyll content (TCH), ascorbic acid content (AA), leaf extract pH, and relative water content (RWC) (Mehmood et al. 2023). This approach helps provide a comprehensive evaluation of plant defense mechanisms against air-pollution-induced stress. Recent studies have validated APTI as a holistic tool for categorizing plants into sensitive, intermediate, and tolerant groups, thereby supporting the selection of species for phytoremediation (Asif & Ma 2024).

APTI consists of two major components: physiological and biochemical. The physiological component comprises 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 the detoxification of acidic pollutants (e.g., SO_2 and NO_x), while RWC helps maintain turgidity and physiological function despite pollutant-induced transpiration stress (Timilsina et al. 2022). The biochemical components of APTI are AA and TCH, which indicate the metabolic proficiency of plants under stressed conditions. AA is a potent antioxidant that serves as a scavenger of reactive oxygen species (ROS) generated by pollutant exposure, thereby helping maintain cell membrane integrity (Najafi Zilaie et al. 2023). The higher the ascorbic acid level, the greater the potential for pollution tolerance (Chauhan et al. 2022). Chlorophyll content is often reduced in plants growing under stressed conditions because of the degradation of photosynthetic pigments. Tolerant plant species, however, commonly maintain stable chlorophyll levels to sustain productivity (Bui et al. 2021).

Beyond these biochemical properties, the APTI of many plant species is strongly influenced by spatiotemporal variations, including seasonal changes and microclimatic conditions (Bui et al. 2023). APTI values often vary seasonally; for example, the post-monsoon period, compared with winter or summer, may show optimal metabolic activity (Bui et al. 2023). Spatial factors such as elevation and proximity to pollution sources also play a significant role. Plants located in industrial regions or high-traffic zones may show higher APTI values than plants at residential sites. For example, a recent study indicated that *M. indica* showed high pollution-tolerance potential, with its highest APTI score across mining sites in the Khalari region, Jharkhand (Singh

& Shukla 2025). This suggests an adaptive physiological response to regular and long-term pollutant exposure (Chauhan et al. 2025). Understanding these seasonal and spatial variations is important for accurate categorization, as a species classified as sensitive in one season may show intermediate tolerance in another (Kaur 2021).

The relationship between APTI and Dust Capturing Capacity (DCC) describes the dual role of plants as biological monitors and physical barriers. A positive correlation has been reported between higher APTI values and dust accumulation in species with rough leaf structures or waxy cuticles, indicating that plants tolerant of greater physiological stress can also act as effective scrubbers of particulate matter (PM) from the atmosphere (Antil et al. 2025). Evaluating both APTI and PM accumulation provides a more holistic assessment of a plant's scrubbing potential than either parameter alone (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. The study area is shown in Fig. 1.

2.2. Sampling

The study area was divided into three zones based on distance from the mining area to assess the air pollution tolerance

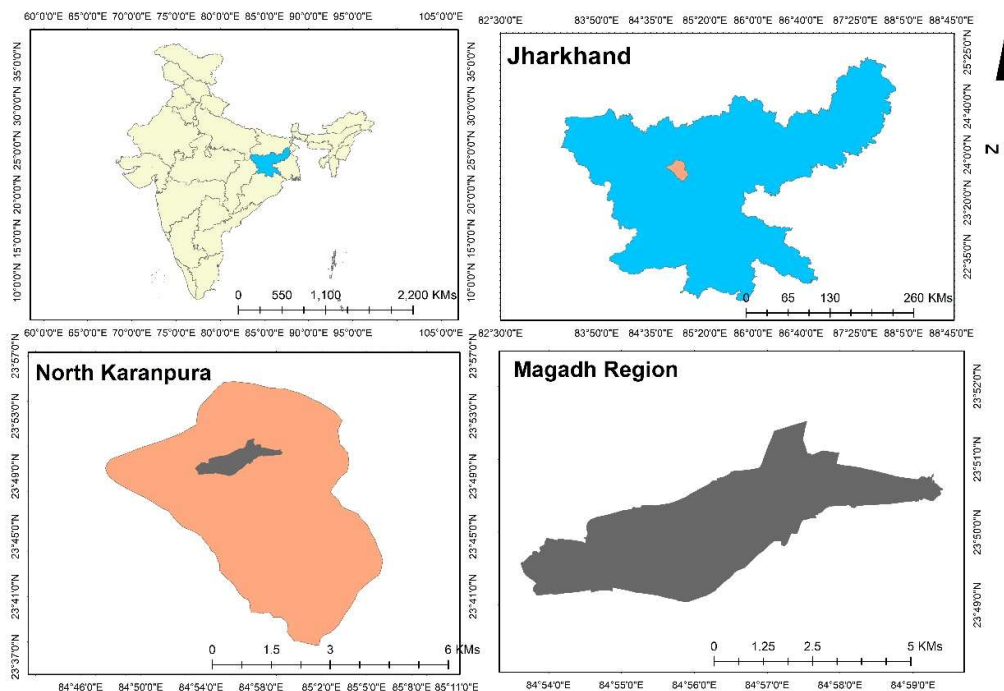


Fig. 1: Domain of the study area.

of roadside vegetation under varying pollution loads. The zones were categorized as follows: core zone, within 500 m of the mining area; buffer zone, located 3–5 km 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 suspended particulate matter (SPM) concentrations were $588.9 \mu\text{g m}^{-3}$ in the buffer zone and $601.4 \mu\text{g m}^{-3}$ in the core zone against the prescribed limit of $600 \mu\text{g m}^{-3}$. Similarly, PM_{10} concentrations were

$99.2 \mu\text{g m}^{-3}$ and $104.2 \mu\text{g m}^{-3}$, while $\text{PM}_{2.5}$ concentrations were $59.1 \mu\text{g m}^{-3}$ and $63.7 \mu\text{g m}^{-3}$ in the buffer and core zones, respectively, compared with the standard limits of $100 \mu\text{g m}^{-3}$ for PM_{10} and $60 \mu\text{g m}^{-3}$ for $\text{PM}_{2.5}$ (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 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 wind rose diagram (Fig. 2), which represented the direction and dispersion pattern of pollutants emitted from open-cast mining activities. This helped identify the most pollution-affected regions for vegetation sampling. Leaf sampling was conducted during November and December under clear atmospheric conditions. Sampling was carried out only when no rainfall had occurred for at least one week before collection to minimize the influence of precipitation on leaf surface characteristics and biochemical parameters. A random sampling method was adopted for leaf collection. Fully mature and healthy leaves were collected from all

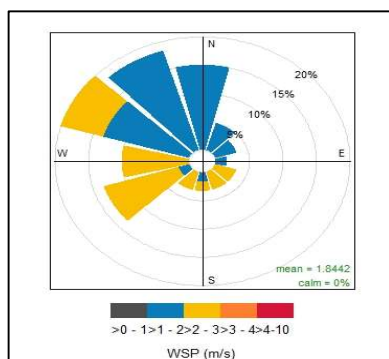


Fig. 2: Wind rose diagram of the study region.

Table 1: Average air quality of the Magadh region.

Sampling location	Buffer zone	Core zone	Limits as per NAAQS GSR 826 & 742(E)	Unit
Parameters				
SPM	588.9	601.4	600	$\mu\text{g m}^{-3}$
PM ₁₀	99.2	104.2	100	$\mu\text{g m}^{-3}$
PM _{2.5}	59.1	63.7	60	$\mu\text{g m}^{-3}$

sides of each selected plant species to ensure uniform representation. From each direction, 15 leaves were collected and pooled to form a composite sample for laboratory analysis. Sampling was performed during the morning hours from 6:00–8:00 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.

2.3. Experimental Analysis

2.3.1. Total Chlorophyll Content (TCH)

The TCH of leaves was determined using the method of Arnon (1949). The formula for determining TCH is given below:

$$\text{TCH} \left(\frac{\text{mg}}{\text{g}} \right) = \frac{(20.2 \cdot A_{645} - 0.02 \cdot A_{663}) \cdot V}{1000 \cdot W \text{ (g)}} \quad \dots(1)$$

Where,

A_{645} and A_{663} are the absorbances at 645 nm and 663 nm, respectively; V and W are the total extract volume (mL) and leaf weight (g), respectively (Jain et al. 2019).

2.3.2. Ascorbic Acid (AA)

AA was determined by the volumetric method described by Sadasivam & Balasubramanian (1987). The formula for calculating AA is given below:

$$A \left(\frac{\text{mg}}{\text{g}} \right) = \frac{0.5(\text{mg}) \cdot V_2 \text{ (mL)} \cdot 10 \text{ (mL)}}{V_1 \text{ (mL)} \cdot 5 \text{ (mL)} \cdot \text{weight of the sample (g)}} \quad \dots(2)$$

where V_1 and V_2 are the volumes of the dye titrated against the stock standard and the sample, respectively.

2.3.3. pH

The pH of leaves was determined using the method described by Singh et al. (1991).

2.3.4. Relative Water Content (RWC)

RWC was determined using the method described by Singh et al. (1991).

$$\text{RWC (\%)} = \frac{(\text{FW} - \text{TW})}{(\text{TW} - \text{DW})} \cdot 100 \quad \dots(3)$$

2.3.5. Air Pollution Tolerance Index (APTI)

The APTI was estimated using the following formula (Singh et al. 1991). The classification of APTI scores is given in Table 2.

$$\text{APTI} = [A \cdot (T + P) + R] \div 10 \quad \dots(4)$$

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

<1: Very sensitive (VS), 1–14: Sensitive (S), 15–19: Intermediate tolerant (IT), 20–24: Moderately tolerant (MT), and >24: Tolerant (T) (Singh et al. 2025).

2.3.6. Anticipated Performance Index (API)

The API of the tree species was assessed using the method of Mondal et al. (2011). API is expressed as a percentage score and was calculated as follows:

$$\text{API (\%)} = \frac{(\text{Total positives})}{16} \cdot 100 \quad \dots(5)$$

Plant species were graded for API determination based on APTI and other biological and socioeconomic characteristics, using Tables 2 and 3.

2.3.7. Dust Capturing Capacity (DCC)

Six leaves from each selected species were measured for leaf surface area and the amount of deposited dust. The DCC of

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 than 9 ft)	-
		Medium (9–45 ft)	+
		Large (more than 45 ft)	++
	Canopy structure	Sparse/irregular/globular	-
		Spreading/crown/open/semi dense	+
		Spreading dense	++
Laminar Structure	Plant type	Deciduous	-
		Evergreen	+
		Leaf Size	
	Texture	Small	-
		Medium	+
		Large	++
Economic value	Frequency	Smooth	-
		Rough	+
		Hardness	
	Frequency	Delicate	-
		Hard	+
		Frequency	
	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 based on 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)

each tree species was determined gravimetrically to evaluate species with high foliar dust deposition. Leaves carrying dust particles were weighed using a balance, and this weight was labeled W_1 for each species. Next, dust adhering to the leaf surface was meticulously removed by gently brushing the leaves with distilled water. The leaves were subsequently dried and reweighed, and this weight was recorded as W_2 . Leaf area was measured using a graphical approach and recorded as A (Das & Prasad 2012).

Finally, dust-capturing capacity (mg cm^{-2}) for each species was calculated using the formula below:

$$W \left(\frac{\text{mg}}{\text{cm}^2} \right) = \frac{W_1 - W_2}{A} \quad \dots(6)$$

2.4. Statistical Analysis

Two-way analysis of variance (ANOVA) was performed to assess significant differences between sites and species.

Pearson's correlation coefficient (PCC) was used to assess the relationships between parameters and the APTI scores of plant species. Differences were considered significant at $p < 0.05$.

3. RESULTS AND DISCUSSION

3.1. Total Chlorophyll Content (TCH)

Spatial variation in the TCH of local flora across the core, buffer, and transition zones acts as a crucial physiological indicator of changing atmospheric stress conditions induced by mining activities. Among the studied species, *Mangifera indica* exhibited the highest overall pigment concentration, showing relative stability with values of 1.78 mg g^{-1} in the core zone, 1.72 mg g^{-1} in the buffer zone, and 1.64 mg g^{-1} in the transition zone, as shown in Fig. 3 and Table 4. This suggests an adaptive mechanism by which the plant synthesizes compensatory chlorophyll to counteract the shading effect caused by heavy coal-dust deposition on the leaf surface. In contrast, *Urena lobata* showed a linear recovery trend, with the lowest TCH in the core zone (1.23 mg g^{-1}) and a significant increase in the transition zone (1.89 mg g^{-1}). This pigment degradation may result from pheophytinization, in which acidic pollutants such as sulfur oxides (mostly SO_2) displace 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 1.39, 1.39, and 1.43 mg g^{-1} in the core, buffer, and transition zones, respectively. This stability

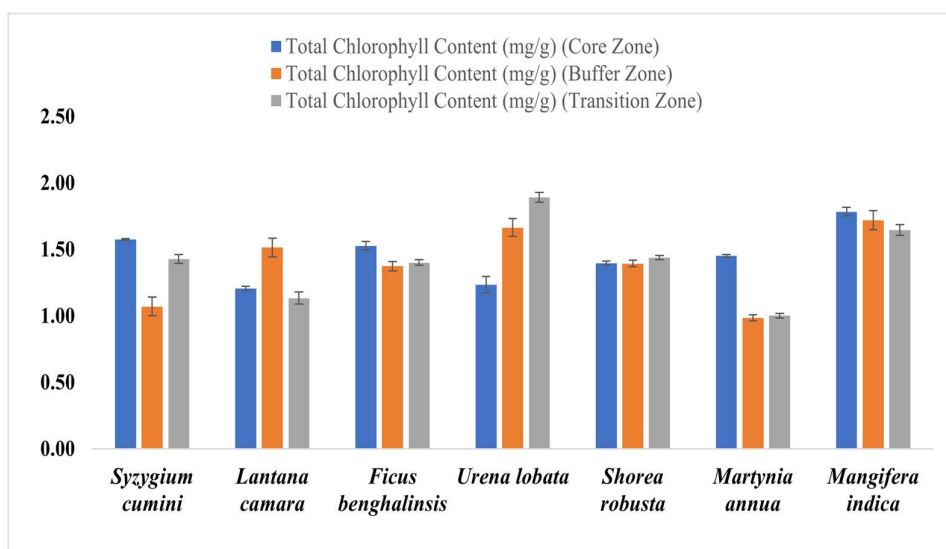


Fig. 3: Total chlorophyll content of leaf extracts of plant species in the core, buffer, and transition zones of the Magadh open-cast coal mining region.

Table 4: Total chlorophyll content of leaf extracts of plant species in the core, buffer, and transition zones of the Magadh open-cast coal mining region.

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

may indicate comparatively higher tolerance to mining-associated environmental stress. Maintenance of chlorophyll content under high-dust conditions could 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 conditions (Rai 2016), although these mechanisms were not directly investigated in the present study. In *Syzygium cumini* and *Martynia annua*, 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 interfere with stomatal functioning, alter leaf temperature, and affect chlorophyll metabolism, including chlorophyllase activity (Lin et al. 2021). The alkaline nature of coal dust may also 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 showed significant variation in TCH among the observed plant species across the core, buffer, and transition zones at $p < 0.05$, as shown in Table 11.

3.2. Ascorbic Acid (AA)

The AA content of native flora across the Magadh coal mining region can serve as a biochemical indicator of scavenging capacity against mining-induced oxidative stress and heavy-metal-laden coal dust. *Syzygium cumini* showed the most variable physiological response, with the highest AA level in the core zone (12.61 mg g⁻¹), declining through the buffer zone (6.61 mg g⁻¹) to the transition zone (4.68 mg g⁻¹), as shown in Fig. 4 and Table 5. This may indicate an enhanced antioxidant defense response under highly polluted conditions, which previous studies have associated with upregulation of the ascorbate–glutathione cycle involved in mitigating oxidative cellular damage (Caverzan et al. 2016).

Similarly, *Mangifera indica* showed significant antioxidant mobilization by maintaining high values in the core zone (7.54 mg g⁻¹) and decreasing toward the buffer (6.17 mg g⁻¹) and transition zones (3.17 mg g⁻¹), further indicating its ability to maintain homeostasis under coal-induced pollution (Singh & Shukla 2025). *Martynia annua* showed a decrease in AA concentration from 4.62 mg g⁻¹ in the core zone to 0.21 mg g⁻¹ in the transition zone, while *Shorea robusta* demonstrated a stable and gradual decrease in AA content from 3.81 mg g⁻¹ in the core zone to 2.33 mg g⁻¹ in the transition zone. *Lantana camara* (0.54 mg



Fig. 4: Ascorbic acid content of leaf extracts of plant species in the core, buffer, and transition zones of the Magadh open-cast coal mining region.

Table 5: Ascorbic acid content of leaf extracts of plant species in the core, buffer, and transition zones of the Magadh open-cast coal mining region.

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

g^{-1} in the core zone to 0.47 mg g^{-1} in the transition zone) and *Urena lobata* (0.68 mg g^{-1} in the core zone to 0.37 mg g^{-1} in the transition zone) maintained consistently lower AA levels. The ANOVA results showed significant variation in leaf AA among the examined plants across different sites in the Magadh region at $p < 0.05$. The higher AA level in the core zone may represent a defensive adaptation by the plants. As AA is an electron donor, it may help stabilize the photosynthetic apparatus by maintaining the reduced state of Cu and Fe cations and may also protect against pheophytinization (Bačkor et al. 2023).

3.3. pH

Leaf-extract pH analysis across the core, buffer, and transition zones of the Magadh open-cast coal mining site indicates a spatial gradient of physiological stress, with a shift toward greater acidity in highly impacted zones. *Syzygium cumini* showed the most pronounced acidification in the core zone (4.81) relative to the buffer (5.08) and transition zones (5.90), as shown in Fig. 5 and Table 6. This variation is primarily driven by the absorption of gaseous pollutants (SO_2 and NO_x) (Anand et al. 2022), which react with water present

Table 6: pH of leaf extracts of plant species in the core, buffer, and transition zones of the Magadh open-cast coal mining region.

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

in the cellular spaces of the leaf matrix to form acidic species such as sulfite and nitrite ions, thereby decreasing leaf pH (Kazi et al. 2021). In contrast, the invasive species *Lantana camara* had an alkaline pH across all zones, ranging from 8.15 in the core zone to 8.87 in the transition zone, indicating resistance to acidic pollutants. *Mangifera indica* and *Ficus benghalensis* both exhibited substantial variation between the core zone (6.12 and 6.91, respectively) and the transition zone (7.93 and 8.01, respectively). This indicates that these two species act as bioaccumulators, in which dissolution of coal dust and gaseous oxides directly lowers cytoplasmic pH; over time, this may impair stomatal conductance and may be linked to the enzymatic efficiency of the hexose-sugar-to-ascorbate conversion pathway (Mehmood et al. 2024, Qadir et al. 2019). *Shorea robusta* showed a moderate but consistent pH shift from 6.03 in the core zone to 6.76 in the transition zone, indicating its moderately tolerant status and capacity to maintain a near-neutral pH, which is an optimal condition for protecting the magnesium content of the chlorophyll molecule from pheophytinization (Mehmood et al. 2024). The ANOVA results showed significant variation in leaf-extract pH among the different sites at $p < 0.05$. The

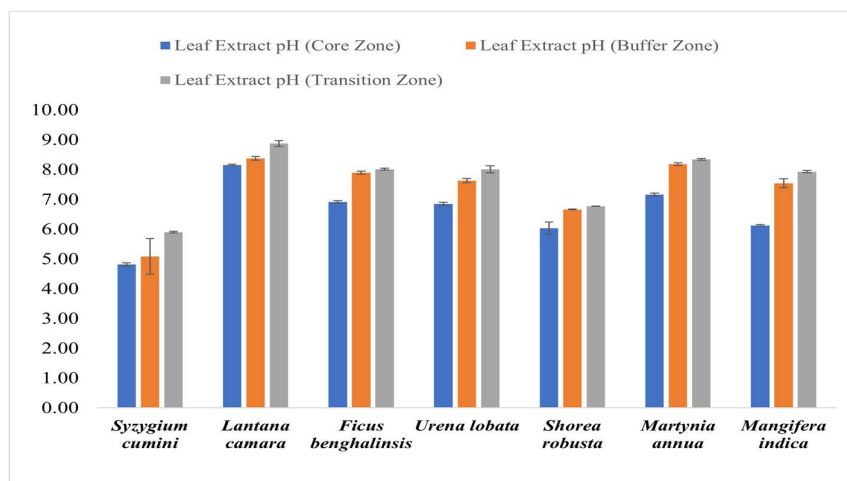


Fig. 5: pH of leaf extracts of plant species in the core, buffer, and transition zones of the Magadh open-cast coal mining region.

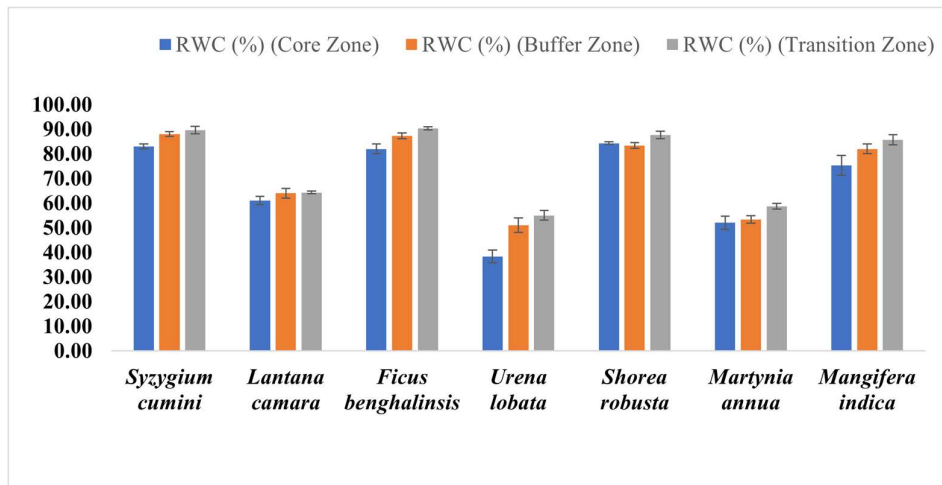


Fig. 6: Relative water content of leaves of plant species in the core, buffer, and transition zones of the Magadh open-cast coal mining region.

reduction in leaf pH in the core zone is an indicator of acid mine stress transmitted through the atmosphere, where the presence of acidic molecules reduces the efficiency of the antioxidant scavenging system of plant species, ultimately leading to degradation of the photosynthetic apparatus and lower primary productivity (Kumar et al. 2021, Mehmood et al. 2024, Najafi Zilaie et al. 2023, Zandi & Schnug 2022).

3.4. Relative Water Content (RWC)

The distribution of RWC across the study area reflects a distinct physiological hierarchy in the capacity of the flora to withstand mining-induced dehydration. The *Martynia annua* and *Urena lobata* exhibited significant hydric stress in the core and buffer zones, where RWC values were as low as 52.2 % and 38.33%, as shown in Fig. 6 and Table 7. This may result from the inhibitory effects of coal dust on stomatal conductance and subsequent disruption of transpiration. In contrast, the higher and more stable RWC maintained by *Shorea robusta* (84.33%) and *Ficus benghalensis* (82%) in the core zone highlights their osmotic stress-adjustment capabilities and membrane integrity, which allow these species to preserve cellular turgidity necessary

Table 7: Relative water content of leaves of plant species in the core, buffer, and transition zones of the Magadh open-cast coal mining region.

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

for maintaining active metabolic processes such as the ascorbate–glutathione cycle under highly dust-contaminated conditions (Hasanuzzaman et al. 2022). The depression of RWC in highly impacted zones may be a consequence of increased protoplasmic permeability caused by gaseous pollutants such as SO₂, facilitating leakage of intracellular water from plant cells (Anand et al. 2022, Singh et al. 2023). The ANOVA results showed significant variation among the different sites at $p < 0.05$. The ability of certain species to maintain higher RWC despite heavy particulate loading serves as a primary determinant of their APTI, as higher water content provides a crucial buffer against acidification of leaf sap and thermal degradation of chlorophyll (Goswami et al. 2023, Singh et al. 2023).

3.5. Air Pollution Tolerance Index (APTI)

The APTI across the core, buffer, and transition zones provides a comprehensive measure of the physiological adaptation of native flora to coal-mining-induced stress from particulate matter and gaseous pollutants. *Syzygium cumini* and *Mangifera indica* emerged as the two most tolerant species in the study area, as shown in Fig. 7 and Table 8. *S. cumini* exhibited a peak APTI of 16.35 in the high-stress core zone, driven by substantial biochemical mobilization of ascorbic acid to counteract the effects induced by ROS. *M. indica* maintained a strong index, from 13.50 in the core zone to 13.91 in the buffer zone, indicating a strong structural capacity to maintain cellular turgidity and chloroplast integrity despite heavy loading of mine-induced dust. *Shorea robusta* demonstrated remarkable stability, with intermediate APTI scores of 11.27, 11.20, and 10.68 in the core, buffer, and transition zones, respectively, indicating ecological resilience and the capacity to maintain physiological homeostasis across the study region. In contrast, *Urena*

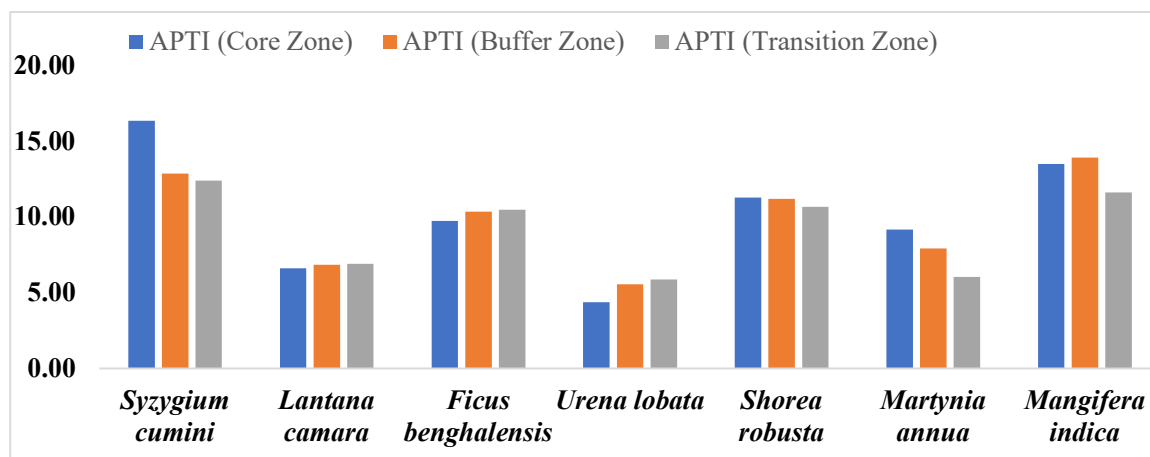


Fig. 7: APTI of plant species in the core, buffer, and transition zones of the Magadh open-cast coal mining region.

lobata and *Lantana camara* had the lowest APTI values. These lower APTI values support categorization of these species as sensitive bioindicators of air pollution resulting from mining activities. The APTI value of *U. lobata* (4.39 in the core zone) reflects a limited ability to buffer acidic pollutants such as sulfur or nitrogen oxides, which may lead to rapid pheophytinization and osmotic collapse (Timilsina et al. 2022). *Ficus benghalensis* had intermediate APTI values ranging from 9.74 to 10.48, indicating moderate sensitivity and gradual recovery in its physiological behavior away from the core zone. *Martynia annua* displayed a strong stress-responsive gradient, decreasing from 9.18 in the core zone to 6.06 in the transition zone. This is most likely due to a localized, acute increase in its antioxidant defense response that rapidly declines away from the immediate pollution source. The ANOVA results confirmed significant variation in APTI values among plants observed in different study zones at $p < 0.05$. These variations highlight that plant tolerance in this coalfield is strongly associated with the combined ability to optimize leaf-sap pH against acidic species, sustain high RWC to prevent thermal degradation of stomata, and mobilize ascorbic acid to protect the photosynthetic apparatus. Species with high APTI values

are therefore valuable for pollution-sink strategies, whereas species with low APTI values are useful for active environmental biomonitoring (Mehmood et al. 2024, Singh & Shukla 2025).

3.6. Anticipated Performance Index (API)

The API analysis of native flora provides a multidimensional evaluation of plant suitability for sustainable greenbelt development in the highly polluted peripheries of the Magadh coalfield by integrating APTI with morphological and socioeconomic attributes. Among the studied species, *Ficus benghalensis* consistently emerged as the most suitable species, securing a Good assessment category with the highest API score of 68.75% (Grade 4) across the core, buffer, and transition zones. Although its APTI value is moderate, its large canopy structure, large leaf size, and hardy texture provide superior physical resistance to pollution, allowing it to act as a highly efficient sink for intercepting and trapping coal particulates (PM_{10} and $PM_{2.5}$) carried by wind. *Syzygium cumini* also demonstrated high API performance, achieving a Good rating (62.5%) in the heavily polluted core zone but shifting to a Moderate classification (56.25%) in the buffer and transition zones. This variation reflects its stress-responsive biochemical profile, in which extreme atmospheric toxicity in the core zone triggers peak antioxidant synthesis, temporarily elevating its functional utility as a bioshield against pollutants. *Mangifera indica* maintained a stable Moderate categorization (56.25%, Grade 3) throughout all studied zones, serving as a reliable biological barrier because of its dense canopy structure, favorable tree habit, and high economic value, although its overall performance was slightly lower than that of *Ficus benghalensis*. *Shorea robusta* demonstrated relatively stable APTI values across the core, buffer, and transition zones, indicating its ability to maintain physiological and

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

Plant species	Core	Buffer	Transition
<i>Syzygium cumini</i>	16.35	12.87	12.40
<i>Lantana camara</i>	6.61	6.85	6.91
<i>Ficus benghalensis</i>	9.74	10.36	10.48
<i>Urena lobata</i>	4.39	5.55	5.87
<i>Shorea robusta</i>	11.27	11.20	10.68
<i>Martynia annua</i>	9.18	7.91	6.06
<i>Mangifera indica</i>	13.50	13.91	11.60

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 also 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* (6.25% in the buffer and transition zones) were classified as Not recommended (Grade 0). These shrubs or herbaceous plants inherently lack the spatial canopy volume, structural hardness, and socioeconomic utility required to modify microclimates. Their architectural limitations, combined with biochemical vulnerability to acidic pollutants and coal-dust deposition, make them unsuitable for phytoremediation strategies; however, these species may be effective as sensitive bioindicators of ecosystem degradation in such regions.

3.7. Dust Capturing Capacity (DCC)

The DCC showed a clear decline from the core zone to the transition zone, indicating atmospheric settling of PM generated by mining activities and vehicular movement. *Mangifera indica* and *Ficus benghalensis* acted as the most favorable physical sinks for suspended atmospheric pollutants, recording peak DCC values of 2.91 mg cm⁻² and 2.50 mg cm⁻², respectively, in the heavily impacted core zone before declining to 0.45 mg cm⁻² and 1.48 mg cm⁻², respectively, in the transition zone, as shown in

Table 9: DCC of leaf surfaces of plant species in the core, buffer, and transition zones of the Magadh open-cast coal mining region.

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

Fig. 8 and Table 9. This high interception capacity is associated with their leaf surface areas, dense evergreen canopies, leathery epidermal textures, and complex epicuticular wax layers, which act as traps for wind-blown dust. Considering understory and pioneer ecological niches, *Lantana camara* (decreasing from 1.76 mg cm⁻² in the core zone to 0.61 mg cm⁻² in the transition zone) and *Urena lobata* (1.46 mg cm⁻² to 0.58 mg cm⁻²) demonstrated substantial particulate retention relative to their smaller leaf area index. This phenomenon is facilitated by high foliar surface roughness and dense proliferation of glandular trichomes or leaf hairs that physically trap wind-blown coal dust. *Shorea robusta* exhibited moderate dust-capturing efficiency, decreasing from 1.33 mg cm⁻² to 0.67 mg cm⁻² from the core to the transition zone, respectively, while *Syzygium cumini* decreased from 1.27 mg cm⁻² to 0.73 mg cm⁻² and the herbaceous *Martynia annua* decreased from 1.15 mg cm⁻² to 0.74 mg cm⁻² over the same gradient. These species recorded the lowest overall dust accumulation. This may reflect smoother leaf surfaces, leaf arrangements at orientations less favorable for dust retention, or canopy architectures that are less optimal for intercepting dust particles. The spatial variation in DCC across all species highlights the rapid

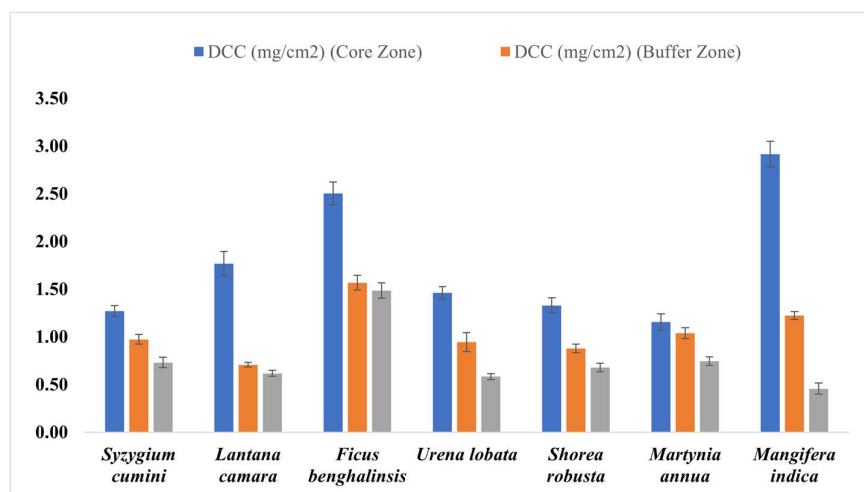


Fig. 8: DCC of leaf surfaces of plant species in the core, buffer, and transition zones of the Magadh open-cast coal mining region.

gravitational settling of heavier particulate fractions, such as PM_{10} and larger coal fragments, onto nearby vegetative barriers with high structural resistance, supporting the integration of efficient dust accumulators such as *M. indica* and *F. benghalensis* into the primary defensive tiers of sustainable greenbelt designs to reduce ambient toxicity.

3.8. Statistical Analysis

The Pearson correlation coefficient (PCC) matrix indicates that APTI is positively correlated with AA ($r = 0.874$) and RWC ($r = 0.800$), suggesting that APTI is strongly associated with AA and RWC, as shown in Table 10. As AA was elevated in plant leaves in highly polluted regions, APTI was also higher in such regions. RWC was also observed to be higher in such areas; therefore, it can be generalized that plants with higher RWC values tend to have greater APTI values in polluted regions. Conversely, leaf-extract pH showed negative correlations with both APTI ($r = -0.678$) and AA ($r =$

-0.779), indicating that lower leaf pH, i.e., greater acidity, is closely related to elevated AA production and greater pollution tolerance. TCH exerted a weaker positive influence on APTI ($r = 0.278$), indicating that although TCH had a weaker correlation with APTI, it was positively associated with the index. Dust deposition showed 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.

4. CONCLUSIONS

The ecophysiological evaluation of native flora across the core, buffer, and transition zones of the Magadh open-

Table 10: Pearson correlation coefficients (PCCs) among biochemical and physiological parameters, dust load, and APTI.

Variable	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

*Significant at $p < 0.05$; ** significant at $p < 0.01$

Table 11: Two-way ANOVA of biochemical and physiological parameters, APTI, and DCC to assess significant differences among sites and species.

Parameter	Source	SS	df	MS	F	Sig.
APTI	Species	562.083	6	93.680	2121.982	<0.001
	Sites	10.936	2	5.468	123.857	<0.001
	Species $\times$ Sites	46.276	12	3.856	87.351	<0.001
AA	Species	412.752	6	68.792	7059.617	<0.001
	Sites	76.205	2	38.103	3910.186	<0.001
	Species $\times$ Sites	89.820	12	7.485	768.132	<0.001
RWC	Species	14726.540	6	2454.423	678.196	<0.001
	Sites	664.222	2	332.111	91.768	<0.001
	Species $\times$ Sites	259.556	12	21.630	5.977	<0.001
pH	Species	59.223	6	9.870	438.936	<0.001
	Sites	13.582	2	6.791	301.993	<0.001
	Species $\times$ Sites	2.236	12	.186	8.287	<0.001
TCH	Species	1.951	6	.325	194.556	<0.001
	Sites	.044	2	.022	13.189	<0.001
	Species $\times$ Sites	1.763	12	.147	87.903	<0.001
DCC	Species	6.793	6	1.132	207.171	<0.001
	Sites	11.483	2	5.741	1050.538	<0.001
	Species $\times$ Sites	4.916	12	.410	74.955	<0.001

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 because of 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 in light of certain limitations. Direct monitoring of atmospheric pollutant 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.

5. ACKNOWLEDGMENTS

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

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