



Assessment of Air Pollution Tolerance and Anticipated Performance indices of some trees and shrubs from Bansra OCP of Raniganj Coalfield, India

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Article Info	ABSTRACT
Article type: Research Article Article history: Received: 10 Jun 2026 Revised: 03 Aug 2026 Accepted: 04 Oct 2026 Keywords: <i>Air Pollution</i> <i>Tolerance Index</i> <i>Anticipated</i> <i>Performance Index</i> <i>Bansra OCP</i> <i>Santiniketan</i> <i>Tolerant Species</i>	Air pollution from open-cast coal mining alters plant physiological processes affecting suitability for biomonitoring and ecological restoration. Comparative information on plant responses across contrasting pollution environments using both Air Pollution Tolerance Index (APTI) and Anticipated Performance Index (API) is limited. The present study assessed the biochemical response of sixteen plant species from Bansra Open Cast Project (OCP) of the Raniganj Coalfield and Santiniketan, a relatively less polluted area in West Bengal, to identify suitable species for pollution monitoring and plantation. Leaf extract pH, relative water content (RWC), ascorbic acid (AA) and total chlorophyll (TC) were analysed to determine APTI. API was calculated by integrating APTI with biological and socio-economic characteristics. Peroxidase activity (PA) and protein content (PC) were analysed as additional marker of environmental pollution. All species were classified as pollution-sensitive ($APTI \leq 10$). In polluted coalfield, biochemical parameters declined resulting in lower APTI for 13 species. Trees <i>Alstonia scholaris</i> and <i>Butea monosperma</i> and shrubs <i>Calotropis procera</i> and <i>Anisomeles indica</i> got the highest APTI in Santiniketan and Bansra, respectively. Trees <i>Alstonia scholaris</i> and <i>Bauhinia acuminata</i> achieved excellent API at both locations, while <i>Butea monosperma</i> and <i>Senna siamea</i> performed well at Santiniketan. Among shrubs, <i>Calotropis procera</i> and <i>Ricinus communis</i> consistently exhibited excellent API, whereas <i>Chromolaena odorata</i> and <i>Ziziphus mauritiana</i> performed better under mining conditions. Integrating APTI with API improved the assessment of plant suitability beyond biochemical tolerance alone. These identified species provide scientific basis for air pollution biomonitoring and highly recommended for green-belt development and ecological restoration in degraded mining-affected areas.

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INTRODUCTION

Air pollution remains one of the most serious environmental challenges worldwide, particularly in regions affected by rapid industrialization, urban expansion and intensive mining activities. The Raniganj Coalfield is one of India's oldest and most intensively exploited coal mining regions, where continuous mining operations generate substantial air pollution and environmental degradation. Open-cast coal mining releases large quantities of particulate matter together with gaseous pollutants, which alter plant physiological processes through oxidative stress, impaired photosynthesis and disruption of cellular metabolism. Because vegetation responds continuously to air pollutants, higher plants have become valuable biological indicators for assessing environmental quality and supporting pollution management strategies (Rai et al., 2013). Plants play a crucial role in pollution monitoring by exhibiting symptoms such as necrosis, chlorosis, epinasty on their leaves and even death in response to NO_x, SO_x

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and PAN (Chaubey et al., 2021; Sharma & Sharma, 2017).

Air pollutants impact important biochemical parameters, like leaf extract pH, ascorbic acid (AA), relative water content (RWC), and total chlorophyll (TC) content of plants. A specific internal leaf pH is required to trigger metabolic processes and enzymatic reactions (nutrient uptake and carbon assimilation) and also support plants to tolerate different types of contaminants (Sabri et al., 2015; Ogunrotimi et al., 2017). RWC is the measure of plant water status and is generally higher in polluted areas compared to non-polluted ones (Sharma & Sharma, 2017). Peroxidase induction is a general response of plants to the uptake of toxic amounts of heavy metals (Liu et al., 2022), low temperature, salt stress, wounding, pathogens, UV radiation and poisonous gases (Ashraf & Scalet., 2005). Peroxidases catalyze the oxidation of a wide variety of elements by reacting with hydrogen peroxide, protect the cell membrane to counteract active oxidants and develop stress resistance (Wang et al., 2023). AA functions as a primary redox buffer and a cofactor for enzymes involved in photosynthesis and hormone biosynthesis, and also serves as a precursor for other antioxidants. Chlorophyll is the principal photoreceptor of the light reaction in photosynthesis. One of the most prominent impacts of air pollution is the steady reduction in chlorophyll content, which decreases the photosynthetic capacity (Gholami et al., 2016). Plant proteins play various enzymatic and structural functions through folding ranging from compact and well-ordered to unfolded and intrinsically disordered, and also act as storehouse of nutrition for developing seedlings (Rasheed et al., 2020).

The Air Pollution Tolerance Index (APTI) has been widely employed as an empirical number to evaluate plant sensitivity or tolerance using four biochemical parameters - leaf extract pH, RWC, AA and TC (Singh & Rao, 1983) as individual responses of these parameters may yield incompatible results for the same plant species (Chouhan et al., 2012). Higher APTI value indicates higher pollution tolerance. Plants help improve air quality through absorption, uptake (by roots, bark, and leaves), transfer, and accumulation of toxic pollutants from the air, and immobilize them in their tissues (Roy et al., 2020). More recently, the Anticipated Performance Index (API) has complemented APTI by integrating biochemical tolerance with biological, ecological and socio-economic characteristics, thereby improving species selection for urban greening and green-belt development around industrial and mining areas (Prajapati & Tripathi, 2008; Sen et al., 2017; Govindaraju et al., 2022).

Although APTI has been extensively employed for evaluating plant responses to air pollutants, several important knowledge gaps remain. First, most previous investigations were restricted to single polluted environment focusing primarily on identifying pollution-tolerant species. Second, few studies evaluated plant responses across contrasting pollution gradients integrating biochemical tolerance with anticipated ecological performance. Third, information on comparative performance of native plant species between the polluted Raniganj Coalfield and a relatively cleaner reference site is lacking, limiting evidence-based species selection for biomonitoring, green-belt development and mine-site restoration. Consequently, there remains limited understanding of whether plant species exhibit consistent tolerance characteristics under markedly different environmental conditions, particularly in coal mining landscapes where complex mixtures of particulate matter and gaseous pollutants prevail.

To address these knowledge gaps, the present study compared sixteen naturally occurring tree and shrub species across highly polluted Bansra Open Cast Project (OCP) of the Raniganj coalfield and a relatively less polluted reference site Santiniketan, by integrating biochemical responses (APTI) with functional performance (API). Raniganj coal mine area is highly susceptible to several pollutants, including CO, NO_x, SO₂, CO₂, and heavy metals (Chakraborty & Gupta (Joshi), 2024; Chakraborty et al., 2025). The study aims to (i) investigate how contrasting air pollution regimes influence key biochemical attributes, (ii) quantify interspecific variation in air pollution tolerance among selected species using APTI, (iii) integrate physiological tolerance with functional and socio-economic attributes through API, and, (iv) identify and recommend

plant species suitable for pollution biomonitoring and sustainable green-belt development in coal mining and urban ecosystems.

MATERIALS AND METHODS

Study area

Bansra OCP is situated in the Raniganj CD block of the Asansol Sadar subdivision in Paschim Bardhaman district, West Bengal. It is located at 23°38'11" N and 87°07'41" E. Bansra OCP is a part of cluster no 10, operated by Eastern Coalfields Limited (ECL), a subsidiary of Coal India, and has the normal production capacity of 0.15 million tons/year (Ministry of Environment, Forests and Climate Change; IA-II (Coal Mining) Division. The area has hot and dry summers and mild winters. In the summer, the temperature soars above 45 °C and in winter, the temperature drops below 10 °C. The monsoon season starts in June and lasts until September. Average annual rainfall is 380 mm.

Santiniketan, a neighbourhood of Bolpur town, is situated in the Bolpur subdivision of Birbhum district, West Bengal, India (23° 67' 76" N and 87° 68' 52" E). The climate is typically sub-tropical. In summer, the temperature ranges from 35°C to 45°C, while in winter, it ranges from 10°C to 15 °C. Rainfall is about 1480 mm per year with maximum rainfall in July-August in the monsoon season. Due to less urbanization and the absence of industry, pollution is low in Santiniketan; however, the number of vehicles is gradually increasing.

Sampling of leaf

Eight tree species and eight shrub species (Table 1), commonly found in both Bansra OCP and Santiniketan, were selected from eight distantly located sampling points (Fig. 1). Fresh leaves were collected from March 2022 to May 2022, appropriately labeled and stored in refrigerator at ambient temperature until analysis for different biochemical tests. All the tests were performed in triplicate for all 16 species from both sites, summing up to 96 samples for each biochemical test.

Biochemical tests

pH was measured following the method proposed by Singh & Rao (1983) using a pH meter at 25°C. The RWC was measured using the method described by Singh (1977) by following the equation $RWC(\%) = [(FW - DW)/(TW - DW)] \times 100$ (FW= Fresh weight, DW= Dry weight, TW= Turgid weight). Ascorbic acid was estimated by the indophenol method (Keller & Schwager, 1977) by the formula, Ascorbic Acid (mg/g) = (0.1/ Reading of standardization) x difference x weight of leaf tissue. Total chlorophyll (TC) was measured by the spectrophotometric method (Arnon, 1949), using a spectrophotometer (Hach DR6000, Germany). Total chlorophyll was calculated using the following equations: Total Chlorophyll = Chlorophyll a + Chlorophyll b where

$$\text{Chlorophyll a (mg/g)} = \frac{[(0.0127 \times \text{O.D. at } 663\text{nm}) - (0.00269 \times \text{O.D. at } 646\text{nm})] \times \text{vol. of supernatant}}{\text{Weight of leaf tissue}}$$

Table 1. List of the selected tree and shrub species.

Name of the trees	Family	Name of the shrubs	Family
<i>Albizia lebbek</i> (L.) Benth.	Fabaceae	<i>Anisomeles indica</i> (L.) Kuntza	Lamiaceae
<i>Alstonia scholaris</i> (L.) R. Br.	Apocynaceae	<i>Calotropis procera</i> (Aiton) W.T. Aiton	Apocynaceae
<i>Azadirachta indica</i> A. Juss.	Meliaceae	<i>Chromolaena odorata</i> L.	Asteraceae
<i>Bauhinia acuminata</i> L.	Fabaceae	<i>Clerodendrum infortunatum</i> L.	Lamiaceae
<i>Butea monosperma</i> (Lam.) Taub	Fabaceae	<i>Hibiscus rosa-sinensis</i> L.	Malvaceae
<i>Dalbergia sissoo</i> DC.	Apocynaceae	<i>Lantana camara</i> L.	Verbenaceae
<i>Leucaena leucocephala</i> (Lam.) de Wit	Fabaceae	<i>Ricinus communis</i> L.	Euphorbiaceae
<i>Senna siamea</i> (Lam.) H.S. Irwin & Barneby	Fabaceae	<i>Ziziphus mauritiana</i> Lam.	Rhamnaceae



Fig. 1. Map showing sampling sites at Bansra OCP and Santiniketan (@Google Earth).

$$\text{Chlorophyll b (mg/g)} = \frac{[(0.0229 \times \text{O.D. at } 646\text{nm}) - (0.00468 \times \text{O.D. at } 663\text{nm})] \times \text{vol. of supernatant}}{\text{Weight of leaf tissue}}$$

Peroxidase activity was measured according to Sadasivam & Manickam (2008) by using the formula, Peroxidase activity (mg/hr) = Difference from the blank set $\times$ 0.34 $\times$ weight of leaf tissue. Protein content was determined with UV-Vis spectrophotometer (Hach DR6000, Germany) by comparing the OD values with the help of a standard curve of stock solution (BSA) (Lowry et al., 1951).

Air pollution tolerance index (APTI) and Anticipated performance index (API)

The air pollution tolerance index (APTI) was estimated using the four biochemical parameters mentioned above, as described by Singh & Rao (1983).

$$\text{APTI} = [A(T+P) + R] / 10$$

Where, A = Ascorbic acid content of leaf (mg/g of fresh weight), T = Total chlorophyll of leaf (mg/g of fresh weight), P = pH of leaf extract, R = Relative water content in percentage. We have followed the tolerance levels based on APTI value, as categorised by Lohe et al. (2015) <1, highly sensitive; 1-10, sensitive; 11-16, moderately tolerant; 17-29, tolerant; and 30-100, highly tolerant.

Anticipated performance index (API) was calculated according to Prajapati & Tripathi (2008) by combining the APTI value with some related socio-economic and biological parameters such as plant habit (PH), canopy structure (CS), type of plant (TP), laminar structure (Size, texture, hardness) and economic value (Abbas et al., 2013). Based on these parameters, different grades (+ or -) are allotted to plants (Supplementary Table 1). The API score obtained by a species represented the percentage of '+' grades allocated out of the total '+' grades. The final API

grade (Supplementary Table 2) is determined based on the score obtained.

Statistical analysis

The biochemical parameters are expressed as mean $\pm$ standard deviation. The significant differences in biochemical parameters between Bansra and Santiniketan, as well as between trees and shrubs, were tested by unpaired t-test. One-way ANOVA tested the significant differences in biochemical parameters among different species. Interrelations among various biochemical parameters were tested by Pearson's correlations. Stepwise multiple regressions identified the most significant parameter for APTI. All statistical tests were performed in SPSS version 20 at 0.05 level of significance.

RESULTS AND DISCUSSION

Tables 2 and 3 display the mean values of the investigated biochemical parameters and the determined APTI values of the selected trees and shrubs, respectively. All the parameters differed significantly among the 16 selected species ($p < 0.001$).

pH of leaf extract

The leaf extract pH among tree species ranged from 4.02 to 6.57 in Bansra OCP, whereas in Santiniketan, it ranged from 3.28 to 6.55. *B. monosperma* and *A. lebbeck* had the highest pH in Bansra and Santiniketan, respectively. *S. siamea* showed the lowest pH in both sites. *L. leucocephala* showed the highest variation in the mean leaf extract pH (4.28–5.75) between the two sites, and *A. scholaris* had the least variation (5.61–5.65). Among shrubs, the leaf extract pH ranged from 5.8 to 7.21 in Bansra OCP, and in Santiniketan, it ranged from 5.62 to 7.77. *C. infortunatum* (5.8) in Bansra OCP and *C. odorata* (5.62) in Santiniketan had the lowest pH values, whereas *L. camara* showed the highest pH levels (7.21 and 7.77) at both sites. The shrub species in both sites displayed almost similar pH values.

The acidic tendency of the leaf extract pH in polluted areas is primarily attributed to the presence of higher amounts of SO_x and NO_x in the air (Swami et al., 2004; Bharti et al., 2018). Plants with lower pH levels are more sensitive to air pollution, whereas species with higher pH levels are more resistant (Singh & Verma, 2007; Escobedo et al., 2008; Kumar & Nandini., 2013). Thus, the level of pH in leaf extracts of plants under polluted conditions is strongly associated with their level of tolerance to air pollutants. A low leaf extract pH showed a good correlation with sensitivity to air pollution (Pasqualini et al., 2001). Most of the tree species in Bansra had slightly higher pH than in Santiniketan, possibly due to deposition of alkaline dust and heavy loose soil on leaves, dissolving into cell sap and making it less acidic. However, t-test indicated no significant difference in mean leaf extract pH between Bansra and Santiniketan ($t=0.437$, $p=0.663$). The mean leaf extract pH values of trees and shrubs differed significantly ($t=2.875$, $p=0.005$), indicating that trees were more sensitive to air pollution than shrubs. Lower leaf pH in seven roadside trees from urban and suburban sites compared to the control sites is reported from Bilaspur, India (Jeet & Mahato, 2025).

Relative water content (RWC)

RWC is the water present in a leaf relative to its full turgidity, and indicates drought resistance. The highest and lowest values of RWC for tree species were observed in *A. scholaris* (86.88%) and *L. leucocephala* (71.39%), respectively, in Bansra OCP; and in *B. monosperma* (93.83%) and *A. lebbeck* (75.06%), respectively, in Santiniketan. *L. leucocephala* showed a wide range of variation (71.39 – 91.11%) in mean RWC between two sites, and *A. scholaris* had the least variation (81.74 – 86.88%). Among shrubs, *C. infortunatum* (70.73%) and *C. procera* (85.64%) had the lowest and highest RWC, respectively, in Bansra OCP; and in Santiniketan, it ranged

Table 2. Mean values of the biochemical parameters and APTI of selected tree species in Bansra OCP and Santiniketan.

Tree species	pH		Relative Water Content (%)		Ascorbic Acid Content (mg/g)		Total Chlorophyll (mg/g)		Peroxidase Activity (mg/hr)		Protein Content (ppm)		APTI	
	Bansra	Santiniketan	Bansra	Santiniketan	Bansra	Santiniketan	Bansra	Santiniketan	Bansra	Santiniketan	Bansra	Santiniketan	Bansra	Santiniketan
<i>Albizia lebbeck</i>	5.61±0.03	6.55±0.04	73.64±2.78	75.06±0.93	0.120±0.0035	0.208±0.0012	4.51±0.0015	2.60±0.029	2.18±0.44	0.77±0.06	245.59±0.45	423.02±0.15	7.49±0.28	7.70±0.09
<i>Astoria scholaris</i>	5.61±0.04	5.65±0.04	86.88±3.78	81.74±3.88	0.033±0.0024	0.018±0.0014	1.88±0.0015	1.08±0.0008	1.25±0.91	2.92±0.31	246.05±0.69	184.23±0.00	8.71±0.38	8.19±0.39
<i>Azadirachta indica</i>	6.35±0.03	6.20±0.05	73.57±1.86	81.12±1.93	0.098±0.0024	0.101±0.0008	2.20±0.0011	3.26±0.0009	1.27±0.49	1.77±0.10	170.14±0.26	194.83±0.40	7.44±0.19	8.21±0.19
<i>Bauhinia acuminata</i>	6.53±0.05	6.25±0.07	72.97±3.34	89.62±1.05	0.045±0.0020	0.072±0.016	3.07±0.0008	3.26±0.030	2.13±0.54	3.29±0.53	336.35±0.15	498.65±0.29	7.34±0.34	9.03±0.09
<i>Butea monosperma</i>	6.57±0.08	6.44±0.06	83.10±4.72	93.83±1.38	0.016±0.0025	0.038±0.0007	1.48±0.0015	1.17±0.0008	1.13±0.59	1.63±0.04	305.29±0.15	353.32±0.00	8.32±0.47	9.41±0.14
<i>Dalbergia sissoo</i>	6.31±0.07	6.43±0.11	72.55±1.28	91.45±0.98	0.030±0.0018	0.021±0.003	2.71±0.05	1.78±0.0008	1.11±0.5	5.60±0.05	231.95±0.52	454.23±0.00	7.28±0.13	9.16±0.10
<i>Leucaena leucoccephala</i>	5.75±0.05	4.28±0.03	71.39±2.99	91.11±4.84	0.035±0.0035	0.058±0.0018	3.39±0.0015	2.06±0.0008	1.75±0.78	0.25±0.02	216.20±0.40	539.38±0.15	7.16±0.29	9.13±0.48
<i>Senna siamea</i>	4.02±0.02	3.73±0.01	79.47±0.63	93.38±0.61	0.071±0.0049	0.056±0.011	4.07±0.0015	3.59±0.0009	0.82±0.52	1.52±0.02	262.11±0.40	463.77±0.52	8.0±0.07	9.38±0.05

Table 3. Mean values of the biochemical parameters and APTI of selected shrub species in Bansra OCP and Santiniketan.

Shrub species	pH		Relative Water Content (%)		Ascorbic Acid Content (mg/g)		Total Chlorophyll (mg/g)		Peroxidase Activity (mg/hr)		Protein Content (ppm)		APTI	
	Bansra	Santiniketan	Bansra	Santiniketan	Bansra	Santiniketan	Bansra	Santiniketan	Bansra	Santiniketan	Bansra	Santiniketan	Bansra	Santiniketan
Anisomeles indica	6.55±0.08	6.49±0.11	78.06±2.77	95.32±0.49	0.024±0.0035	0.076±0.0067	3.76±0.0015	1.67±0.0011	0.68±0.14	2.99±0.41	241.95±0.00	220.89±0.15	7.83±0.28	9.59±0.04
Calotropis procera	5.97±0.03	6.39±0.09	85.69±0.66	85.24±1.62	0.018±0.0035	0.154±0.0053	2.49±0.0015	1.55±0.0063	0.27±0.07	5.26±0.08	104.08±0.15	152.11±0.15	8.58±0.06	8.65±0.16
Chromolaena odorata	5.82±0.08	5.62±0.03	83.74±1.84	79.53±6.01	0.027±0.0062	0.024±0.0024	3.73±0.0015	2.00±0.0008	1.43±0.59	2.72±1.50	192.56±0.15	127.41±0.00	8.40±0.18	7.97±0.60
Clerodendrum infortunatum	5.80±0.04	5.87±0.05	70.73±1.29	78.87±1.58	0.020±0.0024	0.029±0.0062	2.03±0.0015	3.53±0.0008	0.95±0.51	1.88±0.22	155.14±0.00	834.53±0.30	7.09±0.13	7.91±0.16
Hibiscus rosa sinensis	6.08±0.02	6.03±0.07	76.83±1.90	89.23±2.92	0.029±0.0012	0.045±0.0012	1.66±0.0020	2.46±0.0008	1.11±0.57	1.11±0.47	143.47±0.40	199.53±0.30	7.71±0.19	8.96±0.29
Lantana camara	7.21±0.17	7.77±0.07	71.34±2.82	79.12±2.17	0.012±0.0024	0.053±0.0093	2.87±0.0015	3.16±0.0007	1.34±0.56	5.62±0.09	216.05±0.00	198.02±0.15	7.15±0.28	7.97±0.23
Ricinus communis	5.84±0.04	5.65±0.11	80.07±0.35	86.39±1.21	0.086±0.0035	0.123±0.0025	1.98±0.0015	2.24±0.061	0.45±0.10	1.07±0.33	200.74±0.30	290.74±0.30	8.07±0.03	8.74±0.12
Ziziphus mauritiana	6.06±0.02	6.07±0.02	73.54±2.10	53.93±1.55	0.137±0.0035	0.050±0.0059	2.15±0.00074	3.59±0.0008	0.84±0.40	2.29±0.16	353.77±0.26	526.95±0.00	7.47±0.21	5.44±0.16

from 53.93% in *Z. mauritiana* to 95.32% in *A. indica*. RWC in *A. indica*, *H. rosa-sinensis* and *Z. mauritiana* displayed variation between the two sites, whereas *C. procera* showed almost an equal amount of RWC. Mean RWC values significantly differed between the two sites ($p=0.001$), mostly being higher in Santiniketan, but did not differ significantly between trees and shrubs ($p=0.150$). Air pollution causes a reduction in the transpiration rate and damages the leaf engine that pulls water up from the roots (1-2% of the total) (Swami et al., 2004). Bora & Joshi (2014) have recorded high RWC in tree species due to stress. Recent studies also reported higher RWC in polluted urban sites compared to control sites (Rajah et al., 2025; Nkechi et al., 2024; Jeet & Mahato, 2025). Our results are similar to Pillai (2022) who reported lower RWC in polluted roadside trees than in residential areas. The lower RWC in the polluted mining region highlights the sensitivity of the selected plant species towards air pollution. The only exception to this observation was the shrub *Z. mauritiana* possessing significantly higher RWC in Bansra than in Santiniketan.

Ascorbic acid (AA)

A. lebbeck showed the highest AA in both sites, whereas the lowest value was recorded in *B. monosperma* (0.016 mg/g) and *A. scholaris* (0.018 mg/g) from Bansra and Santiniketan, respectively. *S. siamea* showed a wide range of variation of AA (0.056 – 0.071 mg/g) between two sites. Among the shrubs, AA ranged from 0.012 mg/g in *L. camara* to 0.137 mg/g in *Z. mauritiana* in Bansra OCP. It ranged from 0.024 to 0.154 mg/g in Santiniketan. *C. odorata* had the lowest AA, whereas *C. procera* possessed the highest value. Ascorbic acid content in *A. scholaris*, *D. sissoo* and *S. siamea* was slightly higher in Bansra OCP than in Santiniketan. However, the mean AA was significantly higher in Santiniketan than in Bansra ($p=0.015$), but not significantly different between trees and shrubs ($p=0.301$). Generally, ascorbic acid content increases under stress conditions. According to Jyothi and Jaya (2010), a higher ascorbic acid content in the plant is a sign of its tolerance to SO_2 pollution. Kashish et al. (2019) and Yannawar & Bhosle (2013) have also reported higher AA content in leaves due to increased pollution stress. Nkechi et al. (2024) found high AA content in tolerant plant species from both experimental (roadside) and control sites. Rajah et al. (2025) reported higher AA in traffic zone trees than in residential and industrial zones, arguing that it helps neutralize the ROS generated in plant cells through pollutants. Significant drop in AA in the polluted environment established the sensitive nature of most of the selected species; but the individual response of a few species differed. Species such as *A. indica*, *C. procera*, *L. camara* and *Z. mauritiana* exhibited variation in ascorbic acid content in their leaves between two sites, indicating that each of these species, although tolerant in one site, may be sensitive in another site.

Total chlorophyll (TC)

The TC among the tree species of Bansra OCP was highest (4.51 mg/g) in *A. lebbeck* and was lowest in *S. siamea* (1.48 mg/g). In Santiniketan, the highest TC was recorded from *S. siamea* (3.59 mg/g). *A. indica* displayed a wide range of variation in TC (2.2–3.26 mg/g) between Bansra and Santiniketan. Among the shrubs, *A. indica* (3.76 mg/g) and *H. rosa-sinensis* (1.66 mg/g) showed the highest and lowest values of TC, respectively, in Bansra OCP. In Santiniketan, the highest TC was recorded from *Z. mauritiana* (3.59 mg/g) while *C. procera* (1.55 mg/g) had the lowest value. Most of the tree species had slightly higher TC in Bansra OCP than in Santiniketan, but the mean TC did not vary significantly between Bansra and Santiniketan ($p=0.074$) and also between trees and shrubs ($p=0.887$). Reduction of chlorophyll has been widely used to indicate air pollution in contaminated areas. A high amount of pollutants decreases and degrades chlorophyll content in plants at polluted sites (Jyothi & Jaya, 2010). Rao and Leblanc (1966) reported a reduction in chlorophyll due to acidic pollutants like SO_2 , which causes pheophytin formation through the acidification of chlorophyll. Ninave (2001) and Mir et al. (2008) reported

decreased chlorophyll in areas with higher levels of automobile pollution. Rajah et al. (2025) also attributed the reduction in TC in traffic zone trees to vehicular pollution (especially SO₂) and particulate matter, which damage chloroplasts. Jeet and Mahato (2025) also noticed lower TC in tree species from urban and suburban sites. Pillai (2022) attributed the decrease in RWC and TC in urban polluted roadside trees to dust deposition, which affects transpiration through stomatal closure and photosynthesis by preventing gaseous exchange. In contrast, exposure to nitrogenous air pollutants may create fertilization effect leading to increased chlorophyll content in moderately polluted region than in unpolluted regions, as reported by Tripathi & Gautam (2007). It may explain slightly higher chlorophyll in plant leaves from Bansra OCP.

Air pollution tolerance index (APTI)

Different tree and shrub species exhibited varying APTI values, corresponding to their sensitivity or tolerance levels to air pollution. Among trees, it ranged from 7.16 for *L. leucocephala* to 8.71 for *A. scholaris* in Bansra OCP, and 7.70 for *A. lebbeck* to 9.41 for *B. monosperma* in Santiniketan. Tree species such as *A. scholaris*, *B. monosperma* and *S. siamea* had higher APTI values (≥ 8) in both study sites as compared to the other species. Among the shrubs, APTI ranged from 7.09 for *C. infortunatum* to 8.58 for *C. procera* in Bansra OCP, whereas in Santiniketan it ranged from 5.44 for *Z. mauritiana* to 9.59 for *A. indica*. Species such as *A. indica*, *C. procera*, *C. odorata* and *R. communis* had higher APTI values (around eight or more) in both study sites as compared to the other species. The mean APTI significantly differed between the two sites, with most species having lower APTI in Bansra than in Santiniketan ($p=0.001$). However, *A. scholaris*, and two shrub species *C. odorata* and *Z. mauritiana* had higher APTI in Bansra OCP than in Santiniketan. The APTI of trees and shrubs did not differ significantly ($p=0.136$). The APTI values differs from species to species in response to the pollutants. Since all the selected species had $APTI \leq 10$, they fall under the 'sensitive' category, as per Lohe et al. (2015). Many comparative studies reported higher APTI from polluted areas than from unpolluted control sites. Nishad et al. (2020) estimated APTI ranging from 9.7 to 17.22 for *Ficus benghalensis* from control sites and polluted highways in Allahabad. APTI ranging from 15 to 36 for three tree species, including *Polyalthia longifolia*, are reported from residential and roadside areas in Bengaluru (Pillai, 2022). Another study from Tamil Nadu reported a higher APTI (30.52) from the traffic zone than from the residential zone (24.98) for *Polyalthia longifolia* (Rajah et al., 2025). Our APTI values for tree species are similar to the values from urban areas of Bilaspur for *A. scholaris* (8.89), *B. monosperma* (7.72) and *D. sissoo* (8.44) (Jeet & Mahato., 2025). Few studies followed Ghafari et al. (2021) in assigning tolerance levels to APTI values, reporting APTI values of 7 to 8 as moderately tolerant and tolerant (Bui et al., 2023). Such studies also reported seasonal variations in tolerance levels as APTI was affected by changes in temperature and humidity (Bui et al., 2023; Liu & Ding, 2008).

Peroxidase activity (PA)

Among the trees, *A. lebbeck* had the highest value (2.18 mg/hr) and *S. siamea* showed the lowest value (0.82 mg/hr) of the PA in Bansra OCP. In Santiniketan, *D. sissoo* (5.6 mg/hr) and *L. leucocephala* (0.25 mg/hr) showed the highest and lowest values of PA, respectively. A wide range of variation was observed for PA in *D. sissoo* between Bansra OCP and Santiniketan (1.11–5.6 mg/hr). Among the shrubs, *C. procera* (0.27 mg/hr) and *C. odorata* (1.43 mg/hr) exhibited the lowest and highest PA, respectively, in Bansra OCP. In Santiniketan, *R. communis* (1.07 mg/hr) had the lowest value, whereas *L. camara* (5.62 mg/hr) possessed the highest value of PA. All the species exhibited a wide range of variation in their PA between the two sites, except for *H. rosa-sinensis*. Mean PA significantly differed between the two sites ($p<0.001$), with values mostly higher in Santiniketan, but did not differ significantly between trees and shrubs ($p=0.768$). The induction of antioxidant enzyme activity is an important defense

mechanism in plants in response to air pollutant-induced oxidative stress (Liu et al., 2022). Priyadarshini and Sahu (2019) noticed nearly 20 to 60% increased PA in the plants of polluted zone and simultaneous decline in all other important biochemical parameters like AA, TC, PC, carbohydrate content and catalase, and held PA to be primarily responsible for plant protection in the stressed environment. Tripathi & Gautam (2007) also reported 40 to 60% increased PA in tree species when they are shifted from clean control site to polluted bioindicator sites. However, Tyagi et al. (2024) suggested that PA may not be used as a specific indicator of a single air pollutant and can only be considered as a general indicator of oxidative stress. Reduction in PA in Bansra highlights the greater concentration of air pollutants in general.

Protein content (PC)

The PC in the tree leaves ranged from 170.14 to 336.35 ppm in Bansra OCP and from 184.23 to 539.38 ppm in Santiniketan. The highest PC was recorded in *B. acuminata* from Bansra and *L. leucocephala* from Santiniketan. *A. indica* showed the least range of variation (170.14 – 194.83 ppm) in PC, whereas *L. leucocephala* displayed a much wider range of variation (216.2 – 539.38 ppm) between the two sites. Among the shrubs, PC ranged from 104.08 ppm in *C. procera* to 353.77 ppm in *Z. mauritiana* in the Bansra OCP. In Santiniketan, *C. odorata* showed the lowest PC (127.41 ppm), whereas *C. infortunatum* displayed the highest (834.53 ppm) concentration of protein. *Z. mauritiana* in Santiniketan also possessed higher PC, i.e., 526.95 ppm. The mean PC significantly differed between the two sites ($p < 0.001$), mostly being higher in Santiniketan than in Bansra. Mean PC value also differed significantly between trees and shrubs ($p = 0.002$), mostly being higher in trees than in shrubs. Among all the species at the two sites, the shrub *C. infortunatum* from Santiniketan contained exceptionally high protein content. Priyadarshini & Sahu (2019) found 40 to 60% reduction in leaf PC in five tree species from polluted industrial zone around Hindalco smelting unit compared to clean control zones. More recently Singh & Pal (2024) recorded drop in PC in 50 plant species including trees and shrubs from unpolluted zone to opencast mining zone in Bundelkhand. Significant decline in the polluted Bansra OCP establishes protein content as a marker of air pollution.

Decline in important biochemical attributes like AA, RC, PA and PC in the aforementioned results clearly highlights that majority of the selected plant species growing in the coal mining area are facing severe pollution stress. Slightly increased chlorophyll content in the tree species may have provided some compensation against the stress damage. Additionally, a few species responded differently regarding the changes in their biochemical parameters. For example, *A. scholaris* developed higher APTI in the Bansra OCP due to combined effect of increase in AA, RWC, TC and PC under pollution stress. *S. siamea* and *D. sissoo* also had higher AA content in Bansra. Similarly, peroxidase activity was 3 to 7 times higher in *A. lebbeck* and *L. leucocephala* in Bansra OCP. Higher APTI for the shrub *C. odorata* in polluted region is also attributed to the increased AA, RWC, TC and PC; and for *Z. mauritiana* to the increased RWC and AA.

Correlation and regression analysis

The majority of the biochemical parameters displayed significant positive or negative correlation among themselves (Table 4). The highest significant positive correlation was noticed between RWC and APTI. RWC also showed a significant negative correlation with both pH and TC. Recent studies found a high to moderate positive correlation between RWC and APTI (Jeet & Mahato, 2025; Rajah et al., 2025; Nkechi et al., 2024). Rajah et al. (2025) have also reported positive correlations of TC with both RWC and APTI. On the other hand, Bui et al., (2023) found a negative correlation of APTI with both TC and RWC. In the present study, APTI was significantly negatively correlated with TC as well as pH. AA displayed an insignificant weak positive correlation with APTI, TC and RWC, and a weak negative correlation with pH in this study. In contrast, AA was identified as the most significant determinant of APTI, exhibiting

Table 4. Correlations among biochemical parameters. Values in parentheses indicate significance level.

	pH	AA	TC	APTI	PA	PC
RWC	-.208*(.042)	.020(.848)	-.334**(.001)	.999**(.000)	.043(.680)	.017(.873)
pH	1	-.116(.260)	-.182(.076)	-.205*(.045)	.312**(.002)	-.214*(.037)
AA		1	.156(.130)	.060(.563)	.080(.439)	.168(.101)
TC			1	-.328**(.001)	-.041(.689)	.229*(.025)
APTI				1	.046(.657)	.023(.827)
PA					1	.104(.312)

*Correlation is significant at the 0.05 level. ** Correlation is significant at the 0.01 level.

a strong positive correlation with APTI and other biochemical parameters (Rajah et al., 2025; Nkechi et al., 2024; Pillai, 2022). The negative correlation between pH and APTI, as well as the absence of a strong positive correlation between AA and APTI, points to the decrease in pH and AA in response to pollutants, and hence indicates the sensitive nature of the selected species.

Apart from APTI-related parameters, pH was strongly positively correlated with PA and negatively correlated with PC; a strong positive correlation was also recorded between TC and PC. APTI has been regarded as an efficient and cheap way to biomonitor the air pollution. APTI, AA and RWC are shown to be highly positively correlated with key air pollutants in our country, such as NO₂, SO₂ and PM_{2.5}, while TC showing negative correlation with these pollutants, was projected as an early indicator of pollution stress (Rajah et al., 2025). In the present study, a higher APTI value in Santiniketan is associated with a lower concentration of pollutants, as indicated by random data from the study period (e.g., March 29, 2022) and the current year (Supplementary Table 3).

Stepwise multiple regression of APTI on RWC, AA, pH and TC resulted in the following equation:

$$\text{APTI} = -0.043 + 0.100\text{RWC} + 0.875\text{AA} + 0.005\text{pH} + 0.005\text{TC} \pm 0.00489 \text{ S.E. } (R^2 = 1.000).$$

This equation indicates that as RWC increases by one unit, the APTI increases by 0.100 units, keeping effects of other parameters constant. Similarly, every unit increase of AA is associated with a 0.875-unit increase of APTI; this is true only if the effects of remaining parameters are held constant. Every unit increase in pH or TC was associated with only a 0.005 unit increase in APTI, while keeping the effects of all other parameters constant. The standard error of estimate was very low (≈ 0.005) and the R² value indicate the fitness of the regression equation. The correlation and regression analysis established RWC and AA as important determinants for APTI signifying the important role of water balance and antioxidant defense in determining pollution tolerance.

ANTICIPATED PERFORMANCE INDEX (API)

The API is crucial for estimating the tolerance of plants based on socio-economic characteristics, frequency, and APTI (Abbas et al., 2013). The scoring percentage and API grades of the selected tree and shrub species are shown in tables 5 and 6, respectively. The results indicated that the API of tree species was better in Santiniketan compared to Bansra, as four tree species received an excellent grade in Santiniketan, in contrast to only one in Bansra. Moreover, the number of tree species getting a moderate grade reduced from three in Bansra to one in Santiniketan. Among the tree species of Santiniketan, *A. scholaris*, *B. acuminata*, *B. monosperma* and *S. siamea* showed excellent tolerance and are highly recommended for plantation. Other tree species showed moderate to very good tolerance. In Bansra, *A. scholaris* showed excellent, followed by *B. acuminata*, which showed very good tolerance, and hence highly recommended for plantation in that location. The API of shrubs was slightly better in Bansra, as two species, *C. odorata* and *Z. mauritiana*, having poor grade in Santiniketan, were

Table 5. API value of tree species in Bansra OCP and Santiniketan.

Name of the Species	APTI	GRADE	MORPHOLOGICAL			LAMINA STRUCTURE			Economic value	GRADE ALLOTTED				
			PH	CS	TP	SIZE	TEXTURE	HARDNESS		Total plus	SCORE %	API	ASSESSMENT	
Bansra OCP														
<i>Albizia lebbeck</i>	7.49±0.28	+++	++	++	-	-	-	-	++	9	56.25	3	MODERATE	
<i>Alstonia scholaris</i>	8.71±0.38	++++	+	++	+	++	+	+	++	13	81.25	6	EXCELLENT	
<i>Azadirachta indica</i>	7.44±0.19	+++	++	++	+	-	-	-	++	10	62.5	4	GOOD	
<i>Bauhinia acuminata</i>	7.34±0.34	+++	++	+	+	+	+	+	++	12	75	5	VERY GOOD	
<i>Butea monosperma</i>	8.32±0.47	++++	+	-	-	++	+	+	++	11	68.75	4	GOOD	
<i>Dalbergia sissoo</i>	7.28±0.13	+++	++	+	-	-	-	-	++	8	50	3	MODERATE	
<i>Leucaena leucocephala</i>	7.16± 0.29	+++	++	+	+	-	-	-	++	9	56.25	3	MODERATE	
<i>Senna siamea</i>	8.0±0.07	++++	+	++	+	-	-	+	++	11	68.75	4	GOOD	
Santiniketan														
<i>Albizia lebbeck</i>	7.70±0.09	+++	++	++	-	-	-	-	++	9	56.25	3	MODERATE	
<i>Alstonia scholaris</i>	8.19±0.39	++++	++	++	+	++	+	+	++	14	87.5	6	EXCELLENT	
<i>Azadirachta indica</i>	8.21±0.19	++++	++	++	+	-	-	-	++	11	68.75	4	GOOD	
<i>Bauhinia acuminata</i>	9.03±0.09	++++	++	+	+	+	+	+	++	14	87.5	6	EXCELLENT	
<i>Butea monosperma</i>	9.41±0.14	++++	+	++	-	++	+	+	++	14	87.5	6	EXCELLENT	
<i>Dalbergia sissoo</i>	9.16±0.10	++++	++	++	-	-	-	-	++	11	68.75	4	GOOD	
<i>Leucaena leucocephala</i>	9.13±0.48	++++	++	++	+	-	-	-	++	12	75	5	VERY GOOD	
<i>Senna siamea</i>	9.38±0.05	++++	++	++	+	-	-	+	++	13	81.25	6	EXCELLENT	

Table 6. API value of shrub species in Bansra OCP and Santiniketan.

Name of the Species	APTI	GRADE	MORPHOLOGICAL				LAMINA STRUCTURE			Economic value	GRADE ALLOTTED		ASSESSMENT
			PH	CS	TP	SIZE	TEXTURE	HARDNESS	Total plus		SCORE %	API	
Bansra OCP													
<i>Anisomeles indica</i>	7.83±0.28	+++	-	+	-	+	-	-	++	7	43.75	2	POOR
<i>Calotropis procera</i>	8.58±0.06	++++	+	+	+	++	+	+	++	13	81.25	6	EXCELLENT
<i>Chromolaena odorata</i>	8.40±0.18	++++	-	+	-	+	+	-	++	9	56.25	3	MODERATE
<i>Clerodendrum infortunatum</i>	7.09±0.13	+++	-	+	+	+	+	+	++	10	62.5	4	GOOD
<i>Hibiscus rosa-sinensis</i>	7.71±0.19	+++	+	+	+	+	-	+	++	10	62.5	4	GOOD
<i>Lantana camara</i>	7.15±0.28	+++	+	+	+	+	+	+	++	11	68.75	4	GOOD
<i>Ricinus communis</i>	8.07±0.03	++++	+	+	+	++	+	+	++	13	81.25	6	EXCELLENT
<i>Ziziphus mauritiana</i>	7.47±0.21	+++	+	-	+	-	+	+	++	9	56.25	3	MODERATE
Santiniketan													
<i>Anisomeles indica</i>	9.59±0.04	+++++	-	+	-	+	-	-	++	9	56.25	3	MODERATE
<i>Calotropis procera</i>	8.65±0.16	++++	+	+	+	++	+	+	++	13	81.25	6	EXCELLENT
<i>Chromolaena odorata</i>	7.97±0.60	+++	-	+	-	+	+	-	++	8	50	2	POOR
<i>Clerodendrum infortunatum</i>	7.91±0.16	+++	-	+	+	+	+	+	++	10	62.5	4	GOOD
<i>Hibiscus rosa-sinensis</i>	8.96±0.29	++++	++	+	+	+	-	+	++	12	75	5	VERY GOOD
<i>Lantana camara</i>	7.97±0.23	+++	+	+	+	+	+	+	++	11	68.75	4	GOOD
<i>Ricinus communis</i>	8.74±0.12	++++	+	+	+	++	+	+	++	13	81.25	6	EXCELLENT
<i>Ziziphus mauritiana</i>	5.44±0.16	+	++	-	+	-	+	+	++	8	50	2	POOR

reclassified into the moderate category in Bansra. *A. indica* showed the reverse trend, with moderate performance in Santiniketan compared to poor performance in Bansra.

Some previous reports on the API values of a few selected tree species are available. *A. scholaris*, *B. monosperma* and *D. sissoo* performed with moderate grades in the urban roadsides in Bilaspur, central India (Jeet & Mahato, 2025). Previous studies on *A. scholaris* and *B. monosperma* have reported moderate and poor grades from Santiniketan (Kumar et al., 2020), as well as good and excellent grades from Thailand (Yousafzai et al., 2018). Prajapati & Tripathi (2008) have assessed *D. sissoo* with very good grade and *B. monosperma* with good grade in Varanasi, India. Among shrub species, *A. indica* and *R. communis* showed excellent tolerance in both locations. *C. infortunatum*, *H. rosa-sinensis* and *L. camara* also showed good to very good tolerance in both locations. Therefore, these shrub species, except highly invasive *L. camara*, are highly recommended for plantation in both locations. We recommend these species for plantation, both in degraded, polluted ecosystems as well as urban road sides, due to their sensitive bioindicator potential and excellent API grades.

CONCLUSION

The present study demonstrated that integrating the APTI with the API provides a comprehensive framework for evaluating plant responses to air pollution and identifying species suitable for environmental monitoring and ecological restoration. By comparing a severely polluted coal mining landscape with a relatively less polluted reference site, the study showed that plant biochemical responses are strongly influenced by pollution intensity. Important biochemical parameters mostly declined in response to pollution. The consistently lower APTI values observed in the coalfield indicate that prolonged exposure to mining-derived pollutants adversely affects physiological functioning, thereby reinforcing the usefulness of biochemical indicators for assessing plant health under environmental stress. The findings further advance the understanding of plant–air pollution interactions by demonstrating that RWC and AA are the major contributors to variation in APTI among the investigated species. This highlights the importance of water balance and antioxidant defense in determining plant tolerance under polluted conditions. Although all sixteen species were classified as pollution-sensitive (APTI ≤ 10), noticeable interspecific variation was evident. *A. scholaris* and the shrubs *C. odorata* and *Z. mauritiana* maintained comparatively higher tolerance by increasing concentration of biochemical parameters like AA, RWC, TC, PA and PC in the coal mining environment. This indicates their greater adaptive capacity under chronic pollution stress in addition to being important early successional shrubs. When biochemical tolerance was integrated with ecological, structural and socio-economic attributes through API, *A. scholaris*, *B. monosperma*, *B. acuminata*, *S. siamea*, *A. indica*, *Z. mauritiana*, *R. communis* and *C. procera* emerged as the most suitable species for environmental applications.

From a theoretical perspective, this study supports the concept that biochemical tolerance alone does not adequately reflect the field performance of plant species under heterogeneous pollution conditions. The integration of APTI with API offers a more robust approach for evaluating species suitability by combining physiological responses with functional and ecological characteristics. From a practical standpoint, the identified species provide a scientific basis for selecting vegetation for roadside plantations, urban green belts and ecological restoration programmes in mining-affected landscapes. Their use can strengthen biomonitoring initiatives while simultaneously contributing to pollution mitigation, landscape rehabilitation and sustainable urban planning.

A major outcome of this investigation is that species responses to air pollution are highly species-specific and strongly influenced by local environmental conditions. Therefore, vegetation selection for pollution mitigation should rely on integrated physiological and

ecological assessment rather than on a single biochemical indicator. Comparative evaluation across contrasting pollution regimes also demonstrates that reference sites are essential for accurately interpreting plant tolerance and identifying reliable bioindicator species.

Important limitation of the present investigation was that it was confined to sixteen plant species from two locations and was based primarily on few biochemical indices measured during a single assessment period. Seasonal variation, long-term physiological adaptation and the influence of individual air pollutants were beyond the scope of the study. Future research should incorporate multi-seasonal monitoring, direct measurements of atmospheric pollutants, physiological and molecular biomarkers, and validation across additional mining and urban ecosystems. Such studies would improve the predictive capability of APTI- and API-based assessments and facilitate the development of region-specific strategies for green belt planning and environmental management.

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CONFLICT OF INTEREST

The authors declare that there is not any conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/ or falsification, double publication and/or submission, and redundancy has been completely observed by the authors.

LIFE SCIENCE REPORTING

No life science threat was practiced in this research.

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