Evaluation of Urban Tree Species for Air Pollution Control: Integrating Air Pollution Tolerance Index (APTI), Anticipated Performance Index (API), and Socioeconomic Value in Ghana's Central Region

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Abstract

Air pollution presents serious concerns to urbanized environments, necessitating the exploration of tree species capable of minimizing its affects. This study assessed the Air Pollution Tolerance Index (APTI) and Anticipated Performance Index (API) of four common tree species, *Albizia lebbeck*, *Azadirachta indica*, *Khaya senegalensis*, and *Senna siamea* along three major highways and a control road in the central region of Ghana. Physiological and biochemical parameters, including relative water content (RWC), leaf extract pH, ascorbic acid content, and total chlorophyll, were analyzed to calculate APTI, while API incorporated morphological and socioeconomic traits. One-way ANOVA and correlation matrices, were employed to evaluate variations across roads and relationships among some parameters. All the tree plants were classified as pollution-sensitive (APTI < 10), with *Senna siamea* showing relatively higher tolerance. *Azadirachta indica* exhibited significant resilience with consistent RWC and chlorophyll levels, earning the highest API score (81.25%) and an "Excellent" performance rating. In contrast, *Albizia lebbeck* showed significant reductions in chlorophyll and pH under polluted conditions, highlighting its potential as a bioindicator. These findings underscore the importance of integrating physiological, morphological, and socioeconomic criteria in urban tree selection. *Azadirachta indica* emerged as an ideal candidate for urban greenbelt development due to its adaptability and ecological benefits, while *Albizia lebbeck* and *Senna siamea* are valuable for bioindication of air pollution. This study provides a robust framework for sustainable urban greening and pollution mitigation in tropical regions. Further studies should include additional tree species and locations for a broader ecological perspective.

Introduction

In the spate of growth in global population and rapid urbanization, transportation demands have escalated, with an observable increase in the use of private vehicles due to inadequacies in public transport systems, particularly in developing countries, accelerating air pollution and its attendant health effects (Muthu et al., 2021). With population explosion, automobiles have also exploded and so has pollution due to increased traffic density(Lu et al., 2021).Vehicular emissions represent a primary source of air pollution globally, surpassing other human activities (Iqbal et al., 2019) resulting in harmful emission such as SO_2, NO_x, CO, CO_2, VOCs smoke, dust, fumes, and aerosols that affect humans, plants, animals, and the ecosystem.

Several studies have reported air pollution associated effects including shortening new-born telomere length due to maternal exposures to $PM_{2.5}$, PM_{10}, CO, and SO_2 during the third trimester (Song et al., 2019). Lung, asthma, and immunological, cardiovascular, severe reproductive diseases, early death, and lung cancer (Kumar & Maharana, 2020; Rai, 2016). Plants are not spared, vehicular emissions significantly affect various physiological and biochemical processes in plants, including photosynthesis, transpiration, stomatal conductance, proline accumulation, DNA, and heavy metal uptake in plant tissues (Mehmood et al., 2024; Saxena & Kulshrestha, 2016). Air pollution is shown to decrease levels of leaf chlorophyll, carotenoids, proline, and proteins. Ascorbic acid, a critical indicator of plant stress, has been closely associated with air pollution levels, highlighting its role as a biomarker for environmental stress (Bhadauria et al., 2022; Nowak et al., 2018).

Plants grown along roadsides, while exposed to vehicular emissions, are considered effective structures for sinking air pollutants and improving air quality, as they also play a critical role in mitigating air pollution by providing surfaces for interception, absorption, and accumulation of airborne pollutants through apparent morphological, physiological, and biochemical effects (Diener & Mudu, 2021; Linden et al., 2023). The ascorbic acid, chlorophyll, leaf extract pH, and relative water content of plant can be determined to demonstrate their air pollution tolerance index (APTI). APTI an important tool that helps to group plants as either tolerant, intermediate, or sensitive to air pollution. Usually, plants with high APTI are deemed as bio-maker and can be used as buffer in urban greening (Bala et al., 2022; Sahu et al., 2020).

A complementary tool to the Air Pollution Tolerance Index (APTI), the Anticipated Performance Index (API) is useful in selecting plant species categorized as poor, very poor, good, very good, excellent, or best in mitigating air pollution, as it integrates APTI, morphological characteristics, and certain socioeconomic variables (Moore & Chapman, 1986; Prajapati & Tripathi, 2008; Tiwari et al., 1993). In this current study we aimed to investigate the APTI and API values of four most common tree plants in the vicinity of University of Education, Winneba (control road) and along three key highways (polluted roads) in Winneba, Ghana for use in air pollution control.

As a result, the physio-biochemical parameters of leaf extract were used to calculate the air pollution tolerance index (APTI) for the chosen plant species (*Albizia lebbeck, Azadirachta indica*, *Khaya senegalensis*, and *Senna siamea*). The findings of this study can guide the selection of suitable plant species for developing green belts in Winneba, while also contributing to the conservation of pollution-sensitive species and reducing their risk of extinction.

Materials and Methods

Study area

Winneba is located in the Central Region of Ghana and is a coastal town bordering the Gulf of Guinea to the south and surrounded by rolling hills to the north (Fig. 1). The city lies between 5°20' and 5°35' north latitudes and 0°37' and 0°48' west longitudes. The city covers an area of about 17.5 km² and has about 60,000 inhabitants (Service, 2021). Winneba has a tropical climate characterised by warm and humid conditions, with average annual temperatures between 24°C and 30°C and average annual rainfall of about 850 mm. Winneba is close to major highways and is a centre for vehicular traffic, which is known to contribute to local air pollution, especially along major roads (Safo-Adu, Attiogbe, Ofosu, Emahi, Gyampo, et al., 2024; Safo-Adu, Attiogbe, Ofosu, Emahi, Maud, et al., 2024)

Tree species and collection of samples

Albizia lebbeck, Azadirachta indica, *Khaya senegalensis*, and *Senna siamea* are known to be commonest trees species along three key major highways in Winneba (Nkansah & Belford, 2024). Leaf samples for physio-biochemical analysis were collected along the Winneba junction- Windbay Avenue (Highway I), Winneba junction-Swedru (Highway II), Winneba Central-Donkorkyiem roads (Highway III), and the University of Education, Winneba South campus served as the control road. This activity spanned between May and July, 2024 (i.e. dry season) before annual shedding plant leaves. Three replicates of each tree species with diameter at breast height (DBH) of more than 10 cm and height between 5–20 m were sampled within a distance of 20 m away from the edge of the roads. Sampling intervals between each tree species replicate ranged from 0.01 km to1 km along each road. Twenty to thirty physiologically active leaves at the third from the tip of the apical bud were picked from the branch of the tree facing the road between 7:00 and 09:00 hours at each sampling road from each tree species replicate. Samples were kept at -40°C until needed.

Determination of physiological and biochemical traits

Quantification of leaf relative water content

The method outlined by Liu and Ding (2008) was used to calculate the total relative leaf water content (RWC). To calculate the fresh weight, leaf samples from each replication of the tree species were weighed. The leaves were submerged in 150 ml deionized water (Liu & Ding, 2008) for 18.0 h overnight. To find the turgid weight, they were taken out, dried with blotting paper, and weighed. After that, they were oven (Genlab MINIS/30) dried for 1.0 h at 70°C (a consistent temperature was verified using a thermometer) until they had a constant dry weight. Mettler Toledo PB4002-S, a Swiss chemical balance, was used to measure the fresh, turgid, and dry weights. The relative leaf water content was calculated using (Eq. 1) the formula of (Liu & Ding, 2008; Prajapati & Tripathi, 2008; Weatherley, 1950):

Relative water content, RWC = $\frac{(\mathrm{Fw-Dw})}{(\mathrm{Tw\ -\ Dw})}\ x100\%$ Eq. 1

Where: FW = Fresh weight, DW = Dry weight, Tw = turgid weight

Determining leaf-extract acidity/alkalinity

Singh and Rao's (1983) approach was followed in order to estimate the pH of the leaf extract. Samples of leaves were crushed and mashed into a paste using a mortar and pestle. Ten milliliters (10 mL) of deionized (DI) water were used to homogenize five grams (5 g). After filtering the resulting suspension, the pH was determined with a calibrated Jenway 3020 digital pH meter.

Determination of ascorbic acid concentrations

The ascorbic acid concentration (mg/g) of the leaves were estimated using 721 Vis spectrophotometer (Keller & Schwager, 1977; Ogunkunle et al., 2015). Fresh foliage was weighed (0.1g) and grinded. Extraction solution of 1g oxalic acid and 0.15g NaEDTA in 200ml was prepared. To the ground leaf in a test tube, 4ml of the extraction solution was added and centrifuge for 15 minutes at 6000rpm. The supernatant (1 ml) and 5ml of 2,6-dichlorophenolindophenol was mixed with constant shaking and the optical density (OD) of the pink solution (Ps) was measured at 520nm wavelength. A calibration curve was prepared by using 1% aqueous ascorbic acid solution which was diluted to obtain varying concentrations.

Quantification of chlorophyll and carotenoid pigments

The total chlorophyll contents was determined using the spectrophotometric method (Bojović & Stojanović, 2005). Leaf samples weighing 0.005 g of each tree species replicate were homogenized in 5 ml of 80% acetone solution using a mortar and pestle. The homogenate was then transferred to a test tube and centrifuged at 4000 rpm for 2 minutes using Chalice Centrifuge by Wagtech International. The resulting supernatant was transferred into a 5 ml volumetric flask and made up to 5 ml using 80% acetone. The colour intensity of the green pigment was read using a 721 Vis Spectrophotometer (7052208009, made in England) at wavelengths of 645 nm, and 663 nm against a blank. The total chlorophyll (TC) was calculated as follows (Sahu et al., 2020; Verma et al., 2023):

$$\mathrm{Total\ chlorophyll\ (TC)}\ =\frac{20.2\ (\mathrm{A}\ 645)\ +\ 8.02\ (\mathrm{A}\ 663)\ \mathrm{x\ V}}{1000\ \mathrm{x\ W}}$$

Where, A = Absorbance of the extract, V = total volume of extract (ml), and

W = weight of fresh leaf (g).

Air Pollution Tolerance Index of the tree species to vehicular emissions

The Air Pollution Tolerance Index (APTI) is a measure of a plant species' inherent ability to withstand and respond to air pollution stress, serving as an indicator of the impacts of air pollutants, particularly in industrial and non-industrial areas (Enitan et al., 2022; Hazarika et al., 2023). The APTI is well documented as the primary metric that unravels the effects pollutants on the biochemical properties of plant species indicating their tolerance or susceptibility to air pollution (Hazarika et al., 2023; Sahu et al., 2020; Zahid et al., 2023).

The leaf extract pH, relative water content (RWC %), total chlorophyll (TC in mg/g), and ascorbic acid content (AA in mg/g) (Thawale et al., 2011) are used to evaluate the APTI of plant species (tolerance or to pollution including vehicular emissions. The calculation of APTI is performed using the expression (Singh

& Rao, 1983):

$$\mathrm{APTI} = \frac{[\mathrm{AA}(\ \mathrm{TC} + \mathrm{pH}) + \mathrm{RWC}]}{10}$$

According to the APTI index, plants were classified into the following categories

a. Very sensitive (APTI 0 to 1)
b. sensitive (APTI 1 to 16)
c. moderately sensitive (APTI 17 to 29) and
d. tolerant (APTI 30 to 100) (Padmavathi et al., 2013)

Anticipated Performance Index of studied tree species

For each tree species, an Anticipated performance index (API) was determined based on the APTI value and some important biological and socio-economic characteristics (Moore & Chapman, 1986). The method of (Tiwari et al., 1993) was modified and a score was assigned to each tree species (Table 1). According to this scoring system, each tree can receive a maximum of 16 points, which can be expressed as a percentage. The percentage score was expressed as:

$$\%\mathrm{Score} \frac{\text{Grades obtained by plant species}}{\text{Maximum possible grades of any species}}\ \boldsymbol{x}\ 100$$

This percentage is then used to determine the API value category such as such as not recommended, very poor, poor, moderate, good, very good, excellent, and best (Prajapati & Tripathi, 2008) for that tree species when used in green spaces (Table 2).

Table 1
Grading trees based on APTI, morphology, and socio-economic significance

Grading character	Parameters	Pattern of assessment	Grade allotment (point)
Tolerance	APTI	Less than 12	1
		Between 10 and 16	2
		Above 17	3 (maximum)
Morphological	Type of tree	Deciduous	0
		Semi-deciduous	
		Evergreen	1 (Maximum)
	Tree size (height	Small: less than 30 ft (< 9.14 m)	0
		Medium: 30–70 ft (9.17–21.34 m)	1
		Large: above 70 ft (21.36 m)	2 (Maximum)
	Canopy structure	Sparse, irregular, globula	0
		Spreading crown, open, semi dense	1
		Spreading dense	2 (Maximum)
	Laminar structure		
	(a) Leaf size	Less than 225 mm^2	1
		225–2025 mm^2	2
		2025–4500 mm^2	3
		4500–18225 mm^2	4 (maximum)
	(b) Texture	Smooth	0
		Rough, coriaceous, leathery	1 (maximum)
	(c) Hardness	Soft, delicate, fragile	0
		Hardy, robust, sturdy	1 (maximum)
Socioeconomic value	Food, fodder, timber,	Less than three uses	0
	medicinal, raw material, erosion control,	Three or more uses	1
	shade/shelter, ornamental, Reclamation	Five or more uses	2 (maximum)
Modified Tiwari et al. (1993)			

Table 2
Anticipated Performance Index (API) of tree species

Grade	Score (%)	Assessment category
0	Up to 30	Not recommended
1	31–40	Very poor
2	41–50	Poor
3	51–60	Moderate
4	61–70	Good
5	71–80	Very good
6	81–90	Excellent
7	91–100	Best

Data analysis

The Shapiro-Wilk and Levene tests were utilized to evaluate the normality and homogeneity of variance of quantitative data, respectively. One-way analysis of variance (ANOVA) and mean comparisons using Tukey's test at a significance threshold of $P = 0.05$ were used to identify statistical differences in the data. Pearson correlation was performed between Anticipated Performance Tolerance Index (APTI) and physio-biochemical parameters.

Results and Discussion

Relative water content (RWC %)

Variation in relative water content (RWC) across sampling locations is presented in Table 3. For *Albizia lebbeck*, RWC ranged significantly from 59.36% at highway I to 83.22% at CR, with statistically significant differences indicated by the superscripts "a" and "b." This suggests that the control site provides better conditions for water retention in *A. lebbeck* leaves compared to other locations. The low of RWC in *A. lebbeck* at highway I align with findings from similar studies, where species exposed to urban stressors exhibited reduced RWC due to increased transpiration rates and decreased water availability(Sahu et al., 2020; Verma et al., 2023). Conversely, it has been observed that plants with high RWC regulate their physiological processes under harsh conditions, especially when they are exposed to high concentrations of air pollution (Tsega & Prasad, 2014).

Azadirachta indica on the contrary, exhibited relatively stable RWC values across most locations, with no statistically significant differences ($p > 0.05$). The highest RWC (88.42±1.37%) was recorded at Highway II, while the lowest (68.97±8.51%) was observed at Highway I. The stability of RWC in *A. indica* suggests strong water management and physiological adaptability, even under urban stress. This observation is consistent with its established reputation as a drought-tolerant species capable of thriving in arid and polluted environments (Hazarika et al., 2023).

Khaya senegalensis exhibited the lowest RWC among the studied species, with values ranging from 53.80±19.89% at Highway I to 77.29±13.82% at Highway II. Notably, this species was absent at Highway III, further supporting its site-specific distribution and limited adaptability to certain roadside conditions. Low RWC values in polluted environments are likely due to physiological stress, including impaired stomatal regulation and reduced water uptake efficiency, as reported in similar studies on urban tree species(Ogunkunle et al., 2015; Zahid et al., 2023).

Senna siamea exhibited high RWC values across all locations, with the highest recorded at Highway II (89.36±14.13%) and the lowest at Highway III (72.69±36.33%). While no statistically significant differences were observed across the roads, the consistently high RWC highlights this species' ability to maintain hydration under varying environmental conditions. This resilience aligns with findings from Sahu et al. (2020), who reported similar RWC stability in other roadside tree species in urban environments.

Overall, *Albizia lebbeck* was the only species showing significant variation in RWC between locations, particularly at the CR, while the other species maintained consistent water content irrespective of location. These differences may be attributed to species-specific water regulation mechanisms and environmental influences (Zhao et al., 2021).

Table 3: Average relative water content (%) of the tree species

Sampling road	Tree species			
	Albizia lebbeck	*Azadirachta indica*	*Khaya senegalensis*	*Senna siamea*
Highway I	59.36±10.45 [a]	68.97±8.51 [a]	53.80±19.89 [a]	78.29±15.96 [a]
Highway II	73.81±2.06 [ab]	88.42±1.37 [a]	77.29±13.82 [a]	89.36±14.13 [a]
Highway III	71.48±5.70 [ab]	70.21±24.36 [a]	N/P	72.69±36.33 [a]
Control road	83.22±12.54 [b]	68.703±14.19 [a]	60.97±41.06 [a]	83.33±28.87 [a]

Mean ± SE in the same column with different letters in superscript are significantly different (P ≤ 0.05)

N/P= Not present at location

Leaf extract pH

Significant environmental influences are seen in the pH variations of leaf extracts across tree species and sample sites (Table 4). *Albizia lebbeck* exhibited significantly higher pH values at polluted sites (Highways I, II, and III) compared to the control road. The pH ranged from 6.40±0.24 to 6.77±0.14 at the highways, while it was significantly lower (5.13±0.03) at the control road. This trend aligns with studies suggesting that increased exposure to air pollution, particularly alkaline particulate matter, can neutralize leaf acidity, thereby increasing pH levels (Verma et al., 2023; Zahid et al., 2023). The sensitivity of *A. lebbeck* to pollution-induced changes in pH highlights its potential as a bioindicator for urban air quality monitoring (Hazarika et al., 2023).

The pH of *Azadirachta indica* leaves remained relatively stable across all locations, ranging from 6.36±0.23 at Highway I to 6.55±0.45 at the control road. This consistency suggests a robust physiological capacity to maintain leaf pH despite exposure to pollutants. Similar findings by Ogunkunle et al. (2020) indicate that *A. indica* is resilient to varying pollution levels due to its effective buffering mechanisms. Such stability reinforces its suitability for urban green spaces, where environmental stressors are common.

Khaya senegalensis showed a notable increase in pH at the control road (6.63±0.01), significantly higher than the values at Highways I and II (5.99±0.22 and 6.12±0.12, respectively). This variation may be attributed to differences in pollution exposure, as pollutants like sulfur dioxide and nitrogen oxides can alter leaf biochemical properties (Padmavathi et al., 2013). The absence of Khaya senegalensis at Highway III indicates its limited adaptability to specific site conditions, such as elevated pollution or unsuitable microclimates.

Senna siamea exhibited the lowest pH values at highways, ranging from 4.48±0.41 at Highway II to 4.99±0.32 at Highway III. These acidic pH levels suggest a strong physiological response to air pollutants, particularly acidic components such as NO_x and SO_x. At the control road, the pH was significantly higher (6.05±0.12), indicating reduced stress. Such trends are consistent with findings that pollution-sensitive species often exhibit decreased leaf pH under high pollutant loads (Enitan et al., 2022).

Table 4: Average leaf extract pH of the selected tree species

Sampling road	Tree species			
	Albizia lebbeck	*Azadirachta indica*	*Khaya senegalensis*	*Senna siamea*
Highway I	6.69±0.19 ^{b}	6.36±0.23 ^{a}	5.99±0.22 ^{a}	4.97±0.38 ^{a}
Highway II	6.40±0.24 ^{b}	6.37±0.04 ^{a}	6.12±0.12 ^{a}	4.48±0.41 ^{a}
Highway III	6.77±0.14 ^{b}	6.49±0.17 ^{a}	N/P	4.99±0.32 ^{a}
Control road	5.13±0.03 ^{a}	6.55±0.45 ^{a}	6.63±0.01 ^{b}	6.05±0.12 ^{b}

Mean ± SE in the same column with different letters in superscript are significantly different (P ≤ 0.05)

N/P= Not present at location

Plant leaf Ascorbate content

The ascorbic acid (AA) content of leaves is a crucial biochemical parameter that reflects the antioxidant capacity of plants and their ability to cope with oxidative stress induced by environmental pollutants (Ogunkunle et al., 2015). Table 5 presents the average ascorbic acid contents (mg/g) of four tree species sampled along highways and a control road in Winneba, Ghana.

Albizia lebbeck consistently recorded the highest ascorbic acid content, with a peak value of 0.055 mg/g at Highway I. This suggests that *A. lebbeck* exhibits a relatively higher antioxidant capacity compared to the other species, potentially enhancing its tolerance to oxidative stress from vehicular emissions. The findings align with those of Prajapati and Tripathi (2008), who reported that tree species with higher AA content are better equipped to mitigate the adverse effects of urban air pollution.

In contrast, *Azadirachta indica* displayed consistently low AA levels across all sampling locations, with a maximum value of 0.008 mg/g at Highway II. This stability, despite low ascorbic acid content, suggests that *A. indica* may rely on other physiological or biochemical mechanisms to cope with environmental stress, as noted by Zahid et al. (2023).

Across all species, the ascorbic acid content was higher at polluted highway sites than at the control road, though the differences were not statistically significant (P ≤ 0.05). This trend is consistent with findings from Hazarika et al. (2023), which indicate that plants in polluted environments often exhibit elevated antioxidant activity as an adaptive response to counteract oxidative damage caused by air pollutants. For *Khaya senegalensis*, the absence of data at Highway III reflects its limited distribution, potentially influenced by site-specific environmental or ecological factors, as suggested by Verma et al. (2023).

Senna siamea exhibited moderate AA levels, peaking at 0.027 mg/g at Highways I and II, but with a marked decline at the control road (0.008 mg/g). This pattern underscores the potential of *S. siamea* to function as a bioindicator species, given its sensitivity to pollution-induced oxidative stress. Similar findings were reported by Sahu et al. (2020), highlighting the role of medium-AA species in urban air quality monitoring. The overall lower ascorbic acid content at the control road compared to the highways suggests that exposure to vehicular pollution stimulates antioxidant activity in these species, supporting earlier observations by Enitan et al. (2022).

Table 5: Average ascorbic acid contents(mg/g)of selected tree species

Sampling road	Tree species			
	Albizia lebbeck	*Azadirachta indica*	*Khaya senegalensis*	*Senna siamea*
Highway I	0.055±0.04[a]	0.005±0.00[a]	0.020±0.02[a]	0.027±0.02[a]
Highway II	0.018±0.01[a]	0.008±0.01[a]	0.007±0.01[a]	0.027±0.02[a]
Highway III	0.005±0.00[a]	0.004±0.00[a]	N/P	0.010±0.00[a]
Control road	0.003±0.00[a]	0.004±0.00 [a]	0.003±0.00 [a]	0.008±0.01[a]

Mean ± SE in the same column with different letters in superscript are significantly different (P ≤ 0.05)

N/P= Not present at location

Total chlorophyll content of selected plant species

The total chlorophyll content of the selected tree species varied significantly across the sampling locations within the municipality, as presented in Table 6.

The chlorophyll content of *Albizia lebbeck* ranged from 2.032 mg/g at Highway I to 25.246 mg/g at the control site. The significantly higher chlorophyll concentration at the control site suggests that this species performs better under less polluted or undisturbed conditions. Similar findings have been reported by Sahu et al. (2020), who observed reduced chlorophyll levels in *Albizia lebbeck* near urban roads due to the deposition of particulate matter and oxidative stress caused by pollutants. This reduction in chlorophyll content under polluted conditions indicates a sensitivity to air pollution, making this species a potential bioindicator for assessing environmental quality.

The chlorophyll content of *Azadirachta indica* remained relatively stable across sites, with no significant differences (p > 0.05). This stability, with values ranging from 3.141 mg/g at Highway II to 11.336 mg/g at the control road, underscores the resilience of *A. indica* to varying environmental conditions. As corroborated by Zahid et al. (2023), *Azadirachta indica* is known for its tolerance to air pollution, attributed to its robust physiological mechanisms, including efficient antioxidant systems. Its ability to maintain chlorophyll levels under stress highlights its suitability for urban greening in polluted environments.

Khaya senegalensis exhibited consistently low chlorophyll levels, with values ranging from 1.538 mg/g at Highway I to 4.248 mg/g at the control site. The absence of this species at Highway III and its generally low chlorophyll content across sites suggest a limited tolerance to urban pollution. This aligns with findings by Ogunkunle et al. (2015), who reported that species with sparse canopies and lower leaf surface areas, like *K. senegalensis*, are less effective at mitigating air pollution and often exhibit reduced physiological performance in polluted areas.

Senna siamea showed moderate chlorophyll levels, ranging from 4.592 mg/g at Highway II to 8.790 mg/g at the control road, with no statistically significant differences across locations (p > 0.05). This trend suggests a moderate tolerance to pollution. According to Hazarika et al. (2023), species like *S. siamea*, with relatively smaller but durable leaves, can maintain physiological stability even in urban environments, making them valuable for specific ecological roles, such as bioindication and shade provision.

In general, the control road consistently recorded the highest chlorophyll levels across all species, indicating a less stressful environment compared to highways, which are characterized by vehicular emissions and particulate matter deposition. Chlorophyll degradation in polluted sites is a well-documented response to oxidative stress and nutrient imbalances caused by pollution(Verma et al., 2023). The significant differences observed for *Albizia lebbeck* highlight its sensitivity to environmental changes, while the stability of *Azadirachta indica* reinforces its status as a resilient urban tree species.

Table 6: Total Chlorophyll (mg/g) content of selected tree species

Sampling road	Tree species			
	Albizia lebbeck	*Azadirachta indica*	*Khaya senegalensis*	*Senna siamea*
Highway I	2.032±1.98 [a]	7.513±3.18[a]	1.538±0.26 [a]	8.374±6.81 [a]
Highway II	7.919±5.19 [ab]	3.141±2.45 [a]	2.862±2.76 [a]	4.592±2.54 [a]
Highway III	5.735±5.75 [ab]	6.933±0.68 [a]	N/P	4.788±2.36 [a]
Control road	25.246±15.40 [b]	11.336±4.79 [a]	4.248±4.61 [a]	8.790±3.95 [a]

Mean ± SE in the same column with different letters in superscript are significantly different (P ≤ 0.05)

N/P= Not present at location

APTI and classification for selected tree species

The results presented in Table 7 provide a comprehensive evaluation of the Air Pollution Tolerance Index (APTI) for selected tree species across multiple locations, highlighting their relative physiological responses to air pollution. Despite variation in key biochemical parameters such as relative water content (RWC), leaf extract pH, ascorbic acid content (AA), and total chlorophyll (TC), all species were classified as "Sensitive" according to Padmavathi's classification. These findings are consistent with recent studies, underscoring the sensitivity of urban trees to air pollution stress (Hazarika et al., 2023; Zahid et al., 2023).

The calculated APTI values for all species were below 10, classifying them as "Sensitive" to air pollution. These results are in line with Padmavathi et al. (2013), who emphasized that low APTI values reflect limited tolerance to airborne pollutants, often seen in species that rely on specific ecological niches. *Senna siamea* consistently achieved higher APTI values (7.28–8.96) compared to the other species, indicating relatively better adaptation to polluted environments despite its classification as sensitive.

Table 7: Air pollution tolerance index and classification for selected tree species

Tree species	Relative water content (%)	pH	Ascorbic acid (mg/g)	Total chlorophyll (mg/g)	APTI	Padmavathi's classification
Highway I						
Albizia lebbeck	59.36	6.69	0.055	2.032	5.98	Sensitive
Azadirachta indica	68.97	6.36	0.005	7.513	6.90	Sensitive
Khaya senegalensis	53.80	5.99	0.020	1.538	5.39	Sensitive
Senna siamea	78.29	4.97	0.027	8.374	7.87	Sensitive
Highway II						
Albizia lebbeck	73.81	6.04	0.018	7.919	7.41	Sensitive
Azadirachta indica	88.42	6.37	0.008	3.141	8.85	Sensitive
Khaya senegalensis	77.29	6.12	0.007	2.862	7.74	Sensitive
Senna siamea	89.36	4.48	0.027	4.592	8.96	Sensitive
Highway III						
Albizia lebbeck	71.48	6.77	0.005	5.735	7.15	Sensitive
Azadirachta indica	70.21	6.49	0.004	6.933	7.03	Sensitive
Senna siamea	72.69	4.99	0.010	4.788	7.28	Sensitive
Control road						
Albizia lebbeck	83.22	5.13	0.003	25.246	8.33	Sensitive
Azadirachta indica	68.70	6.55	0.004	11.336	6.88	Sensitive
Khaya senegalensis	60.97	6.63	0.003	4.248	6.10	Sensitive
Senna siamea	83.33	6.05	0.008	8.790	8.34	Sensitive

Anticipated Performance Index (API) of tree species along highways in Winneba, Ghana

The findings in Table 8 provide a multidimensional evaluation of the four tree species based on their Air Pollution Tolerance Index (APTI), morphological traits, and socioeconomic value. These parameters were integrated to compute the Anticipated Performance Index (API), which is a critical metric for assessing the suitability of tree species for greenbelt development and urban greening initiatives.

The API scores ranged from 68.75% (*Albizia lebbeck* and *Senna siamea*) to 81.25% (*Azadirachta indica*), categorizing the species from Good to Excellent in performance. *Azadirachta indica* exhibited the highest API grade of 6 (Excellent), indicating its enhanced adaptability, functional traits, and overall utility along the highways. This aligns with its established reputation as a resilient species capable of thriving in polluted and arid conditions (Zahid et al., 2023). Conversely, *Khaya senegalensis* received a "Very Good" rating (75%), while *Albizia lebbeck* and *Senna siamea* were rated as "Good."

The integration of APTI, morphological traits, and socioeconomic value provides a robust framework for selecting tree species for urban greening. *Azadirachta indica*'s high API score and dense canopy make it an excellent choice for urban greenbelts, contributing both ecological and socioeconomic benefits. Although *Albizia lebbeck*, *Khaya senegalensis*, and *Senna siamea* have lower API scores, they remain valuable for specific applications, such as bioindicators of air pollution.

Table 8: Assessment of tree species ranking based on APTI, morphological traits, and socioeconomic value

Grading parameter	*Albizia lebbeck*	*Azadirachta indica*	*Khaya senegalensis*	*Senna siamea*
APTI	1	1	1	1
Type of plant	1	1	1	1
Plant size (height)	2	2	2	2
Canopy structure	1	2	0	1
Laminar structure				
1. leaf size	3	4	4	3
2. texture	0	0	1	0
100. hardness	1	1	1	1
Socio-economic value	2	2	2	2
Total (+)	11	13	12	11
API (%)	68.75	81.25	75	68.75
API (Grade)	4	6	5	4
Assessment	Good	Excellent	Very good	Good

Pearson's correlation coefficient (r) matrices between biochemical parameters and APTI of tree species

The correlation matrix presented in Table 9 highlights the relationships between the Air Pollution Tolerance Index (APTI) and key physiological and biochemical parameters: Relative Water Content (RWC), leaf pH, Ascorbic Acid (AA), and Total Chlorophyll (TC). These correlations were analyzed across various highways and a control road.

A consistently strong positive correlation ($r \approx 1.000$, $p < 0.01$) was observed between RWC and APTI across all roads, indicating that higher RWC significantly enhances a plant's ability to tolerate air pollution. RWC is essential for maintaining cellular hydration and supporting physiological processes under environmental stress, making it a critical factor in resilience to pollution. Plants with elevated RWC are better equipped to maintain metabolic stability in polluted environments (Setu et al., 2024).

Negative correlations between leaf pH and APTI were observed, with coefficients ranging from -0.477 to -0.814. Although these correlations were not statistically significant, the trend suggests that lower leaf pH may be associated with higher pollution tolerance. Acidic leaf pH may help neutralize acidic pollutants, thereby enhancing a plant's adaptive capacity to environmental stressors (Setu et al., 2024).

The relationship between AA and APTI varied significantly across roads, with correlation coefficients ranging from -0.228 to 0.941. Notably, Highway III showed a strong positive correlation ($r = 0.941$), suggesting that elevated ascorbic acid levels in specific environments enhance pollution tolerance. Ascorbic acid acts as an antioxidant, mitigating oxidative stress caused by air pollutants, thereby playing a vital role in the biochemical defense mechanisms of plants (Setu et al., 2024).

The correlation between TC and APTI was inconsistent, ranging from strongly positive ($r = 0.947$) to strongly negative ($r = -0.996$), with none of the relationships reaching statistical significance. This variability indicates that chlorophyll content alone may not reliably predict a plant's pollution tolerance. While chlorophyll is indispensable for photosynthesis, its interaction with pollution tolerance is complex and likely influenced by additional physiological and environmental factors (Setu et al., 2024).

Table 9: Correlation matrix between the APTI values and some studied physio-biochemical parameters

Biochemical parameter	Highway I	Highway II	Highway III	Control road
	APTI	APTI	APTI	APTI
RWC	1.000**	1.000**	.999*	1.000**
pH	-.665	-.477	-.798	-.814
AA	-.228	.267	.941	.517
TC	.947	-.512	-.996	.653

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

Conclusion

This study assessed the air pollution tolerance and anticipated performance of *Albizia lebbeck, Azadirachta indica, Khaya senegalensis*, and *Senna siamea* along major highways and a control road in Winneba, Ghana. The findings revealed that all four species are sensitive to air pollution, with varying degrees of physiological and biochemical responses. Despite their sensitivity, the species demonstrated specific ecological and socioeconomic contributions, highlighting their potential utility in urban greening and air quality monitoring.

Albizia lebbeck exhibited significant reductions in chlorophyll and ascorbic acid content under polluted conditions (highways), confirming its role as a bioindicator rather than a pollution-mitigating species. *Azadirachta indica* demonstrated resilience, maintaining relatively stable chlorophyll levels and robust water management, making it highly suitable for urban greenbelts. *Khaya senegalensis*, with its low relative water content and sparse canopy, displayed limited adaptability to highly polluted environments, suggesting a restricted role in urban greening. *Senna siamea*, with its high water retention and moderate biochemical performance, emerged as a bioindicator of air pollution.

Declarations

Financial support

This research was entirely self-funded.

Competing Interests

The authors declare no conflicts of interest.

Data statement

The research data would be made available upon reasonable request.

Authors' Contributions

Conceptualization: Francis Kwaku Nkansah, Ebenezer J. D. Belford and Jonathan Nartey Hogarh; Methodology: Francis Kwaku Nkansah, Ebenezer J. D. Belford, Jonathan Nartey Hogarh, Alfred Formal analysis: Francis Kwaku Nkansah; Investigation: Francis Kwaku Nkansah; Resources: Francis Kwaku Nkansah; Data curation: Francis Kwaku Nkansah, Ebenezer J. D. Belford and Jonathan Nartey Hogarh; Writing—original draft preparation: Francis Kwaku Nkansah; Writing—review and editing: Ebenezer J. D. Belford and Jonathan Nartey Hogarh; Supervision: Ebenezer J. D. Belford and Jonathan Nartey Hogarh. All authors have read and approved the published version of the manuscript.

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Ethical considerations

This study did not involve humans or animals as subjects, there was no harm anticipated to human or animal life. Ethical issues (Including plagiarism, misconduct, data fabrication and/or falsification, double publication and/or submission, redundancy, etc.) have been completely observed by the authors.

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Figures

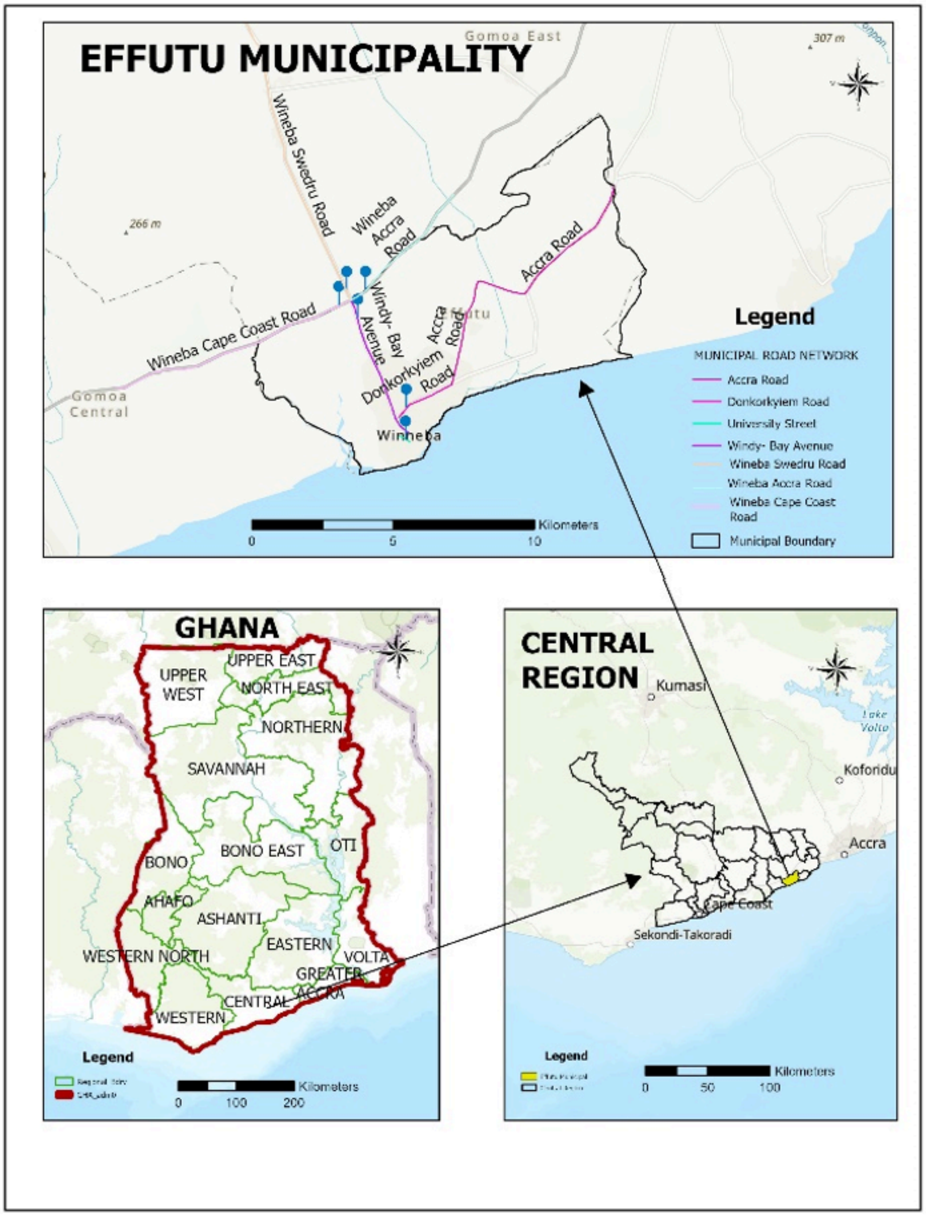

Figure 1

Map of study area indicating the highways