



Evaluation of air pollution tolerance index and anticipated performance index of six plant species, in an urban tropical valley: Medellín, Colombia

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Abstract

High atmospheric pollution levels in urban areas have become a global problem that threatens both human health and urban ecosystems. Trees that grow near areas with vehicular and industrial emissions can be highly affected, since they constitute the main barrier for emitted pollutants, with trees being either tolerant or sensitive to them. Different methodologies worldwide have been implemented to evaluate the tolerance and sensitivity of tree species to atmospheric pollutants. In this research, the air pollution tolerance index (APTI) and the anticipated performance index (API) are evaluated in order to determine both the degree of tolerance or sensitivity of trees to pollutants in the air and their performance in urban areas. To this end, six tree species found in four biomonitoring zones in the city of Medellín, Colombia, were selected: *Mangifera indica*, *Tabebuia chrysantha-rosea*, *Erythrina fusca*, *Jacaranda mimosifolia*, *Fraxinus uhdei*, and *Spathodea campanulata*. A total of 54 individual trees were evaluated by means of the APTI and API, and it was determined that the species with the highest tolerance ($APTI \geq 16$) and the best performance ($81 < API < 90$) was *Mangifera indica*, which highlights the importance of this species in urban areas with air quality problems. On the other hand, it was determined that the most sensitive species ($APTI \leq 11$) are *Tabebuia chrysantha-rosea*, *Erythrina fusca*, and *Spathodea campanulata*, while the species with poor performance ($41 < API < 50$) are *Tabebuia chrysantha-rosea*, *Erythrina fusca*, and *Jacaranda mimosifolia*. These values, therefore, can be used to classify which species can be planted as pollutant sinks and which as air quality bioindicators and thus highlight the importance of urban forests and trees for environmental management and planning in big cities with air quality problems.

Keywords Particulate matter · Air pollution · Urban ecosystems · APTI · API · Tolerance · Performance

Introduction

Reports from the Department of Economic and Social Affairs of the United Nations (UNDESA) estimate that for 2050, 60% of the world population will be settled in urban areas (United Nations Department of Economic and Social Affairs 2015). This implies rapid urbanization processes, which is a key

factor in the alteration and degradation of cities' spatial structure, environment, and ecology (Kumara 2015), because of the growing demand for food, fuel, energy, water, and industrial raw materials, among others. This in turn generates high levels of emissions to the atmosphere, causing pollution not only in the city of origin, but also in other surrounding cities (Baklanov et al. 2016; Lyu et al. 2016; Rodríguez Martín et al. 2015). Presence of urban forests and trees, however, has been recognized as beneficial in these places since their presence has been correlated with atmospheric pollutant removal and climate change mitigation (FAO 2018; Nowak et al. 2014). All the same, in urban centers with air quality problems, anatomical, morphological, physiological, and biochemical disturbances have been observed in urban forests and trees (Chan and Yao 2008; Gulia et al. 2015; Rendon et al. 2014; Uka et al. 2017). Particulate matter (PM) and other gases are among the atmospheric pollutants that can cause negative effects and

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have a high potential of affecting urban forests and trees (Kumar Prajapati 2012; Rai 2016). The effects depend on PM concentrations in urban areas and on vegetation characteristics, reaching impacts that include reduction of incident light due to the deposition of particles on leaves, which can induce stomatal closure and produce interference with gaseous exchange, thus altering the thermal balance of the plant (S. N. Singh and Verma 2007). Additionally, it has been found that pollutant deposition on leaves produces effects such as the transformation of nitrates and sulfates into acid form and an increased level of trace and heavy metals such as lead (Grantz et al. 2003). Thus, evaluating the tolerance and sensitivity of urban forests and trees has been fundamental to estimate the degree of stress produced on vegetation by exposure to atmospheric pollutants (e.g., particulate matter and other contaminants; Lodenius 2013).

In this regard, one of the methodologies used to evaluate the tolerance and sensitivity of urban forests and trees to atmospheric pollutants is the air pollution tolerance index (APTI) (Singh et al. 1991), which incorporates the biochemical parameters of a tree to determine the degree of impact to its organism (Kaur and Nagpal 2017). Additionally, the anticipated performance index (API) supplements the APTI with biological and socioeconomic parameters of the tree in order to determine its performance in urban areas (Govindaraju et al. 2012). Both indexes have been widely used across the globe in order to characterize different tree species according to their tolerance and performance (Alotaibi et al. 2020; Banerjee et al. 2021; Govindaraju et al. 2012; Javanmard et al. 2020; Kaur and Nagpal 2017; Qiu et al. 2019; Skrynetska et al. 2018; Watson et al. 2021). In countries like India, China, Poland, Nigeria, and Pakistan, these indexes have been successfully used to report those tree species that are key in the development of green belts surrounding highly polluted areas since they are instrumental for the development and management of the ecosystem they live in given their tolerance and performance as well as their high capacity to filtrate and retain PM in the atmosphere (Achakzai et al. 2017; Liu et al. 2013; Ogunkunle et al. 2015; Skrynetska et al. 2018, 2019). The mentioned reports of the trees species have shown consensus regarding the classification of the trees using the APTI and API indexes, without a finding in conflicting reports between the studies consulted. For example, *Mangifera indica* L. (which is part of this study) has been found in several investigations as an excellent performer (Govindaraju et al. 2012; Pathak et al. 2011; Watson et al. 2021).

In recent years, the city of Medellín (Colombia) has been the focus of attention for citizens, public administrators, and other sectors of society due to its consistent failure to comply with Colombian regulations (Order 2254 of 2017 of the Ministry of Environment and Development), with high levels of pollutants in the air (mainly PM) being reported, exceeding the limits recommended by the World Health Organization (WHO) (Bedoya and Martínez 2009; Buitrago-Sierra et al. 2018; Green and Sánchez 2017; Luna et al. 2018). In view

of this context, the present study evaluated the APTI and API indexes of six tree species found in four zones currently under air quality monitoring by the city administration in order to determine their tolerance or sensitivity to the presence of atmospheric pollutants. This allows identification of the most adequate or tolerant species capable of filtering atmospheric pollutants, without a complete disturbance to its physiology and metabolism, as well as those sensitive species that could serve as air quality bioindicators in urban areas as a strategy to control pollution and as a tool for tree planning in Medellín and other cities in the world.

Materials and methods

Study area

The present study was carried out in the municipality of Medellín, located on the central mountain range of the Colombian Andes (Fig. 1). Medellín is at the geometrical center (6° 15' 06" N, 75° 33' 48" W) of the metropolitan area of the Aburrá Valley, which has a population of nearly 4 million inhabitants divided into 10 municipalities, with 62% of them living in Medellín (Aguiar-Gil et al. 2020; Correa et al. 2009). The city has been recognized as one of the main industrial and economic centers in Colombia (Restrepo et al. 2016), with a textile sector that began its development in the mid-twentieth century and other industrial sectors (food, shoes, wood, paper, printing, refinery, chemical products, among others) currently under active development. Medellín has generated higher economic growth thanks to increased productivity, innovation, and attraction of human capital (Sánchez 2013). As a result of economic growth, it has attracted migration from rural areas (Doyle 2016), expanding the urban area of the city from the base of the valley up to its hillsides (Rendon et al. 2014) and resulting in high population and motor vehicle density (23.676 inhabitants/km² and 7.199 motor vehicles/km², respectively) (Posada et al. 2017).

According to the Colombian Administrative Department of Statistics (DANE), in 2018, the population of the municipality was 2,427,129 inhabitants (Medellín CómoVamos 2019), on a surface of 37.621 ha, with 27.1% of the area corresponding to urban ground, 1.1% to urban-expansion areas, and 71.8% to rural land. As regards altitude, Medellín extends between 1460 and 3200 meters above sea level (Alcaldía de Medellín 2006), and its climate is characterized by a bimodal rainfall pattern: March, April, and May (MAM) and September, October, and November (SON). This rainfall pattern is associated with the dynamics of the Intertropical Convergence Zone (ITCZ), which determines two seasons (dry and humid), with a mean annual temperature of 22°C, ranging from 14 to 32°C (Toro et al. 2006).

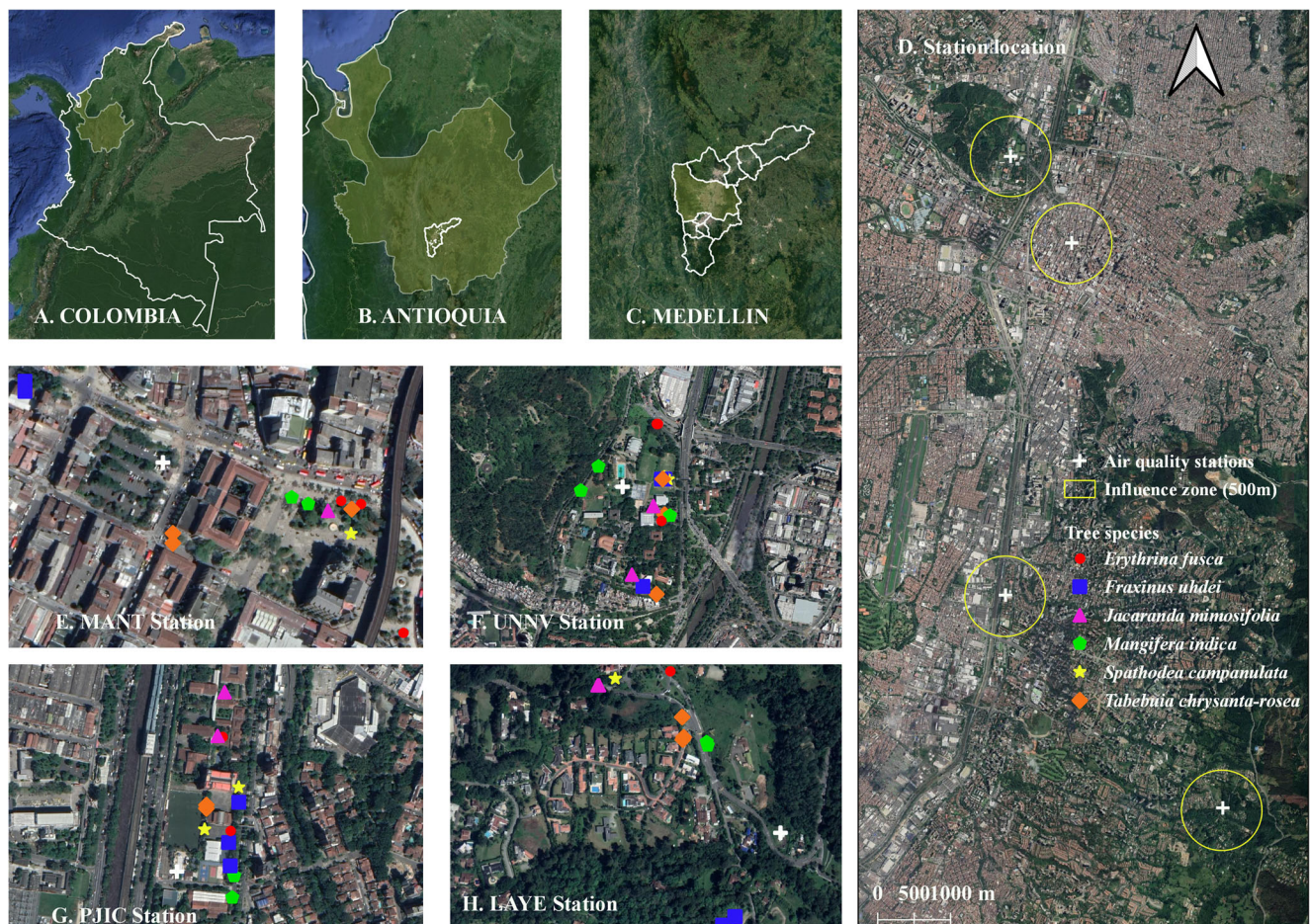


Fig. 1 Location of **a** Colombia in South America, **b** Antioquia and the Aburrá Valley in Colombia, **c** Medellín in the Aburrá Valley, **d** biomonitoring stations in the study area, **e** UNNV station, **f** MANT station, **g** PJIC station, and **h** LAYE station

Air quality

In the last 5 years, air quality in Medellín has experienced periodic critical increases in the levels of particulate matter $PM_{2.5}$, which according to local studies is the result of a combination of high emissions, complex topography, and climate and weather conditions unfavorable for the vertical dispersion of pollutants (Herrera-Mejía and Hoyos 2019; Roldán-Henao et al. 2020). As a consequence, a strong relation between premature mortality in Medellín and the Aburrá Valley and increased levels of $PM_{2.5}$ has been found (Bedoya and Martínez 2009; Aguiar-Gil et al. 2020), generating an additional public health problem. According to regional studies, this can be attributed to an increase in motor vehicle density—and therefore in emissions from mobile sources—in the territory (AMVA and Clean Air Institute 2017), with a growth of 500% for motorcycles and 97% for cars (public and private) between 2000 and 2011. Thus, for 2016, the Aburrá Valley reported a total of 1,301,291 motor vehicles, with 56.26% corresponding to motorcycles, 35.89% to automobiles, and the remaining 7.85% corresponding to trucks (2.19%), taxis (1.75%), special service vehicles (1.45%), and special service

buses (0.97%) (AMVA-UPB 2018). This has caused an increase in the number of vehicle trips per day, from 4.9 million in the first decade of the twenty-first century to more than 5.6 million trips per day in the second decade of the century (Martínez-Jaramillo et al. 2017). However, the most critical period in terms of air quality in Medellín and the Aburrá Valley occurs during the months of February and March, when the Intertropical Convergence Zone (ITCZ) is at its southernmost position. During this period, descending air masses over northern South America (NSA) cause convection suppression and subsidence inversions more frequently, and these atmospheric conditions are unfavorable for pollutant dispersion (Mendez-Espinosa et al. 2019). Together with the complex topography of the valley where the city is located, this results in increased levels of PM, which according to The Clean Air Institute and regional studies exceed European and American regulations and the WHO's air quality guidelines (Bedoya and Martínez 2009; Buitrago-Sierra et al. 2018; Gómez et al. 2011; Green and Sánchez 2017; Luna et al. 2018). As a consequence, the early warning system of Medellín and the Aburrá Valley (Sistema de Alerta Temprana de Medellín y el Valle de Aburrá-Siata.gov.co

2021-) and the environmental authority of the metropolitan area (Area Metropolitana del Valle de Aburra-AMVA, and Clean Air Institute 2017) have acknowledged air quality as one of the main environmental concerns in the region, with PM_{2.5} being considered the criterion pollutant for decision-making. SIATA has implemented an important number of air quality stations that measure PM, NO_x (nitrogen oxides), O₃ (ozone), CO (carbon monoxide), and SO₂ (sulfur dioxide). These stations are distributed across the valley to monitor the levels of pollutants in the atmosphere.

Biomonitoring zones

For the present study, four biomonitoring zones (Table 1) were located within the area of influence of SIATA’s air quality monitoring stations, which measure pollutants such as PM_{2.5}, PM₁₀, NO₂, and O₃. According to Correa-Ochoa et al. (2020), there are gradients of pollutant concentration in the air over the biomonitoring zones, and the latter exhibit particular physical and environmental conditions associated with the variability of the study area in terms of topography and elevation (Fig. 1). The four biomonitoring areas are described below:

- MANT (Museo de Antioquia): located in the city center, this area is characterized by its high historical and cultural value for the city, as it encompasses the Museum of Antioquia and Plaza Botero. This is a highly commercial area with emissions mainly from mobile sources. Vegetation is scarce in the area, as there is low interaction between roots and the soil.
- UNNV (Universidad Nacional Núcleo el Volador): is characterized by a combination of high vehicular traffic and vegetation and by its proximity to touristic, cultural, and academic sites of the city, such as Parque Norte, Parque Explora, Planetarium, Parque de los Deseos, Botanical Garden, El Volador hill, and two public universities (University of Antioquia and National University).
- PJIC (Institución Universitaria Politécnico Colombiano Jaime Isaza Cadavid): located in a highly urbanized area, it is close to residential and institutional areas and to two

high-traffic avenues connecting the municipalities in the metro area: Avenida Regional (regional and national traffic) and Avenida Las Vegas (metropolitan traffic). The vegetation state near the station is scarce, although bastion vegetations are found inside PJIC education center.

- LAYE (tanques La Ye): characterized by the abundance of vegetation, emissions in this area are mainly from mobile sources, as this area connects the city with the San Nicolas Valley and the José María Córdova International Airport.

Selection of species

Tree species were selected considering spatial and physical characteristics. Preliminary identification of urban trees in the areas surrounding SIATA’s air quality monitoring stations was carried out with the aid of the Urban Tree System (SAU), the Virtual Catalog of Flora of the Aburrá Valley (Catalogo Flora Valle de Aburra 2021), and previous studies (Correa-Ochoa et al. 2020). Then, the trees found were filtered by spatial location considering only those within a 500-m radius from the air quality monitoring stations to ensure they were in their area of influence. Additionally, the selected tree species should be present near the four stations (Table 1) so that the results would be comparable across stations. In order to ensure that the selected trees are adult specimens, a girth at breast height (GBH) higher than 30 cm was used as a selection criterion. Tree species and individual trees selected are presented in Table 2.

Air pollution tolerance (APTI) and anticipated performance indexes (API)

APTI

The APTI score is determined from four biochemical parameters of the trees: ascorbic acid (A), total chlorophyll content (T), pH of the leaf extract (P), and relative water content (R), which combined provide a basis

Table 1 Location and type of air quality station in the biomonitoring zones

Station	Station type	Geographic location coordinate system (WGS_1984)		Altitude (MASL)
		N	W	
MANT	Traffic	6.25256	-75.5695	1478
UNNV	Population representativeness	6.26337	-75.5777	1476
PJIC	Population representativeness	6.20897	-75.5777	1498
LAYE	Population representativeness	6.18254	-75.5506	1964

Table 2 Tree species and number of individual trees selected for sampling in each area

Common name	Species name ^a	Number of individuals per zone				
		MANT	UNNV	PJIC	LAYE	Subtotal
Bucaro	<i>Erythrina fusca</i> Lour. (EF)	3	3	2	1	9
Gualanday	<i>Jacaranda mimosifolia</i> D.Don (JM)	1	2	2	2	7
Guayacan	<i>Tabebuia chrysantha</i> (Jacq.) G.Nicholson- <i>Tabebuia rosea</i> (Bertol.) Bertero ex A.DC. (TB)	3	3	2	3	11
Mango	<i>Mangifera indica</i> L. (MI)	2	3	3	2	10
Tulipan africano	<i>Spathodea campanulata</i> P.Beauv. (SC)	1	2	2	1	6
Urapan	<i>Fraxinus uhdei</i> (Wenz.) Lingelsh (FU)	2	3	3	3	11
Subtotal		12	16	14	12	
Total		54				

^a The Plant List 2021

for classifying tree species as tolerant (if the APTI score is high) or sensitive (if the APTI score is low) (Singh et al. 1991). In the case of total chlorophyll content and pH values, chlorophyll degradation in leaves is related with acid values of the pH value due to stress conditions caused by atmospheric pollution. The role of ascorbic acid content, however, is instrumental, because it protects chlorophyll from damage induced by hydrogen peroxide (H₂O₂), which originates at pH values higher than 3 from dismutation of superoxide radicals (H₂O₂) by superoxide dismutase (SOD). Additionally, levels of ascorbic acid in tree organisms foster integration of chlorophyll (a and b), which helps the development of resistance to atmospheric pollution. Lastly, including relative water content in the equation accounts for cell capacity to maintain their integrity in the presence of atmospheric pollutants. The whole term of the equation, comprising the four biochemical parameters, is divided into 10 in order to obtain a manageable value, as shown in Equation 1 (Singh et al. 1991; Uka et al. 2017),

$$APTI = \frac{A(T + P) + R}{10} \quad (1)$$

where *A* is given in mg/g of dry leaf, *T* in mg/g of dry leaf, *P* is the pH of leaf extract, and *R* is given as percentage.

API

The APTI score together with biological and socioeconomic parameters of the urban trees under study (Table 3) allows the computation of the API score and classification of trees according to their capacity to develop in an urban environment under stress factors, such as the presence of atmospheric pollutants (Table 4).

Determination of physiological and biochemical parameters

The physiological and biochemical parameters of the trees were determined by using triplicates to ensure quality control of the data. The methodology used for determining the biochemical parameters is presented below.

Relative water content (R)

In order to estimate the relative water content, a leaf was cut into 10 1-cm-diameter discs, while for the *Jacaranda mimosifolia* species, a sample of 30 simple leaves was selected for the procedure, and the method suggested by Sen and Bhandari (1978) was used (see Equation 2):

$$R(\%) = \frac{FW - DW}{TW - DW} \times 100 \quad (2)$$

where *FW* or fresh weight (g) was determined by weighing fresh discs, *TW* or turgid weight (g) was determined after submerging the discs in distilled water for 4 h, and *DW* or dry weight (g) was determined after introducing discs in the oven for 12 h at 65°C.

pH of the leaf extract (P)

Leaf pH was measured using the method proposed by Prasad and Rao (1982) with a sample of 0.5 g of fresh leaf material, ground and macerated, and mixed in 50 mL of distilled water. Then, the pH of the supernatant was measured using a Hach HQ40d multi-parameter measuring device.

Total chlorophyll content (T)

Total chlorophyll content was estimated by using the method described in Govindaraju et al. (2012). A

Table 3 Classification of trees according to biochemical, biological, and socioeconomic parameters (Govindaraju et al. 2012)

Grading character	Pattern of assessment	Grade allotted ^a
a) Tolerance		
APTI	9E–12	+
	12.1–15	++
	15.1–18	+++
	18.1–21	++++
	21.1–24	+++++
b) Biological and socioeconomic		
Plant habit (Ph)	Small	-
	Medium	+
	Large	++
Canopy structure (Cs)	Sparse/irregular/globular	-
	Spreading crown/open/semi-dense	+
	Spreading dense	++
Type of plant (Tp)	Deciduous	-
	Evergreen	+
c) Laminar structure		
Leaf size (Ls)	Small	-
	Medium	+
	Large	++
Texture (Tx)	Smooth	-
	Coriaceous	+
Hardiness (H)	Delineate	-
	Hardy	+
Economic value (Ev)	Less than three uses	-
	Three or four uses	+
	Five or more uses	++

^a The sum of (+) shall be lower than or equal to 16, which corresponds to 100%

sample of 0.5 g of fresh leaves ground and macerated was mixed in 10 mL of 80% acetone. The mix was centrifuged at 2500 rpm for 3 min, and the supernatant was collected in a brown container. This procedure was repeated until the precipitate became white to ensure total extraction of the chlorophyll. The collected supernatant was analyzed with a spectrophotometer (UV-

Visible Thermoscientific Evolution 201), and absorbance was measured at 645 and 663 nm.

Finally, the absorbances obtained were used to calculate total chlorophyll content by applying Equations 3 to 5.

$$Ta = \frac{12.7 * D_{663} - 2.69 * D_{645}}{1000 * W} \times V \tag{3}$$

$$Tb = \frac{22.9 * D_{645} - 4.68 * D_{663}}{1000 * W} \times V \tag{4}$$

$$T \left(\frac{mg}{g} DW \right) = (Ta + Tb) \times \left(\frac{FW}{DW} \right) \tag{5}$$

where *D* is the absorbance of the leaf extract (measured at a wavelength indicated by the subscript); *V* is the volume of extract in mL; *W* is the weight of the fresh leaf material collected for analysis; and *FW/DW* corresponds to the relation between fresh and dry leaf weight (Singh et al. 1991).

Table 4 Anticipated performance index (API) (Govindaraju et al. 2012)

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

Ascorbic acid content (A)

Ascorbic acid content in leaf samples was estimated according to the methodology described by Bajaj and Kaur (1981). First, 0.1 g of ground and macerated fresh leaf material was added to 4 mL of extractant solution of oxalic acid 0.05M EDTA; then, 1 mL of orthophosphoric acid 0.05M was added, followed by 1 mL of sulfuric acid (5% v/v). To this mixture were added 2 mL of ammonium molybdate and 2 mL of distilled water. The solution was allowed to react for 15 min at ambient temperature. Then, the solution was centrifuged at 2500 rpm for 3 min, and absorbance was measured at 760nm using a UV-Visible ThermoScientific Evolution 201 spectrophotometer. The concentration of ascorbic acid in the samples was calculated from the standard curve of ascorbic acid previously elaborated in the Laboratory of Environmental Studies of the Faculty of Engineering, University of Antioquia, taking into account the relation between fresh and dry leaf weight (Singh et al. 1991).

Statistical and mathematical analysis

The statistical analysis of the data was performed using a two-way analysis of variance (ANOVA), where the relation between certain variable Y (response variable) and certain categorical variables X (factors) is considered. In this study, two-way ANOVA was used with API scores as a response variable and species and station as factors (Banerjee et al. 2021; Ben Amor et al. 2021). Concurrently, component analysis was used with the aim of comparing the percentage of variability contributed by each factor (species and station) to the total variance of the dependent variable (API score). In addition, the mathematical technique of cluster ordering was applied, which groups observations with similar characteristics. In this case, the criteria used were the physiological (P and R) and biochemical (T and A) characteristics of each individual tree

since the capacity of each tree species to absorb and adsorb atmospheric pollutants through leaf surface varies considerably (Singh and Verma 2007). This technique uses Euclidean distance between observations according to Ward's method. The analyses were carried out with the Statgraphics Centurion XVI software. II. Descriptive analyses of air quality were carried out by using R language, version 3.6.2, and were downloaded directly from SIATA's website (https://siata.gov.co/siata_nuevo/)

Results and discussion

Air quality

Figs. 2, 3, 4, and 5 show the results of the air quality analysis carried out for each of the monitoring stations under study, with figures indicating months of the year (January is month 1 and December is month 12). Fig. 2 shows the annual cycle (monthly box-plots) of PM_{2.5} and O₃ records at LAYE station from September 2015 to December 2019. In Fig. 2a, during the first months of the year, it can be seen that the medians of concentration data exceed the maximum admissible standard limits established for Colombia (annual average 25 µg/m³ at 298 K and 1 atm). From January to March, there are pollution episodes when guideline recommendations of annual concentrations of PM_{2.5} are exceeded, with March being the most critical month. The remaining months show low fluctuations between them, but concentrations remain below the recommended annual mean. It is important to highlight that the lowest levels of PM_{2.5} occur in June. On the other hand, the annual mean cycle of O₃ at LAYE and UNNV was calculated from data corresponding to daylight hours of the day cycle (from 06:00 to 18:00 h). This pollutant shows bimodal behavior throughout the year: February and August are the months with the highest records for this

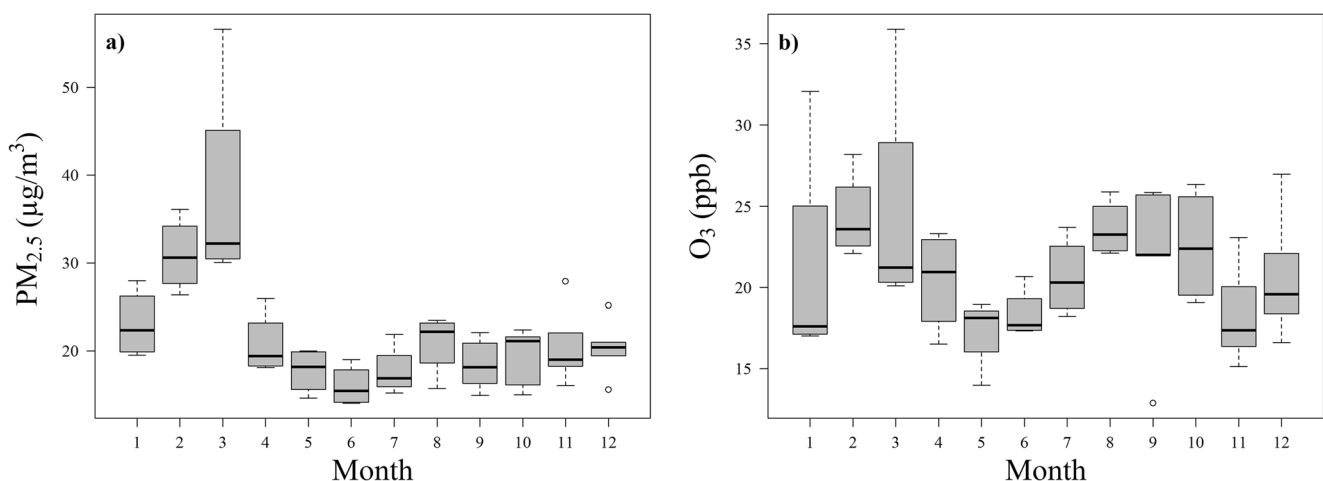


Fig. 2 Mean annual cycle of **a** PM_{2.5} and **b** O₃ at LAYE station

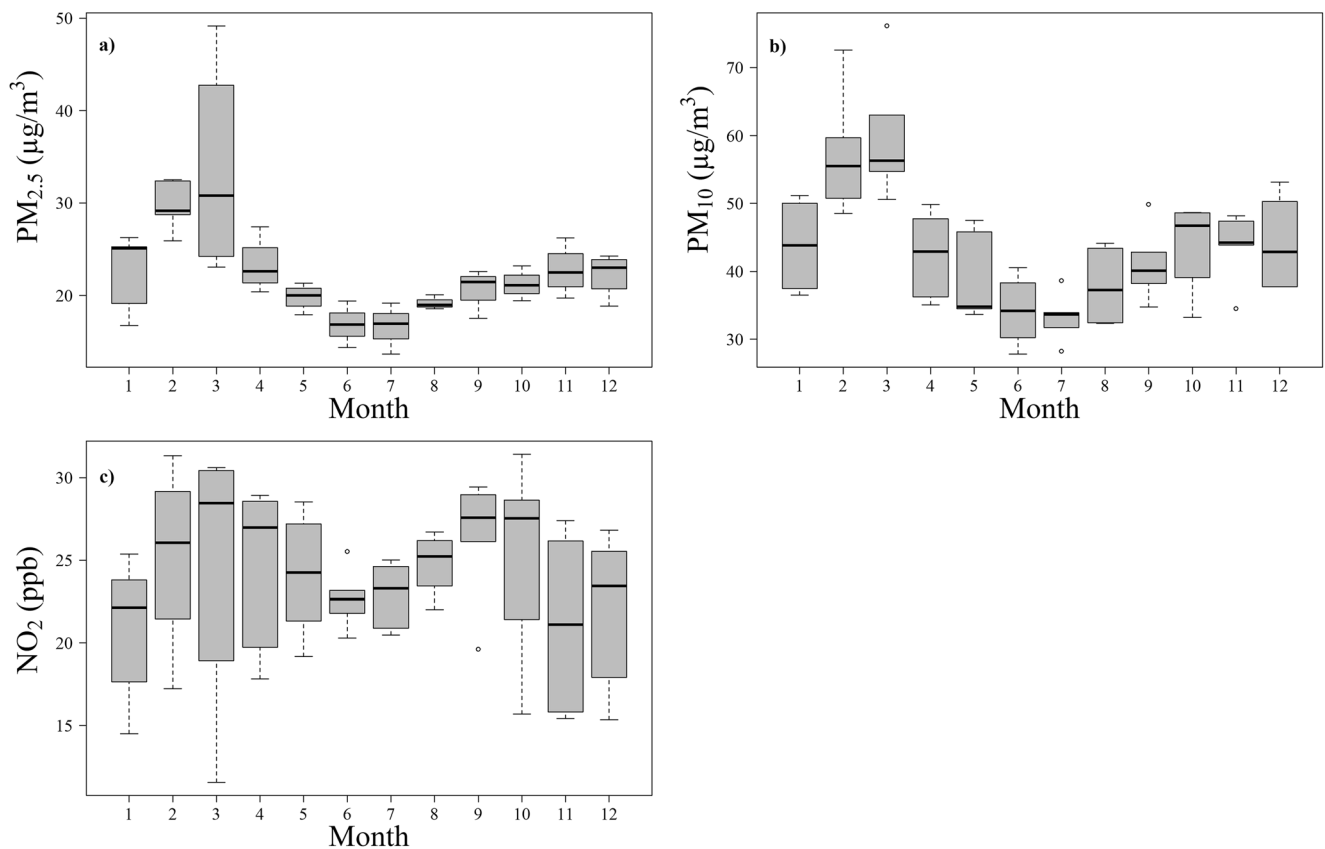


Fig. 3 Mean annual cycle of **a** PM_{2.5}, **b** PM₁₀, and **c** NO₂ at PJIC station

pollutant, while May, June, and November show the lowest levels. Colombian regulations establish a maximum permissible concentration of 100 µg/m³ (298 K and 1 atm) for O₃, for an exposure time of 8 h, which corresponds to 50 ppb. As can be observed in Fig. 2b, concentrations range between 15 and 35 ppb, levels that cause little harm to human health.

Fig. 3 shows the annual mean cycle of records of pollutants PM_{2.5}, PM₁₀, and NO₂ at PJIC station (January 2015 to December 2019). Figures show records surpassing the Colombian regulations on PM_{2.5} and PM₁₀ (Fig. 3 a and b) for an annual exposure time (25 and 50 µg/m³, respectively), corresponding to 32.5% and 34.8% of the data. For both particle sizes, a bimodal behavior can be observed, with February, March, October, and November being the months with the highest levels of the pollutant. Additionally, it is possible to notice the behavior at LAYE station, which shows that March is the most critical month according to recorded values of PM_{2.5}. As regards concentrations of NO₂ (Fig. 3c), a bimodal behavior similar to PM₁₀ at the same station is observed. Increases in the levels of pollutants can be observed in Fig. 3 for the months of March and September, reaching concentrations up to 30 ppb (56.4 µg/m³). This value is below the current Colombian regulations, which establish an annual permissible maximum of 60 µg/m³.

Fig. 4 shows the mean annual cycle of PM_{2.5}, NO₂, and O₃ at UNNV station from January 2014 to December 2019 (the station was relocated to Fiscalía General de la Nación-Antioquia [District Attorney’s Office] on February 25, 2020). A very similar behavior throughout the year can be observed in Fig. 4a, with the exception being the months of February and March, when there are increased levels of PM_{2.5} in comparison with the rest of the year. However, 50.7% of the records for this pollutant exceed the Colombian annual limit value of PM_{2.5}. Fig. 4 b, in turn, shows that NO₂ does not exceed the levels of 25 ppb during the most critical months (February, March, September, and October). On the other hand, O₃ values do not reach harmful levels for health (see Fig. 4c), as was the case at LAYE station.

Fig. 5 shows the mean annual cycle of PM_{2.5} and PM₁₀ at MANT station. The bimodal behavior recorded in the previous stations can be noticed in both figures. The figure shows that PM_{2.5} and PM₁₀ concentrations are higher in February and March. Additionally, the exceedance percentage against annual Colombian limits was 67.8% for PM_{2.5} and 57.4% for PM₁₀.

From Figs. 2, 3, 4, and 5, it is possible to infer that the criterion pollutant in the stations under study corresponds to particulate matter, both PM_{2.5} and PM₁₀. This is in line with the findings of other studies, where PM is reported as a critical

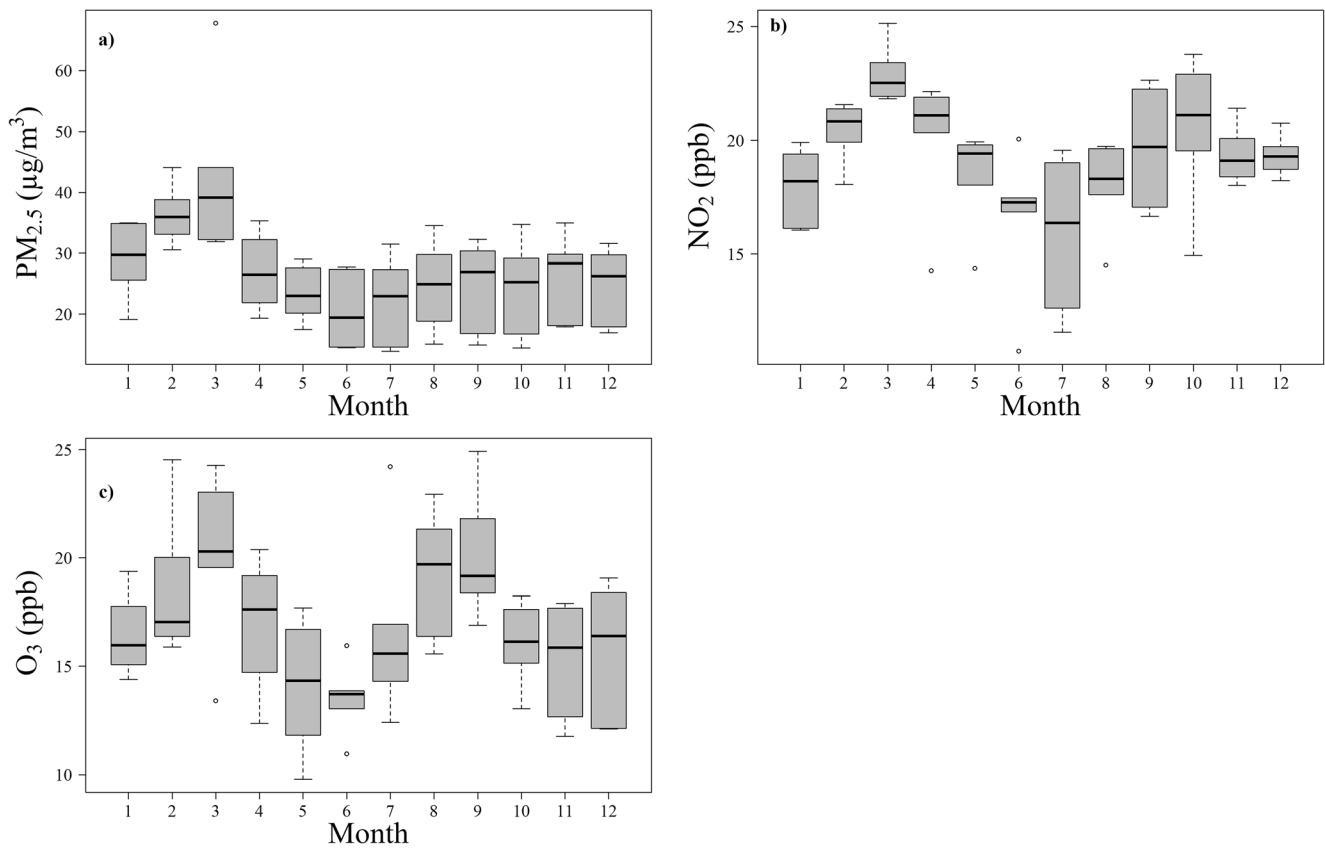


Fig. 4 Mean annual cycle of **a** PM_{2.5}, **b** NO₂, and **c** O₃ at UNNV station

pollutant in Medellín and the Aburrá Valley (Aguar-Gil et al. 2020; AMVA-UPB 2015; Correa-Ochoa et al. 2020; Herrera-Mejía and Hoyos 2019; Roldán-Henao et al. 2020). Additionally, it is important to highlight that the most critical month in terms of atmospheric pollution is March, and the environmental authority of the metropolitan area (AMVA) considers this a period of “environmental contingency.” However, it has been determined that in March 2016, there was an unusual increment in this yearly environmental

contingency, which according to local studies represented a critical air quality episode that highlighted the relation between local meteorological conditions, variability of the atmospheric boundary layer (ABL), and pollutant concentrations (Correa-Ochoa et al. 2020; Herrera-Mejía and Hoyos 2019).

From what can be observed in Fig. 6, the Mann Kendall test was applied, which allows analyzing the trend of a time series based on its tau and *p*-value. To this end, the seasonality of the four time series associated with the four stations was

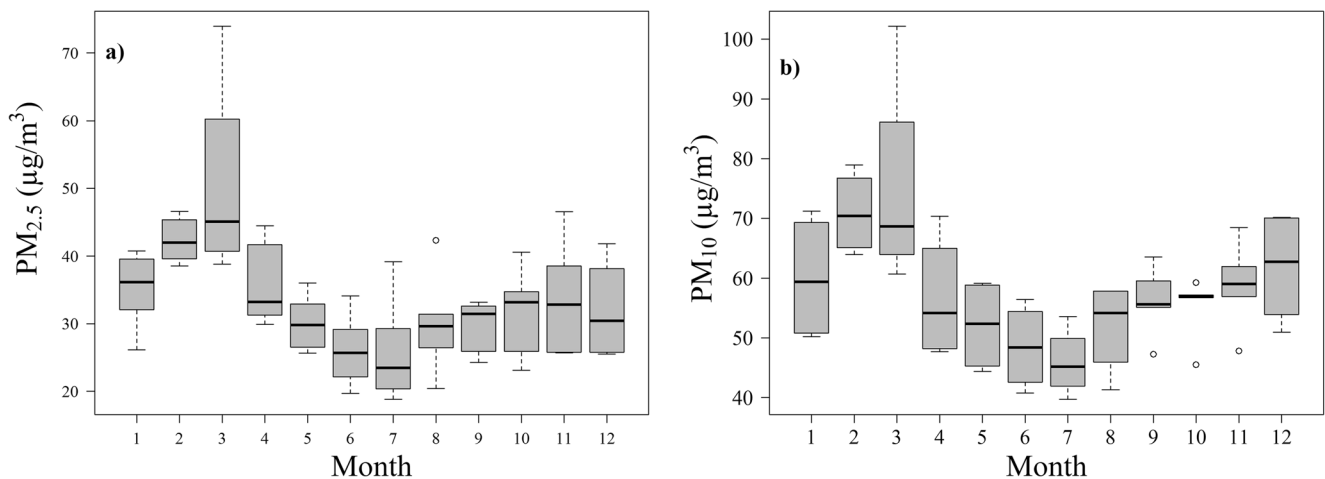


Fig. 5 Mean annual cycle of **a** PM_{2.5} and **b** PM₁₀ at MANT station

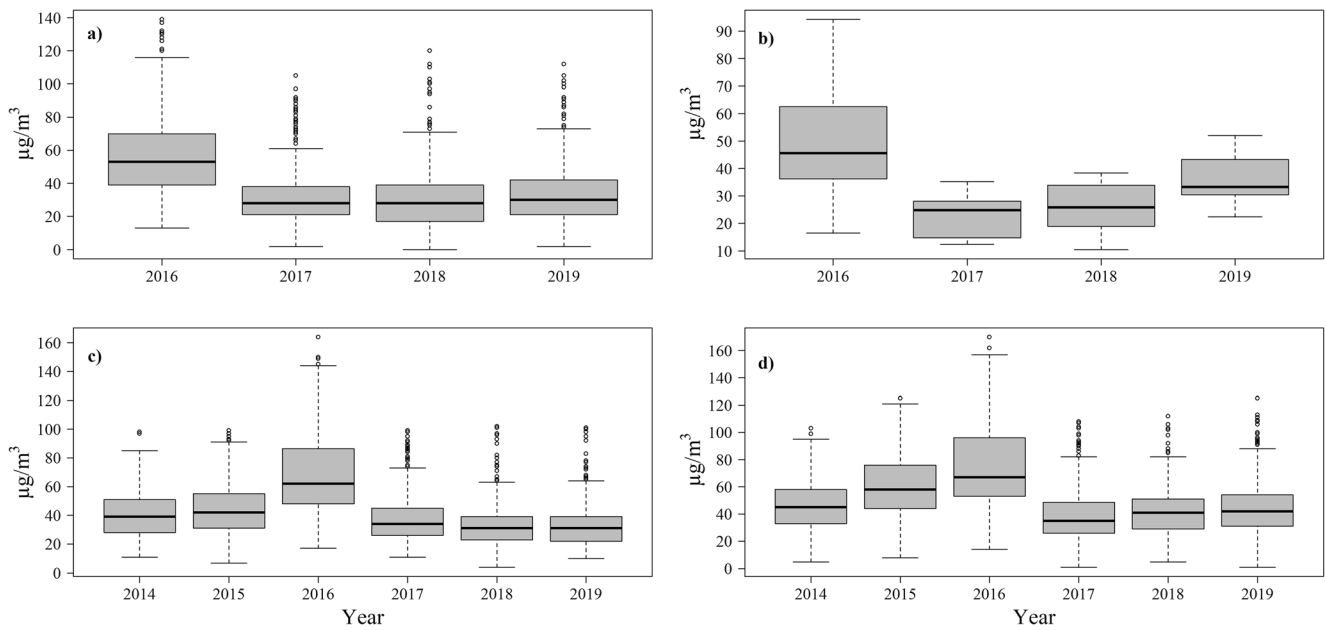


Fig. 6 Annual analysis of PM_{2.5} in March at **a** LAYE, **b** PJIC, **c** UNNV, and **d** MANT stations

extracted, and then the test was applied. It can be observed in Fig. 7 that, in general, the series trend is reducing, which is reaffirmed by the tau value, except for PJIC station. The resulting values for PM_{2.5} are presented in Fig. 7a–d, as follows: LAYE station (Fig. 7a), with tau value -0.651 and p -value of approximately zero; PJIC station (Fig. 7b) with tau value 0.0366 and p -value 0.7446 (not significant); UNNV station (Fig. 7c), with tau value -0.724 and p -value of approximately zero; and, finally, MANT station (Fig. 7d), with tau value -0.768 and p -value of approximately zero. Therefore, it is possible to deduce that PM_{2.5} has been reducing

significantly over time at LAYE, UNNV, and MANT stations, responding to management plans implemented by the environmental authority (AMVA), such as the integral plan for air quality management in the Aburrá Valley (Plan Integral de Gestión de la Calidad del Aire del Valle de Aburrá-PIGECA) approved in December of 2017 and the operational protocol to deal with atmospheric pollution episodes developed in 2019 (Plan Operacional para enfrentar Episodios de Contaminación Atmosférica en el Area Metropolitana del Valle de Aburra- POECA) (AMVA 2019; AMVA and Clean Air Institute 2017). These results show statistically

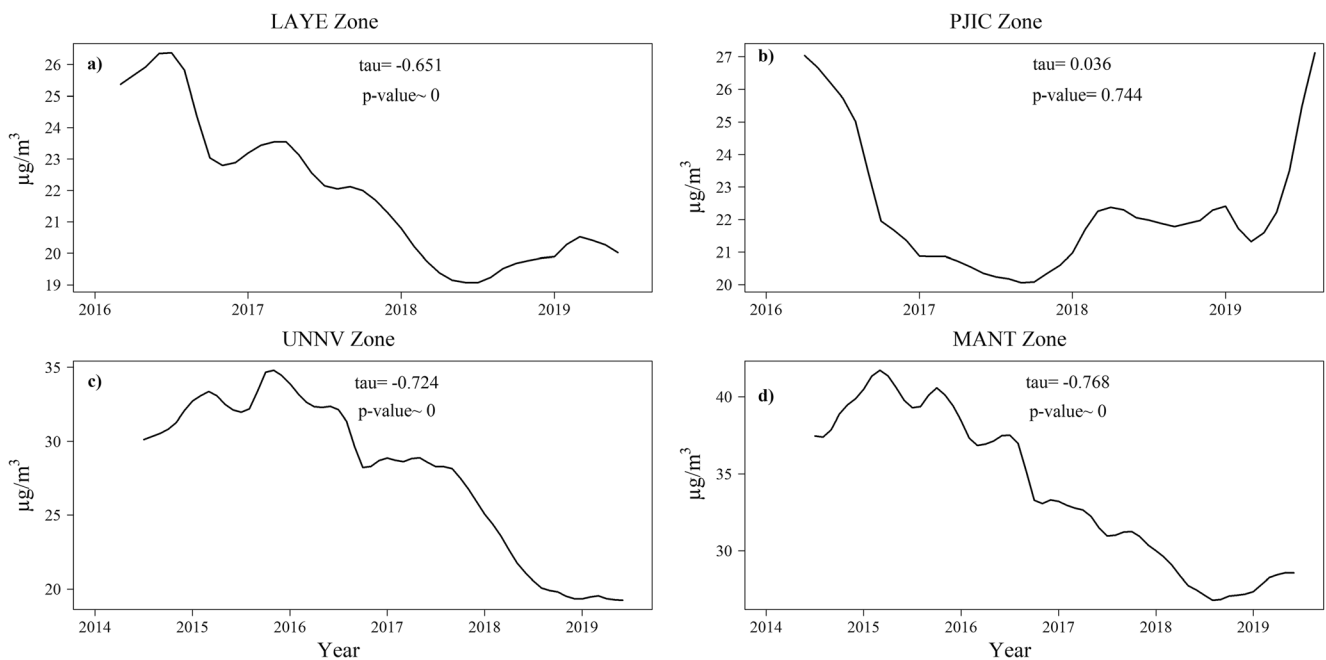


Fig. 7 Analysis of PM_{2.5} trends at **a** LAYE, **b** PJIC, **c** UNNV, and **d** MANT stations

Table 5 Classification of biomonitoring areas according to PM_{2.5} levels

Station	Source area classification	PM _{2.5} exceedances (%)	Classification (Correa-Ochoa et al. 2020)
MANT	Class I	100%	1
UNNV	Class I	100%	2
PJIC	Not applicable	--%	3
LAYE	Not applicable	--%	4

Table 6 Air pollution tolerance index (APTI)

Zone	Classification	Species name	A (mg g ⁻¹)	T (mg g ⁻¹)	P	R (%)	APTI		
LAYE	4	<i>Mangifera indica</i>	8.48	3.25	4.90	91.17	16.00		
		<i>Mangifera indica</i>	12.33	1.13	4.07	95.84	15.00		
		<i>Tabebuia chrysantha-rosea</i>	3.25	1.90	5.83	99.17	12.00		
		<i>Tabebuia chrysantha-rosea</i>	3.69	2.11	5.71	96.37	12.00		
		<i>Tabebuia chrysantha-rosea</i>	2.17	6.07	5.21	85.06	10.00		
		<i>Erythrina fusca</i>	2.92	2.35	5.85	92.94	11.00		
		<i>Jacaranda mimosifolia</i>	2.36	5.08	4.83	77.74	10.00		
		<i>Jacaranda mimosifolia</i>	2.73	5.65	4.56	89.64	11.00		
		<i>Fraxinus uhdei</i>	2.67	5.97	5.09	81.02	9.00		
		<i>Fraxinus uhdei</i>	1.66	5.58	5.22	72.30	9.00		
		<i>Fraxinus uhdei</i>	3.06	5.06	5.39	89.48	12.00		
		<i>Spathodea campanulata</i>	3.26	4.29	5.43	80.66	11.00		
		PJIC	3	<i>Mangifera indica</i>	7.21	3.96	5.64	88.13	15.00
				<i>Mangifera indica</i>	7.79	4.32	5.70	93.97	17.00
<i>Mangifera indica</i>	8.01			4.99	5.79	97.17	18.00		
<i>Tabebuia chrysantha-rosea</i>	2.02			1.97	6.14	87.61	10.00		
<i>Tabebuia chrysantha-rosea</i>	2.40			5.32	6.17	81.87	10.00		
<i>Erythrina fusca</i>	2.35			5.76	6.16	88.74	11.00		
<i>Erythrina fusca</i>	1.90			5.10	6.04	82.87	10.00		
<i>Jacaranda mimosifolia</i>	1.33			3.56	5.60	81.50	9.00		
<i>Jacaranda mimosifolia</i>	2.02			3.57	5.43	78.46	9.00		
<i>Fraxinus uhdei</i>	1.48			4.75	6.29	87.75	10.00		
<i>Fraxinus uhdei</i>	2.56			4.95	6.03	82.09	11.00		
<i>Fraxinus uhdei</i>	2.11			2.93	6.11	84.55	10.00		
<i>Spathodea campanulata</i>	1.68			3.18	5.91	88.29	10.00		
<i>Spathodea campanulata</i>	1.74			5.24	5.97	89.43	10.00		
UNNV	2	<i>Mangifera indica</i>	10.64	3.42	5.20	93.24	18.00		
		<i>Mangifera indica</i>	7.77	2.72	5.54	88.11	15.00		
		<i>Mangifera indica</i>	7.61	3.99	5.59	90.43	16.00		
		<i>Tabebuia chrysantha-rosea</i>	1.37	4.42	6.55	89.14	10.00		
		<i>Tabebuia chrysantha-rosea</i>	2.50	6.56	6.40	90.87	12.00		
		<i>Tabebuia chrysantha-rosea</i>	1.58	4.40	6.81	85.61	10.00		
		<i>Erythrina fusca</i>	2.50	4.73	5.91	80.99	10.00		
		<i>Erythrina fusca</i>	2.40	3.62	6.24	75.25	9.00		
		<i>Erythrina fusca</i>	2.78	4.63	6.21	86.79	11.00		
		<i>Jacaranda mimosifolia</i>	1.11	4.31	5.18	86.24	9.00		
		<i>Jacaranda mimosifolia</i>	1.78	2.27	5.50	84.57	9.00		
		<i>Fraxinus uhdei</i>	2.71	1.59	6.00	74.21	9.00		
		<i>Fraxinus uhdei</i>	5.34	2.30	6.03	83.24	12.00		
		<i>Fraxinus uhdei</i>	2.05	4.09	6.27	86.75	10.00		
<i>Spathodea campanulata</i>	1.29	3.12	5.93	82.09	9.00				
<i>Spathodea campanulata</i>	1.85	4.56	5.84	83.48	10.00				
MANT	1	<i>Mangifera indica</i>	8.59	3.75	5.41	93.52	17.00		
		<i>Mangifera indica</i>	7.58	4.48	5.29	95.20	16.00		
		<i>Tabebuia chrysantha-rosea</i>	1.58	1.87	5.89	78.90	9.00		
		<i>Tabebuia chrysantha-rosea</i>	1.16	2.67	6.48	74.26	8.00		
		<i>Tabebuia chrysantha-rosea</i>	1.78	2.80	6.66	92.21	10.00		
		<i>Erythrina fusca</i>	2.17	4.70	5.94	89.65	11.00		
		<i>Erythrina fusca</i>	2.32	6.29	5.99	94.35	12.00		
		<i>Erythrina fusca</i>	2.38	4.74	5.81	92.68	11.00		
		<i>Jacaranda mimosifolia</i>	2.55	4.55	4.85	93.21	11.00		
		<i>Fraxinus uhdei</i>	1.31	4.39	6.08	71.55	8.00		
		<i>Fraxinus uhdei</i>	3.58	2.81	5.79	67.82	9.00		
		<i>Spathodea campanulata</i>	1.92	5.63	5.83	82.57	10.00		

APTI ≤ 11, sensitive species; 11–16, intermediate species; ≥ 16, tolerant species (S. N. Singh and Verma 2007)

significant negative trends for LAYE, UNNV, and MANT stations. It is important to note that, in spite of the reduction in concentration, the results indicate that levels of particulate matter in Medellín and the Aburrá Valley are not yet below the permissible 24-h and annual limits established by Colombian regulations (Order 2254 of 2017).

Classification of biomonitoring areas

The methodology of source area classification described in the Colombian Sole Regulatory Decree of the Environmental Sector No. 1076 of May 2015 was used to classify biomonitoring areas (see Table 5). Based on this classification, it is possible to determine the percentage of exceedance of the annual standard, by using moving averages calculated from daily data from two previous years. For MANT and UNNV stations, the percentage of exceedances was 100%, so they were classified as Class I (highly polluted area), while the percentage of exceedances for PJIC and LAYE stations was 0%, so classification does not apply. However, according to a local study that used the percentage of exceedances to classify the four stations selected for the present work, MANT is the most polluted area, followed by UNNV, then PJIC, and, finally, LAYE (Correa-Ochoa et al. 2020).

Tolerance

Biochemical characteristics

Ascorbic acid (A) plays an instrumental role in the tree given its capacity to replace water in photosynthetic reactions allowing cell wall synthesis and carbon fixation (Rai 2016). It has been found that high concentrations of ascorbic acid give trees greater capacity of resistance and tolerance to stress factors such as atmospheric pollution (Singh and Verma 2007). In this regard, the biochemical analysis carried out in the present study shows that ascorbic acid values for the 54 individual trees under analysis range between 1.11 and 12.33 mg g⁻¹ (see Table 6 and Fig. 8d). The highest values for LAYE, UNNV, MANT, and PJIC zones were recorded for the *Mangifera indica* species (12.33, 10.64, 8.59, and 8.01 mg g⁻¹, respectively). On the other hand, the lowest value of the parameter was recorded at LAYE zone in the *Fraxinus uhdei* species (1.66 mg g⁻¹); at PJIC and UNNV zones, the lowest values corresponded to the *Jacaranda mimosifolia* species (1.33 and 1.11 mg g⁻¹, respectively); and at MANT zone, the lowest content of ascorbic acid was recorded for the *Tabebuia chrysantha-rosea* species (1.16 mg g⁻¹).

As regards total chlorophyll content (T), it has been indicated that trees sensitive to atmospheric pollution can have inhibited photosynthetic activity, resulting in chlorophyll depletion and carotenoids in their leaves (Rai 2016; Uka et al. 2017). The results obtained show that T values for the 54 trees

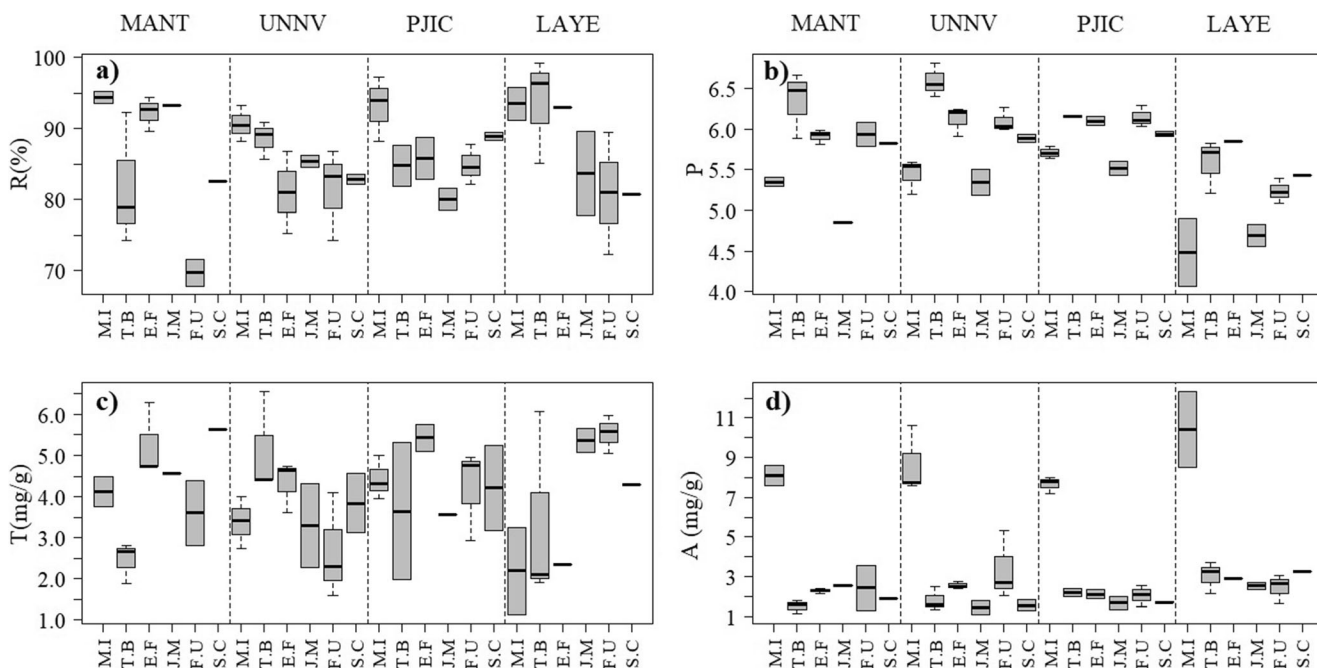


Fig. 8 Results of the biochemical parameters of 54 trees in four areas. **a** Relative water content (%), **b** pH of the leaf extract, **c** total chlorophyll content (mg/g), and **d** ascorbic acid (mg/g). M.I., *Mangifera indica*; T.B,

Tabebuia chrysantha-rosea; E.F, *Erythrina fusca*; J.M, *Jacaranda mimosifolia*; F.U, *Fraxinus uhdei*; S.C, *Spathodea campanulata*

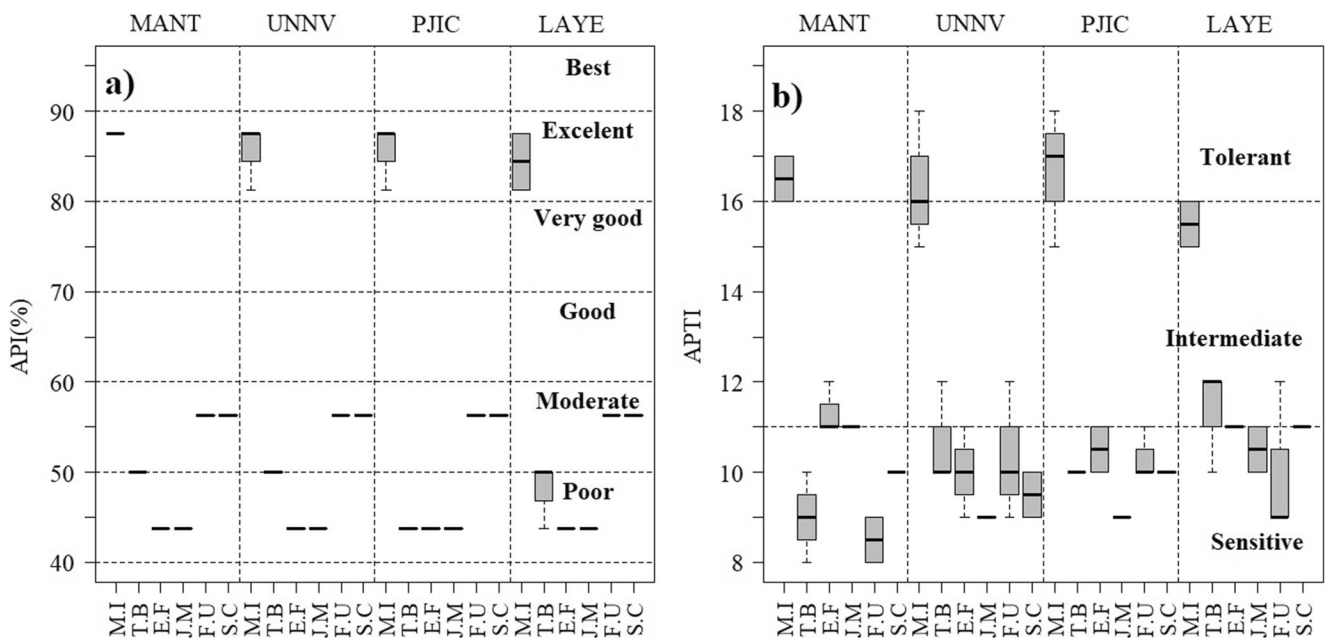


Fig. 9 Indexes results for the study zones: **a** API; **b** APTI. M.I, *Mangifera indica*; T.B, *Tabebuia chrysantha-rosea*; E.F, *Erythrina fusca*; J.M, *Jacaranda mimosifolia*; F.U, *Fraxinus uhdei*; S.C, *Spathodea campanulata*

range between 1.13 and 6.56 mg g⁻¹ (see Table 6 and Fig. 8c). The highest values for total chlorophyll content at each bio-monitoring zones were the following: *Tabebuia chrysantha-rosea* (6.56 mg g⁻¹) at UNNV and (6.07 mg g⁻¹) at LAYE, *Erythrina fusca* (5.76 mg g⁻¹) at PJIC, and *Spathodea campanulata* (5.63 mg g⁻¹) at MANT. On the other hand, the lowest chlorophyll values were the following: *Mangifera indica* (1.13 mg g⁻¹) at LAYE, *Tabebuia chrysantha-rosea* (1.97 and 1.87 mg. g⁻¹) at PJIC and MANT, respectively, and *Fraxinus uhdei* (1.59 mg g⁻¹) at UNNV.

As regards the results of pH of leaf extract (P) of the 54 trees, values ranged between 4.07 and 6.81 (see Table 6 and Fig. 8b). The highest (most basic) values per zone are reported as follows: at UNNV and MANT, *Tabebuia chrysantha-rosea* with a pH of 6.81 and 6.66, respectively, and at PJIC and LAYE, *Erythrina fusca* with a pH of 6.29 and 5.85, respectively. The importance of a pH close to neutral lies in that tolerant trees have an optimal environment for photosynthetic reactions, while little tolerant trees tend to generate stomatal sensitivity and reduced photosynthetic activity (Rai 2016). On the other hand, the lowest (most acidic) values were reported for *Mangifera indica* with a pH of 4.07 at LAYE, and *Jacaranda mimosifolia* with a pH of 5.43, 5.18, and 4.85 at PJIC, UNNV, and MANT, respectively.

Relative water content (R) is characterized by means of turgor, growth, stomatal conductance, transpiration, photosynthesis, and respiration (Balasubramanian et al. 2018); and at high percentages, it allows trees to maintain physiological balance under stressful environmental conditions (Rai 2016). In this sense, the results obtained show that R values for the 54 trees range between 67.82 and 99.17% (see Table 6 and Fig.

8a). Specifically, the highest values are recorded for *Tabebuia chrysantha-rosea* (99.17%) at LAYE and *Mangifera indica* 97.17%, 95.20%, and 93.24% at PJIC, MANT, and UNNV, respectively. The lowest values, in turn, are recorded for *Fraxinus uhdei* (74.21%, 72.30%, and 67.82%), at UNNV, LAYE, and MANT, respectively, and *Jacaranda mimosifolia* (78.46%) at PJIC.

APTI

Out of 54 trees under study, 12.96% were classified as tolerant, all of them of the *Mangifera indica* species. In turn, 33.33% and 53.70% were classified as intermediate and sensitive, respectively, as established in Singh and Verma (2007). From the above, it is possible to infer that the classification of individual trees as tolerant responds to high concentrations of ascorbic acid, as can be observed in the results consolidated in Table 6 and Fig. 9. The tolerant response of *Mangifera indica* has been reported in studies such as Govindaraju et al. (2012),

Table 7 Biological and socioeconomic species parameters

Species name	Ph	Cs	Tp	Ls	Tx	H	Ev
<i>Mangifera indica</i>	++	++	+	++	+	+	++
<i>Tabebuia chrysantha-rosea</i>	++	+		+		+	+
<i>Erythrina fusca</i>	++	+		+		+	+
<i>Jacaranda mimosifolia</i>	+			++	+	+	+
<i>Fraxinus uhdei</i>	++	++		+	+	+	+
<i>Spathodea campanulata</i>	++			++	+	+	++

Table 8 Anticipated performance index (API) score of 54 trees

Zone	Classification	Species name	APTI	Ph	Cs	Tp	Ls	Tx	H	Ev	Total	Score	Category
LAYE	4	<i>Mangifera indica</i>	+++	++	++	+	++	+	+	++	14	87.5	Excellent
		<i>Mangifera indica</i>	++	++	++	+	++	+	+	++	13	81.25	Excellent
		<i>Tabebuia chrysantha-rosea</i>	+	++	+	-	+	-	+	+	7	43.75	Poor
		<i>Tabebuia chrysantha-rosea</i>	+	++	++	-	+	-	+	+	8	50	Poor
		<i>Tabebuia chrysantha-rosea</i>	+	++	++	-	+	-	+	+	8	50	Poor
		<i>Erythrina fusca</i>	+	++	+	-	+	-	+	+	7	43.75	Poor
		<i>Jacaranda mimosifolia</i>	+	+	-	-	++	+	+	+	7	43.75	Poor
		<i>Jacaranda mimosifolia</i>	+	+	-	-	++	+	+	+	7	43.75	Poor
		<i>Fraxinus uhdei</i>	+	++	++	-	+	+	+	+	9	56.25	Moderate
		<i>Fraxinus uhdei</i>	+	++	++	-	+	+	+	+	9	56.25	Moderate
		<i>Fraxinus uhdei</i>	+	++	++	-	+	+	+	+	9	56.25	Moderate
		<i>Spathodea campanulata</i>	+	++	-	-	++	+	+	++	9	56.25	Moderate
PJIC	3	<i>Mangifera indica</i>	++	++	++	+	++	+	+	++	13	81.25	Excellent
		<i>Mangifera indica</i>	+++	++	++	+	++	+	+	++	14	87.5	Excellent
		<i>Mangifera indica</i>	+++	++	++	+	++	+	+	++	14	87.5	Excellent
		<i>Tabebuia chrysantha-rosea</i>	+	++	+	-	+	-	+	+	7	43.75	Poor
		<i>Tabebuia chrysantha-rosea</i>	+	++	+	-	+	-	+	+	7	43.75	Poor
		<i>Erythrina fusca</i>	+	++	+	-	+	-	+	+	7	43.75	Poor
		<i>Erythrina fusca</i>	+	++	+	-	+	-	+	+	7	43.75	Poor
		<i>Jacaranda mimosifolia</i>	+	+	-	-	++	+	+	+	7	43.75	Poor
		<i>Jacaranda mimosifolia</i>	+	+	-	-	++	+	+	+	7	43.75	Poor
		<i>Fraxinus uhdei</i>	+	++	++	-	+	+	+	+	9	56.25	Moderate
		<i>Fraxinus uhdei</i>	+	++	++	-	+	+	+	+	9	56.25	Moderate
		<i>Fraxinus uhdei</i>	+	++	++	-	+	+	+	+	9	56.25	Moderate
<i>Spathodea campanulata</i>	+	++	-	-	++	+	+	++	9	56.25	Moderate		
<i>Spathodea campanulata</i>	+	++	-	-	++	+	+	++	9	56.25	Moderate		
UNNV	2	<i>Mangifera indica</i>	+++	++	++	+	++	+	+	++	14	87.5	Excellent
		<i>Mangifera indica</i>	++	++	++	+	++	+	+	++	13	81.25	Excellent
		<i>Mangifera indica</i>	+++	++	++	+	++	+	+	++	14	87.5	Excellent
		<i>Tabebuia chrysantha-rosea</i>	+	++	++	-	+	-	+	+	8	50	Poor
		<i>Tabebuia chrysantha-rosea</i>	+	++	++	-	+	-	+	+	8	50	Poor
		<i>Tabebuia chrysantha-rosea</i>	+	++	++	-	+	-	+	+	8	50	Poor
		<i>Erythrina fusca</i>	+	++	+	-	+	-	+	+	7	43.75	Poor
		<i>Erythrina fusca</i>	+	++	+	-	+	-	+	+	7	43.75	Poor
		<i>Erythrina fusca</i>	+	++	+	-	+	-	+	+	7	43.75	Poor
		<i>Jacaranda mimosifolia</i>	+	+	-	-	++	+	+	+	7	43.75	Poor
		<i>Jacaranda mimosifolia</i>	+	+	-	-	++	+	+	+	7	43.75	Poor
		<i>Fraxinus uhdei</i>	+	++	++	-	+	+	+	+	9	56.25	Moderate
<i>Fraxinus uhdei</i>	+	++	++	-	+	+	+	+	9	56.25	Moderate		
<i>Fraxinus uhdei</i>	+	++	++	-	+	+	+	+	9	56.25	Moderate		
<i>Spathodea campanulata</i>	+	++	-	-	++	+	+	++	9	56.25	Moderate		
<i>Spathodea campanulata</i>	+	++	-	-	++	+	+	++	9	56.25	Moderate		
MANT	1	<i>Mangifera indica</i>	+++	++	++	+	++	+	+	++	14	87.5	Excellent
		<i>Mangifera indica</i>	+++	++	++	+	++	+	+	++	14	87.5	Excellent
		<i>Tabebuia chrysantha-rosea</i>	+	++	++	-	+	-	+	+	8	50	Poor
		<i>Tabebuia chrysantha-rosea</i>	+	++	++	-	+	-	+	+	8	50	Poor

Table 8 (continued)

<i>Tabebuia chrysantha-rosea</i>	+	++	++	-	+	-	+	+	8	50	Poor
<i>Erythrina fusca</i>	+	++	+	-	+	-	+	+	7	43.75	Poor
<i>Erythrina fusca</i>	+	++	+	-	+	-	+	+	7	43.75	Poor
<i>Erythrina fusca</i>	+	++	+	-	+	-	+	+	7	43.75	Poor
<i>Jacaranda mimosifolia</i>	+	+	-	-	++	+	+	+	7	43.75	Poor
<i>Fraxinus uhdei</i>	+	++	++	-	+	+	+	+	9	56.25	Moderate
<i>Fraxinus uhdei</i>	+	++	++	-	+	+	+	+	9	56.25	Moderate
<i>Spathodea campanulata</i>	+	++	-	-	++	+	+	++	9	56.25	Moderate

where it is concluded that because of this the species is key in the development of green belts.

Results for the biochemical parameters are shown in Fig. 8. As can be observed in Fig. 8 a and d, high values prevail for the *Mangifera indica* species, which provides a defense and physiological-balance mechanism in environments with stress factors. Additionally, the percentage of R (Fig. 8a) of the trees exceeded 80% across all biomonitoring zones, except for one tree of the *Fraxinus uhdei* species located in the most polluted area. On the other hand, the pH of leaf extract (Fig. 8b) did not reach values close to neutrality (pH close to 7.0). In this regard, it was noticed that the pH values of the *Mangifera indica* species were lower than 6 across all biomonitoring zones, with the most acidic values especially at LAYE (located at 1964 m.a.s.l.). *Mangifera indica* species is characterized by growing at altitudes below 2000 m.a.s.l. and requires high luminosity. The aforementioned zone is characterized by high biodiversity so that for individual trees growing in this area, there is competition over resources such as light, and the photosynthetic capacity of the leaves might exceed the light available for photosynthesis (Craine and Dybzinski 2013). Thus, although the LAYE zone is not under stress factors associated with atmospheric pollutants, competence over resources might be a stress factor affecting photosynthetic processes; and this can be reflected in acidic pH values.

As regards chlorophyll content (Fig. 8c), individual trees of the *Tabebuia chrysantha-rosea* species show high variability across all zones. This might be associated with its deciduous nature, seeing that various trees of the same species located in the same area can present important differences in a reduced space. Additionally, it is observed that species like *Jacaranda mimosifolia* and *Fraxinus uhdei*, which showed low concentrations

of chlorophyll at the most polluted zones (MANT and UNNV), showed high concentrations at the station with the lowest pollution level (LAYE), which demonstrates their potential as bioindicators. Finally, Fig. 8 d shows high concentrations of chlorophyll for the *Mangifera indica* species, as compared with the remaining species under analysis. However, it is possible to observe the same behavior observed for chlorophyll, with *Tabebuia chrysantha-rosea*, *Spathodea campanulata*, and *Erythrina fusca* showing the highest concentrations of ascorbic acid at LAYE zone.

Performance

Biological and socioeconomic characteristics

Inclusion of biological and socioeconomic characteristics allows the classification of the trees as urban trees, thus selecting the best trees to be included in urban plantation programs such as green belt development (Govindaraju et al. 2012; Kaur and Nagpal 2017; Satpute and Bhalerao 2017). The following parameters are used to evaluate the performance of species: plant habitat (Ph), canopy structure (Cs), type of plant (Tp), leaf size (Ls), texture (Tx), hardiness (H), and economic value (Ev). Each evaluated tree can obtain a maximum total value of 16 points, which corresponds to the best performance. For the species under analysis in the present study, the assessment was as follows (Table 7):

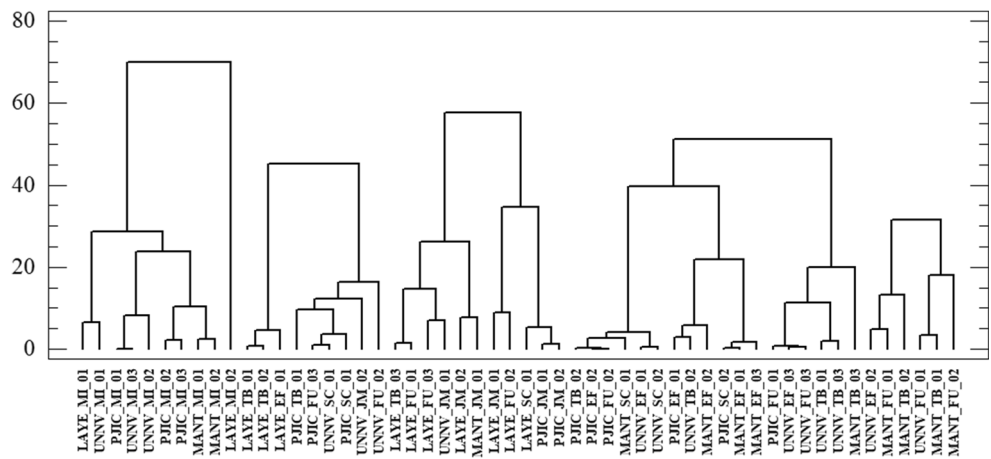
API

The API scores obtained for the 54 individual trees range from 43.75 to 87.5% (see Table 8). *Mangifera*

Table 9 ANOVA and variance component analysis

Factor/statistical	Fisher test	p-value	Variance component analysis
Species	455.70	0.000	96.12%
Stations	3.63	0.024	2.11%
Species*stations	3.58	0.001	--

Fig. 10 Cluster analysis for the 54 trees. M.I, *Mangifera indica*; T.B, *Tabebuia chrysantha-rosea*; E.F, *Erythrina fusca*; J.M, *Jacaranda mimosifolia*; F.U, *Fraxinus uhdei*; S.C, *Spathodea campanulata*



indica was classified as an excellent performer, followed by *Fraxinus uhdei* and *Spathodea campanulata*, which were classified as moderate performers, and then by *Tabebuia chrysantha-rosea*, *Jacaranda mimosifolia*, and *Erythrina fusca*, classified as poor performers. These results indicate that, as per its biochemical, biological, and socioeconomic characteristics, *Mangifera indica* is the optimal species to be included in green belt development plans. However, the species *Fraxinus uhdei* and *Spathodea campanulata*, of moderate performance, can also be included, because in spite of their low tolerance to atmospheric pollutants, their biological and socioeconomic characteristics allow them to have an adequate performance in urban environments. Finally, *Tabebuia chrysantha-rosea*, *Jacaranda mimosifolia*, and *Erythrina fusca* can be included when the objective is to use them as bioindicators of air quality, since they report conditions of high susceptibility to atmospheric pollutants and poor performance in urban environments.

Results of the API and APTI scores are plotted in Fig. 9. Fig. 9 a shows that *Mangifera indica*, apart from its tolerance, has the highest performance of the evaluated species and, according

to regional and international studies, has a high capacity for particulate matter removal given its functional characteristics (Jissy Jyothi and Jaya 2010; Liu et al. 2013; Pathak et al. 2011; Vasquez Bedoya and Arroyave Maya 2019).

Statistical and mathematical analysis

Two-way ANOVA and variance component analysis

Statistical results from two-way ANOVA and variance component analysis are presented in Table 9.

This analysis indicates that the Fisher test for each factor and their interaction included in two-way ANOVA are statistically significant (p -value < 0.05). According to this, the species, the stations, and their interaction have an effect on the API score. On the other hand, results of the variance component analysis show that the factor whose effect contributes the highest percentage to API variability is the species, with 96.12%, while the station only contributes 2.11%. Based on this, it is possible to deduce that the spatial factor is equally significant for evaluating the performance of an individual tree (Banerjee et al. 2021; Ben Amor et al. 2021; Govindaraju et al.

Fig. 11 Cluster analysis removing the effect of the *Mangifera indica* species. M.I, *Mangifera indica*; T.B, *Tabebuia chrysantha-rosea*; E.F, *Erythrina fusca*; J.M, *Jacaranda mimosifolia*; F.U, *Fraxinus uhdei*; S.C, *Spathodea campanulata*

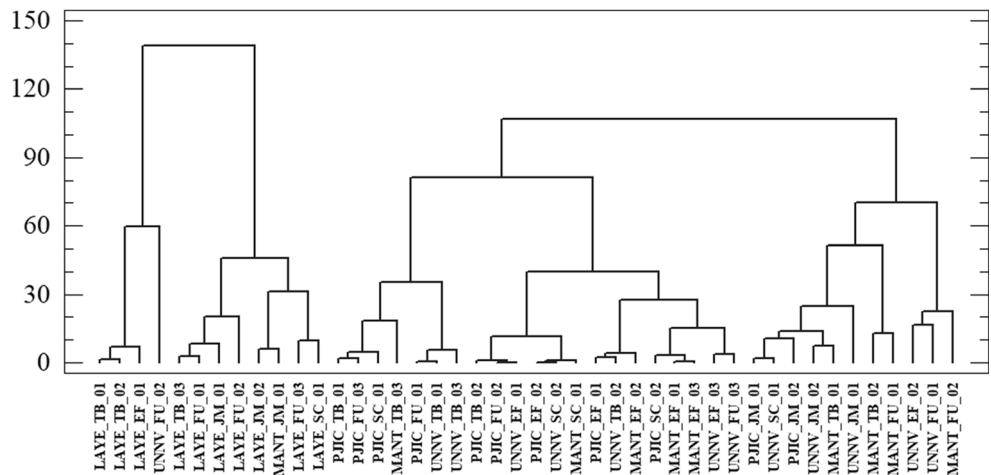
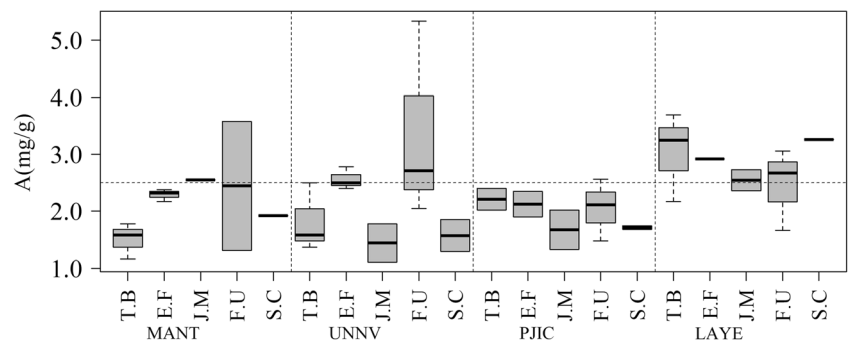


Fig. 12 Ascorbic acid (mg/g) after removing the effect of the *Mangifera indica* species. T.B, *Tabebuia chrysantha-rosea*; E.F, *Erythrina fusca*; J.M, *Jacaranda mimosifolia*; F.U, *Fraxinus uhdei*; S.C, *Spathodea campanulata*



2012; Kaur and Nagpal 2017; Mohammadi et al. 2018; Skrynetska et al. 2019); in short, a tree's response also depends on the area it grows and its environmental conditions.

Cluster analysis

Cluster analysis was carried out by using physiological (P, R) and biochemical (A, T) characteristics of individual trees as criteria. The first stage of the analysis (Fig. 10) included the 54 trees studied. This analysis was highly influenced by *Mangifera indica* because of the high concentrations of ascorbic acid recorded for individual trees of this species. Therefore, in order to extract the influence of this parameter, the analysis was repeated after removing observations corresponding to said species. The second stage of the analysis corresponds to the cluster of 44 trees (as shown in Fig. 11), where it is possible to observe the influence of the spatial factor (and not the species) since the first group corresponds to observations at LAYE zone, which compared to the remaining observations presented higher levels of ascorbic acid (Fig. 12). From the analysis, it is possible to deduce that (a) these species are sensitive to changes in environmental conditions and (b) ascorbic acid is a biochemical parameter that allows detection of environmental changes, which highlights its importance as a bioindicator of air quality.

Fig. 10 shows that the ascorbic acid recorded for the species of the LAYE biomonitoring zone is above 2.5 mg g⁻¹ which is a higher concentration than in the other zones, except for the *Fraxinus uhdei* species in the MANT and UNNV zones. From the above, it is possible to conclude that (a) the species *Tabebuia chrysantha-rosea*, *Erythrina fusca*, *Jacaranda mimosifolia*, and *Spathodea campanulata* show sensitivity to stress factors such as air pollution over the stations and (b) the species *Fraxinus uhdei* and *Jacaranda mimosifolia* show a tolerant response due to ascorbic acid and can therefore be grouped in Cluster 1 together with the species found at LAYE.

Conclusions

This study highlights the importance of biomonitoring in cities characterized by variables such as high population, motor vehicle growth, and high levels of atmospheric pollutants. Studies of this type are scarce for the city of Medellín and are not part of the development of environmental planning and management policies for decision-making, which could focus on improving air quality. The use of the APTI and API indexes in Medellín and the Aburrá Valley advances the state of the art focused on the response of tree species to stress factors (e.g., atmospheric pollution). From this study, it is possible to conclude that the *Mangifera indica* species has biochemical and biological mechanisms that make it an excellent performer in highly polluted urban areas. In other words, the exposure to and deposition of particulate matter do not generate the possible negative effects in its organism caused by this pollutant, and on the contrary, this species can adapt to changes in its environment. The species *Tabebuia chrysantha-rosea*, *Erythrina fusca*, and *Jacaranda mimosifolia*, on the other hand, were classified as having poor performance and high sensitivity. These species can thus be used as bioindicators: when they are located in strategic areas, they allow following up the levels of atmospheric pollutants by monitoring and controlling their biochemical and biological parameters. This study serves as a starting point for integrating the urban vegetation component as an alternative for improving air quality, by articulating tree tolerance of stress factors as well as their interception capacity (pollutant sinks) and bioindication capacity (response to the presence of pollutants). Future research should include species like *Syzygium malaccense*, which grows in the Aburrá Valley and is reported in other studies as a good performer (Anake et al. 2018); *Retrophyllum rospigliosii*, reported as having high capacity of PM deposition and offering ecosystem services such as water regulation and bird refuge (Vasquez Bedoya and Arroyave Maya 2019); and *Ficus benjamina*, which is common in the Aburrá Valley and has high capacity of PM capture and heavy metal deposition (Vasquez Bedoya and Arroyave Maya 2019).

Author contribution MC: Term, methodology, writing – review and editing, funding acquisition

JM: Methodology, formal Analysis, writing – review and editing

JS: Writing – review and editing, project administration

CC: Writing – review and editing, project administration

DA: Writing – review and editing, project administration

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