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Assessing Urban Habitat Quality Using Chemical, Physiological, and Spectral Leaf Properties in Abidjan (Côte d'Ivoire)

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Abstract

In the majority of African urban areas, there is a pervasive issue of air pollution that poses a significant threat to the environment. It is evident that air pollution has the capacity to exert an influence on the anatomy and physiology of plants. It has been demonstrated that plants are capable of absorbing gaseous pollutants and particulate matter, as well as heavy metals, through their leaves. The present study concentrated on the prospective value of leaf chemical, physiological, and spectral characteristics as straightforwardly quantifiable plant parameters in the cost-effective evaluation of urban habitat quality. The geographical area selected for the study was the city of Abidjan, located in the West African nation of Côte d'Ivoire. In the designated study area, two distinct land use classes were identified: namely, "main roads" and "parks". The concentration of heavy metals (lead and copper), the total chlorophyll content, stomatal resistance, and leaf reflectance were measured in the leaf samples of *Jatropha integerrima* Jacq. The stomatal resistance of leaf surfaces was found to be significantly higher ($p < 0.05$) on the Main roads as compared to the Parks. Furthermore, Parks exhibited markedly diminished ($p < 0.05$) lead and copper values in comparison to Main roads. The two habitats exhibited divergent patterns of leaf adaxial and abaxial reflectance, indicating potential variations in leaf structure and physiology, particularly with respect to total chlorophyll content. A significant ($p < 0.05$) and positive correlation was identified between total chlorophyll content and stomatal resistance. Conversely, an opposite, yet non-significant ($p > 0.05$), relationship was observed between total chlorophyll content and heavy metal concentration, as well as between stomatal resistance and heavy metal concentration. It was determined that a range of leaf characteristics in plants can be utilised as bioindicators of air quality in urban environments.

Keywords

Air Pollution, Urban Habitat Quality, Tree Leaf Properties, Bioindicators

1. Introduction

Urban air pollution has been identified as a significant environmental concern in contemporary society. Despite the prevalence of urban air pollution, it is imperative to recognize that pollutants have the capacity to contaminate air in all geographical locations. The substances in question comprise a variety of gases, particulate matter, and heavy metals. The potential consequences of exposure to these substances include detrimental effects on human health and plant life, in addition to environmental degradation. In urban environments, the predominant sources of air pollutants are road traffic and industrial activity [1].

It is therefore evident that the evaluation of urban air quality constitutes a pivotal component within the broader framework of environmental risk assessment. As asserted by [2], the monitoring of urban habitat pollution is of particular importance in the reduction of ecological risks.

Current techniques for the determination and monitoring of air quality generally involve the collection of air samples at particular sites and the subsequent analysis of these samples in a laboratory setting [3]. This monitoring approach is relatively expensive, which is a limiting factor for cities in low-income countries, such as Ivory Coast [4]. An alternative method that has been proposed is the utilisation of plants as bioindicators. Indeed, leaves represent pivotal interaction sites between plants and the atmosphere, and are perpetually exposed to ambient air pollution [5] at a given location due to the inherent immobility of plants. As [6] demonstrates, air pollutants have been shown to have a detrimental effect on the health of plant leaves, resulting in a range of adverse effects and visible injury symptoms. As posited by [2] [7], methodologies founded upon bioindicators, bioassays, or biomonitoring techniques, employing spectral, chemical, physiological, or anatomical characteristics of tree leaves, facilitate a direct evaluation of the deleterious effects of air pollution.

The findings of plant bioassays can provide an indication of the impacts of air pollution on the environment and thus of the level of environmental stress [8]. However, it is important to note that the response of plants to air pollutants cannot be extrapolated directly to predictions of human health responses.

The objectives of this study were to: (1) evaluate urban air quality, using reflectance in the visible spectrum, physiological characteristics (total chlorophyll and minimal stomatal resistance), and chemical characteristics (heavy metals (lead and copper)) content of tree leaves between different urban habitats, and (2) determine the interrelationships between these different parameters in relation to the activities performed in these areas.

2. Materials and Methods

2.1. Study Area

The present study was conducted in the city of Abidjan, the largest city in Côte d'Ivoire, with a human population of over 4 million inhabiting an area of 422 km^2. The exhibition features a comprehensive array of industrial activities and vintage engine motor vehicles, representing a significant historical and cultural snapshot of West African industrial development and automotive heritage. As is the case in other cities in the Global South, Abidjan is characterised by automobile emissions, which are a significant source of environmental pollution. The city of Abidjan boasts a number of parks and gardens. In these green spaces, air pollution levels are comparatively low [9].

2.2. Plant Species Characteristics and Experimental Setup

The study was performed on one ornamental species used in Abidjan, *i.e. Jatropha integerrima* Jacq. (Euphorbiaceae). *J. integerrima* is an evergreen shrub or small tree with glossy leaves and densely adaxially hairy leaves when young. The plant has a rounded or narrowly domed form and grows up to 4 m tall with a spread of 3 m or so, although in cultivation it is usually smaller. Leaves are extremely variable; they may be entire and elliptic or oval, or they may be fiddle-shaped, or they may have three sharply pointed lobes.

Plants were grown in 13-litre pots with compost and soil for 3 months in a municipal garden (municipal plant nursery) relatively far from any source of motor vehicle and industrial pollution (**Figure 1**). Potted plants were used instead of naturally growing trees to ensure uniformity in age, size, and exposure conditions across all sampling sites, thereby minimizing environmental variability and enhancing comparability of results. After three months of growth, two pots of the study species, which reached a height of about 1 m, were placed side by side in the selected sites on main roads and parks, separated from one another by 1 m. In each habitat, these plants remained exposed to ambient air for three consecutive months. To ensure consistent exposure to vehicular emissions, the plants were strategically positioned along the roadside, at a distance of a few meters from the edge of the roadway (**Figure 2**).

Main roads were composed of two busy roads *i.e*: Lagoon Boulevard and North Highway, where traffic intensity was greater than 6000 vehicles per hour during rush-hour traffic [4]. Two sampling locations were on each road. The coordinates of these sites are: 05˚20.944'N-04˚00.828'W and 05˚19.866'N-04˚01.127'W on Lagoon Boulevard, and 05˚21.813'N-04˚04.982'W and 05˚21.559'N-04˚03.984'W on North Highway. Leaf sampling was also conducted in two parks: municipal plant nursery (05˚26.24'N-03˚59.352'W and 05˚26.218'N-03˚59.361'W) and botanical garden (05˚22.18'N-03˚53.28'W and 05˚21.85'N-03˚53.01'W) (**Figure 3**). At each sampling site, six pots were selected, and five mature leaves were collected from each pot, yielding a total of 30 leaf samples per site. These samples were used as replicates in the ANOVA to ensure adequate statistical power for the analysis.

Figure 1. Plants grown in a municipal garden.

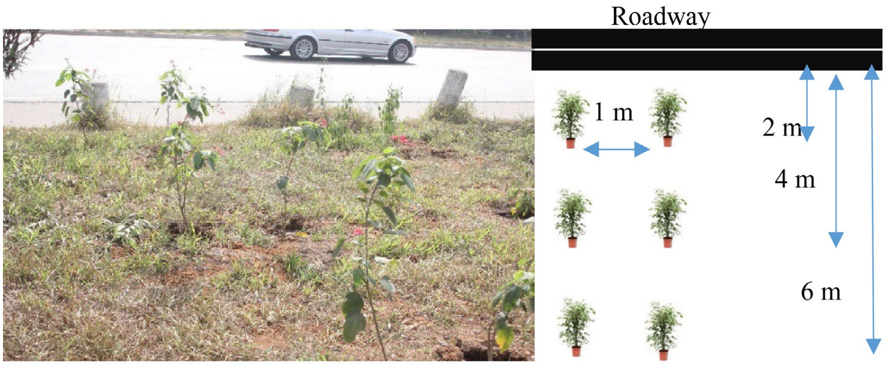

Figure 2. Arrangement of plants along a roadway.

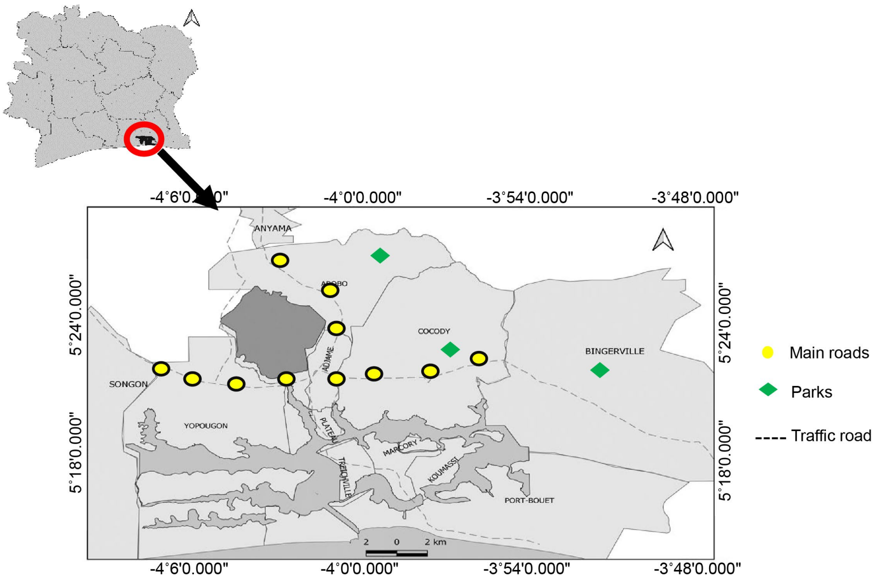

Figure 3. Indication of the sampling sites and the considered land use classes in the urban environment of Abidjan.

2.3. Chemical Leaf Measurement

Chemical determination of trace elements (Pb, Cu) was carried out by means of ICP-MS, Perkin-Elmer Elan 6000 (Serveis Científico-Tècnics, University of Barcelona) with quality assurance ensured through the use of certified reference materials, procedural blanks, and replicate measurements to verify accuracy and precision. The ICP-MS was equipped with a Meinhard concentric nebulizer, cyclonic spray chamber, Pt cones, and quadrupole mass analyzer. The measuring time was 50 milliseconds, the integration time was 1 s, and 3 replicates were used for this study. Typical instrument operating conditions for the ICP-MS were: RF power 1150 W, plasma Ar flow rate 15 L/min, and nebulizer Ar flow rate 0.8 L/min. Leaf samples (100 mg) were digested in Teflon TM containers using HNO_3 (1 - 2 ml) and H_2O_2 (0.5 - 1 ml) for 14 h at 90˚C. All concentrations are expressed in $mg \cdot g^{-1}$ on a dry weight basis.

The calibration was done with 4 standard solutions Cu (0, 4, 8, 20, 40 ppb) and Pb (0, 2, 4, 10, 20 ppb), prepared by dilution of standard solutions 1000 ppm certified traceable to National Institute of Standards and Technology (NIST). All standards were prepared daily after subsequent appropriate dilution with high-purity deionized water (Millipore, USA). The isotopes used for the measurement were ^{63}Cu and ^{208}Pb, and rhodium (^{103}Rh) was used as an internal standard corrector. Rhodium allows us to correct for matrix-induced variation and instrumental drift [10].

2.4. Total Chlorophyll Content

Total chlorophyll content (TCH) of the leaves was measured according to the method described by [11]. Three grams of fresh leaves were blended and then extracted with 10 ml of 80% acetone and left for 15 min. The liquid portion was decanted into another tube and centrifuged at 2500 rpm for 3 min. The supernatant was then collected and the absorbance was then measured at 646.6 nm and 663.6 nm using a spectrophotometer. Calculations were made using Equation (1):

$$\text{Chlorophyll a } (mg \cdot g^{-1}) = 12.25\ (A663.6) - 2.55\ (A646.6)$$

$$\text{Chlorophyll b } (mg \cdot g^{-1}) = 20.31\ (A646.6) - 4.91\ (A663.6)$$

$$\text{TCH } (mg \cdot g^{-1}) = 17.76\ (A646.6) + 7.34\ (A663.6) \tag{1}$$

2.5. Stomatal Resistance

Stomatal imprints were made by applying a very thin coat of colorless nail varnish on the abaxial leaf, thereby avoiding the midrib and the leaf margin, while the leaf remained attached to the plant. Subsequent to drying (15 - 20 minutes), the adhered nail varnish film was gently peeled off using transparent tape and was subsequently fixed on a clean labelled microscopic slide. Stomatal resistance was determined using a microscope (Olympus CX 30) connected to a camera (LC 20) (**Figure 4**) as described by [7]. The theoretical minimal stomatal resistance (Rs) was calculated as defined in Equation (2):

$$\mathrm{Rs} = \frac{4l}{n\pi LWD} + \frac{L+W}{4nLWD} \tag{2}$$

where Rs is the stomatal resistance ($\mathrm{s \cdot m^{-1}}$), l is the stomatal pore depth (m), D is the diffusion coefficient of water vapour in air ($24.2 \times 10^{-6}\ \mathrm{m^2\ s^{-1}}$ at 20˚C), n is the stomatal density (number of stomata $\mathrm{m^{-2}}$), L is the length (m), and W the width (m) of widely opened stomata. Stomatal depth was assumed as 10 µm [12].

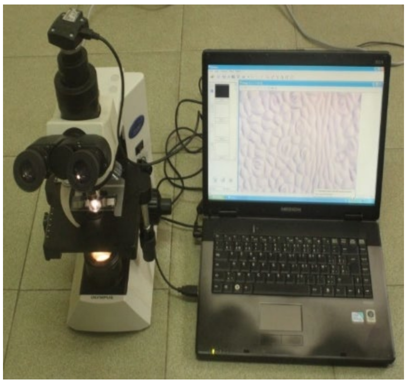

Figure 4. Stomatal resistance measurement device.

2.6. Leaf Reflectance Measurements

The field-level leaf reflectance measurements were performed under standard illumination conditions using a field illumination setup as described by [13]. A Canon EOS 550D RGB reflex camera equipped with a zoom lens (EF-S 18 - 55 mm f/3.5-5.6 IS) was used and mounted on the field illumination setup. The inner side of the setup is coated with non-reflecting black paint, intended to avoid indirect illumination (stray light) of the target as much as possible, thus avoiding multiple scattering conditions as much as possible. The camera is locked on top of the leaf reflectance measurement setup with a camera mounting cylinder (**Figure 5**). The setup allows keeping the distance between the camera objective and the target leaf surface constant throughout all measurements. In the setup, the illumination of a leaf is performed with two warm-white LED light sources (Ostar, 2005), which, during field campaigns, can be fed with the electric power of a fully charged battery. The maximum peak wavelength for the red, green, and blue of LEDs is 645, 550, and 490 nm, respectively. In the device, a removable grid made of transparent thin nylon wire is used to flatten and fix a leaf at the bottom of the setup. Immediately after sampling the leaves from the sample trees, imagery was acquired from both the adaxial and abaxial sides of a sampled leaf. The measurement time for tree leaf harvesting and the imaging of both leaf sides takes less than 5 minutes. We converted leaf imagery after transfer to a computer platform into R (Red), G (Green), and B (Blue) 1-byte grey images. Leaf reflectance has been computed for both the upper (adaxial) and lower (abaxial) leaf surfaces. By superimposing a polygon on the leaf surface, a leaf mask is obtained. We define this polygon as the leaf region of interest (ROI) for reflectance determinations by using

ENVI 4.4 (Research Systems, Boulder, Colorado, USA). Leaf reflectance (in percentage) is computed for the R, G, and B spectral bands using the leaf R, G, and B digital numbers ($R_{\text{l, |u03bb}}$) and the white reference target panel digital number ($R_{\text{r, |u03bb}}$) according to Equation (3) [13] [14].

$$R_{l,\lambda} = 100 \times R_{r,\lambda} \times \frac{DN_{l,\lambda}}{DN_{r,\lambda}} \tag{3}$$

$R_{l,\lambda}$ and $R_{r,\lambda}$ are, respectively, leaf and white reference target reflectance for band λ (nm), with λ indicating the R, G, or B spectral band. $DN_{l,\lambda}$ and $DN_{r,\lambda}$ are the leaf ROI digital number and white reference target (range: 0 - 255), respectively.

Figure 5. Leaf reflectance measurement device.

2.7. Statistical Analysis

All data were analyzed using Statistica software, version 7.1 (StatSoft Inc., 1984-2005). Descriptive statistics, including mean and standard deviation, were calculated for leaf reflectance parameters, and chemical and physiological leaf characteristics. Means were compared using a one-way analysis of variance (ANOVA) procedure and a Fisher-LSD test. Differences were considered significant at $p < 0.05$.

3. Results and Discussion

3.1. Chemical and Physiological Leaf Characteristic Measurements

The variations observed in copper (Cu) and lead (Pb) concentrations in *J. integerrima* leaves across different land use classes highlight the direct influence of anthropogenic activities on the environmental quality of urban areas. Main roads exhibited significantly higher levels of Cu (7.97 $mg \cdot g^{-1}$) and Pb (3.64 $mg \cdot g^{-1}$) (**Table 1**) compared to parks (Cu: 5.01 $mg \cdot g^{-1}$; Pb: 0.42 $mg \cdot g^{-1}$), suggesting accumulation resulting from intense road traffic and vehicle emissions. This trend aligns with findings from other urban studies, where proximity to road infrastructure is frequently associated with increased metal pollution. Indeed, the study conducted by [15], which used *Hibiscus tiliaceus rubra* as a bioindicator, also demonstrated that different road axes in Abidjan city presented the highest lead, copper, and zinc concentrations. These findings confirm the link between traffic density and metal contamination. These significant differences ($p < 0.05$) support the notion that green spaces such as parks may function as buffer zones, offering relative protection against heavy metal contamination.

Table 1. Chemical composition (Cu and Pb) and physiological parameters (total chlorophyll (TCH) content and stomatal resistance (Rs)) of *J. integerrima* leaves in main roads and parks. Different small letters above indicate significant differences between both habitats.

	Chemical composition		**Physiological parameters**	
Land use classes	Cu (mg·g^{-1})	Pb (mg·g^{-1})	TCH (mg·g^{-1})	Rs (s·m^{-1})
Main roads	7.97^{b} ± 2.59	4.45^{b} ± 1.28	0.67^{a} ± 0.13	54.14^{b} ± 9.47
Parks	2.36^{a} ± 1.07	0.86^{a} ± 0.09	1.03^{a} ± 0.42	41.33^{a} ± 5.77

A similar trend was observed for stomatal resistance (**Table 1**), which exhibited significantly higher values in roadside environments (54.14 s·m^{-1}) compared to park zones (41.33 s·m^{-1}). These findings suggest that proximity to traffic-intensive areas may impact plant physiological behavior, potentially as a stress response to elevated levels of atmospheric pollutants. This observation is consistent with the results of [16], who reported increased stomatal resistance in plants exposed to traffic-related air pollution. The rise in resistance may reflect an adaptive mechanism employed by plants to limit the uptake of pollutants by reducing gas exchange under stressful conditions [17]. The results showed no statistically significant differences in total chlorophyll content between the two land use classes according to **Table 1**. Nevertheless, higher chlorophyll levels were recorded in Parks (1.03 mg·g^{-1}), while lower values were observed along Main roads (0.67 mg·g^{-1}). This trend suggests that even in the absence of significant variation, land use may still influence foliar physiology. Several studies [18] [19] have highlighted that changes in chlorophyll content can serve as a physiological response of leaves to air pollution. In support of these previous findings, [20] have indicated that chlorophyll levels in plants tend to decrease under pollution stress conditions, reinforcing the potential of chlorophyll as a biomarker for atmospheric contamination.

3.2. Adaxial and Abaxial Leaf Reflectance

Adaxial reflectance values of *J. integerrima* leaves are significantly ($p < 0.05$) higher in parks than on main roads for all spectral bands (**Figure 6**), while the reverse is observed for the abaxial leaf side in the red and green bands, contrary to the blue band; but the difference is non-significant for the blue band ($p > 0.05$) (**Figure 7**). However, the highest reflectance values are observed in the green band, and the lowest in the blue band. Overall, the values range from 14.91% to 23.42% in the red band, from 29.65% to 36.46% in the green band, and from 6.09% to 15.45% in the blue band.

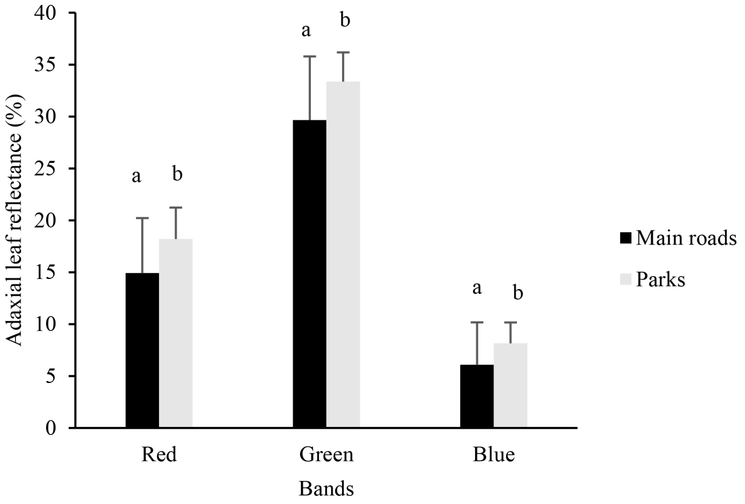

Figure 6. Mean of adaxial leaf reflectance of *J. integerrima* in the spectral bands studied. Different small letters indicate significant differences between land use classes. Error bars are standard deviations. Significant $p < 0.05$.

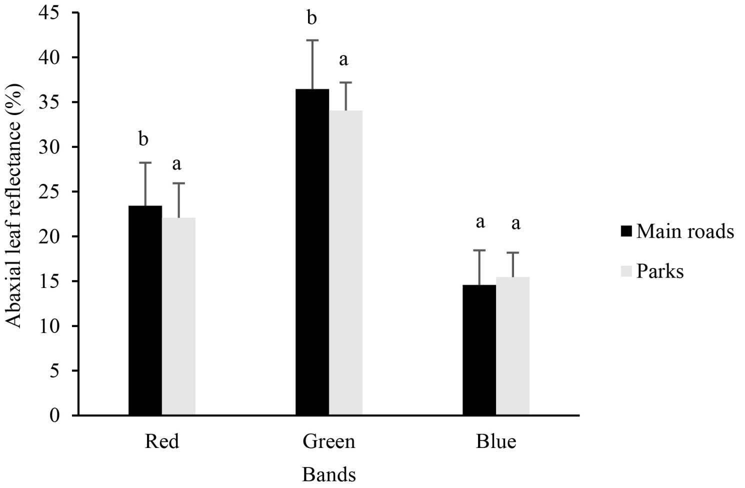

Figure 7. Mean of abaxial leaf reflectance of *J. integerrima* in the spectral bands studied. Different small letters indicate significant differences between land use classes. Error bars are standard deviations. Significant $p < 0.05$.

The elevated adaxial reflectance values of *J. integerrima* leaves observed in parks may be attributed to structural alterations in leaf tissues caused by contrasting environmental conditions. Indeed, *J. integerrima* leaves possess trichomes on their adaxial surface. These hair-like structures, combined with the high wettability of the leaf surface [21], enhance the retention of airborne particles [21] and metallic deposits [22]. Thus, leaves collected near roadways may exhibit cuticular erosion and reduced epidermal thickness due to prolonged exposure to atmospheric pollutants [23]. These structural degradations are known to alter leaf optical properties, particularly in the visible spectrum [24]. Similar findings have been reported in urban vegetation studies, where leaf reflectance is used as a proxy for environmental stress [25].

Abaxial leaf reflectance trends might be explained by lower leaf chlorophyll content in Main roads compared to Parks (**Table 1**). It has indeed been documented that leaf reflectance in the visible range of the spectrum is controlled by pigments [26], and that a lower leaf chlorophyll content leads to a higher leaf reflectance [27]. Additionally, the abaxial leaf reflectance of *J. integerrima* was found to be non-significantly higher in park environments compared to roadside locations specifically in the blue spectral band. This subtle difference contrasts with the reflectance behavior observed across the broader visible spectrum. Several studies have reported that leaf reflectance in the blue range (approximately 400–500 nm) is more strongly influenced by internal leaf structure than by chlorophyll content [28] [29].

3.3. Correlations between Heavy Metal Concentrations, Stomatal Resistance, and Total Chlorophyll Content

This part highlights three correlations among physiological and chemical parameters in plants exposed to environmental stressors.

A strong positive correlation ($R^2 = 0.937$) was observed between total chlorophyll content and stomatal resistance (**Figure 8**), suggesting a physiological response aimed at optimizing photosynthetic efficiency. Higher chlorophyll levels are typically associated with increased photosynthetic capacity [30]. This relationship may reflect an adaptive mechanism in plants under stress, particularly drought or pollutant exposure, where stomatal regulation plays a role in maintaining cellular homeostasis [31].

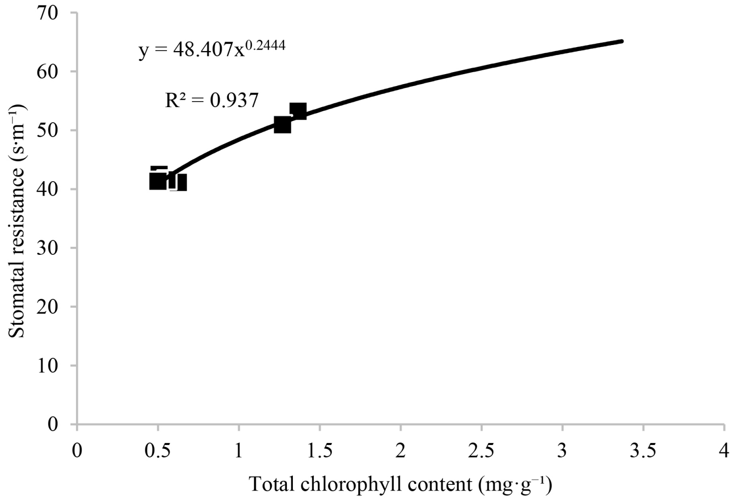

Figure 8. Correlation between total chlorophyll and stomatal resistance.

The negative correlation between chlorophyll content and heavy metals concentration (**Figure 9**) suggests that chlorophyll synthesis may be slightly inhibited by metal toxicity. Heavy metals such as cadmium, lead, and mercury are known to interfere with chlorophyll biosynthesis and degrade chloroplast structure [32]. This observation is further supported by [33] [34], who demonstrated that lead and cadmium exposure reduces chlorophyll levels by disrupting key enzymes involved in biosynthesis. However, the weak correlation ($R^2 = 0.421$) observed may indicate the presence of tolerance mechanisms, such as metal sequestration or antioxidant activity, that mitigate the impact on chlorophyll levels [35].

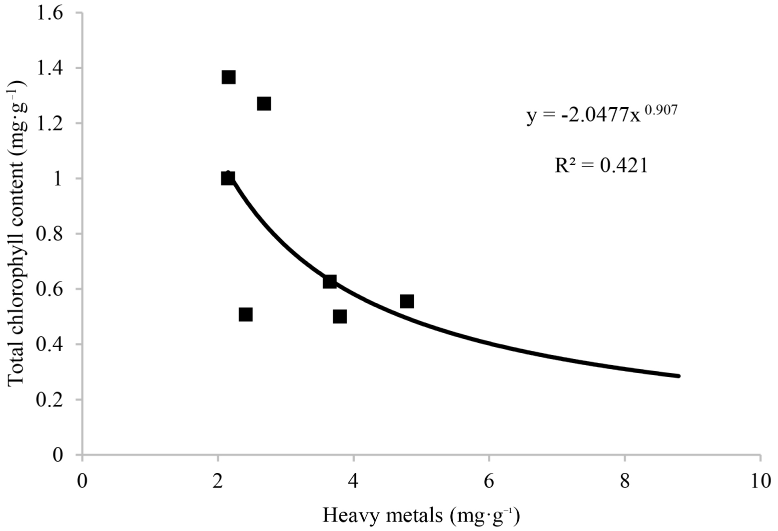

Figure 9. Correlation between total chlorophyll and heavy metal accumulation.

Similarly, stomatal resistance tends to decrease with increasing metal concentration (**Figure 10**). This could be due to metal-induced oxidative stress affecting guard cell function, leading to impaired stomatal regulation [36]. Also, [37] reported that exposure to zinc and copper altered stomatal behavior in *Brassica juncea*, reflecting disrupted turgor regulation under stress. However, the low strength of the correlation ($R^2 = 0.114$) suggests that stomatal behavior remains relatively stable, possibly due to compensatory physiological responses or limited metal uptake in the studied plant [38]. These results are in contrast with the results obtained by [39] for *Ficus benjamina* L., using biomagnetic leaf properties (leaf Saturation Isothermal Remanent Magnetisation, SIRM) in the same study area. Indeed, these authors revealed a positive correlation obtained between leaf SIRM and stomatal resistance. The observed difference between both studies and the considered species confirms that anatomical and physiological reactions of plants to stress such as air pollution are species-dependent. Indeed, according to [40], *F. benjamina* was categorized as an intermediate tolerant species, and *J. integerrima* was categorized as an intermediate sensitive species to air pollution according to [41] classification. Additionally, the classification by [42] emphasizes how plant species vary not only in pollutant uptake but also in internal detoxification and functional stability under stress conditions.

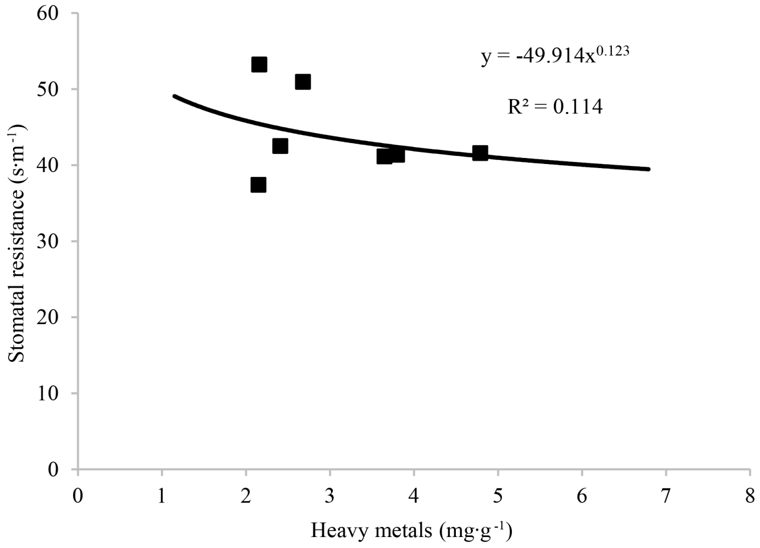

Figure 10. Correlation between stomatal resistance and heavy metal accumulation.

4. Conclusions

These findings underscore the potential of employing diverse leaf morphological and physiological traits as bioindicators for urban air quality assessment. The observed changes in chlorophyll content, stomatal resistance, and leaf reflectance between both habitats suggest that plant responses to atmospheric conditions can provide valuable insights into environmental stress levels. Consequently, plant leaves may serve as reliable and cost-effective tools for monitoring air pollution in urban ecosystems, thereby contributing to the development of more sustainable urban planning and environmental management strategies.

It is important to acknowledge that several uncontrolled environmental variables may have influenced the measured leaf traits. Factors such as local microclimatic conditions, seasonal meteorological fluctuations, soil composition, and proximity to traffic can affect both metal accumulation and physiological responses in plants. While efforts were made to standardize growing conditions using potted plants, these external influences could not be fully eliminated and may contribute to site-specific variability observed in the data.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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