ISSN: 2755-0168

Journal of Biotechnology & Bioinformatics Research

SCIENTIFIC Research and Community

Review Article

Open Access

Plant Biomarkers, Air Pollution and One Health Resilience: Urban Evidence from Psidium guajava in Douala, Cameroon

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ABSTRACT

Accelerating urbanization across Africa is intensifying particulate air pollution, threatening ecosystem integrity, urban liveability, and public health within the One Health framework. Urban vegetation provides critical natural mitigation infrastructure by intercepting airborne particulates and improving environmental quality; however, resilience thresholds of tropical species remain insufficiently understood. Generating such evidence is essential for designing climate-resilient African cities and cost-effective nature-based solutions. This study investigated physiological responses of Psidium guajava L. to dust pollution across urban (PK14), residential (Entrée Kotto), and suburban (Lendi) zones of Douala, Cameroon over a 12-month period. Leaf dust load and key stress biomarkers; total chlorophyll, ascorbic acid, relative water content (RWC), leaf extract pH, and Air Pollution Tolerance Index (APTI) were assessed as indicators of plant health and environmental stress. Results revealed a threshold-dependent response. Moderate dust loads (≤2.4%) significantly enhanced chlorophyll accumulation ($\beta = 1.607$, $p = 0.017$) and optimized leaf pH, indicating adaptive compensation under low-to-moderate stress. Beyond this threshold, elevated dust exposure caused marked physiological decline, with peak dust loads reaching 3.9% in the urban site and significant reductions in water status (RWC; $r = -0.74$, $p = 0.01$). APTI values ranged from 6.0–9.7, identifying P. guajava as a sensitive bioindicator suitable for urban air-quality surveillance. Seasonal rainfall moderated dust deposition, whereas highly urbanized locations experienced greater stress intensity.

These findings demonstrate that plant biomarkers can provide low-cost early-warning tools for pollution monitoring in data-scarce cities. They further show that strategic urban greening and species selection can strengthen pollution mitigation, ecosystem quality, and human wellbeing. Integrating vegetation-based interventions into city planning offers a practical pathway for advancing climate adaptation and One Health outcomes across rapidly growing African urban centres.

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Received: September 17, 2026; **Accepted:** September 22, 2026; **Published:** September 28, 2026

Keywords: Particulate Matter, Psidium Guajava, Plant Biomarkers, Dust Deposition, APTI, Hormesis, One Health

Introduction

Rapid urbanization in African cities is accompanied by increasing traffic density, industrial development, construction, biomass burning and expansion of informal settlements. These processes generate complex mixtures of particulate matter (PM), including directly emitted particles and secondary aerosols. In urban environments, particulate pollution therefore represents not only an atmospheric problem but also an ecological stressor capable of affecting vegetation, ecosystem functioning and urban food systems [1-3].

Particulate matter is commonly classified according to aerodynamic diameter, with PM2.5 referring to particles ≤2.5 μm and PM10 to particles ≤10 μm. Particle size influences atmospheric residence time, transport, deposition and interaction with biological surfaces [4]. Fine particles are particularly important because of their large surface area relative to mass and their ability to carry chemically reactive constituents, including metals and secondary inorganic compounds [3,5].

The biological consequences of PM exposure extend beyond human health. Plants intercept atmospheric particles through leaf surfaces, thereby functioning as passive sinks for particulate pollution. However, the same interception can expose foliage to excessive particulate loading. Deposited particles may alter leaf surface properties, reduce light penetration, obstruct stomata and interfere with gas exchange and photosynthetic processes. Dust deposition can consequently become a physiological burden rather than an exclusively beneficial ecosystem service [6-10].

Plant responses to particulate pollution are not necessarily linear. Depending on the intensity and duration of exposure, low or moderate stress may stimulate compensatory physiological responses, whereas prolonged or excessive exposure can overwhelm these mechanisms. Such non-linear responses are

consistent with the concept of hormesis, in which a low dose of a stressor may stimulate biological responses while higher doses become inhibitory. Chlorophyll responses are particularly relevant because chlorophyll content reflects the capacity of leaves to maintain photosynthetic activity under environmental stress [11-14].

Other physiological and biochemical indicators provide complementary information. Relative water content (RWC) reflects plant hydration status and is sensitive to disruptions in transpiration and water regulation. Leaf extract pH is associated with biochemical adjustment under pollution stress, while ascorbic acid (AsA) represents an important component of antioxidant defence against reactive oxygen species (ROS) [15-17]. Together, these parameters can provide a more informative assessment of plant stress than any single indicator.

The Air Pollution Tolerance Index (APTI) combines ascorbic acid, chlorophyll, relative water content and leaf extract pH to characterize plant responses to air pollution [18-20]. Species with high APTI values are generally considered more tolerant, whereas species with low values are more sensitive and potentially useful as bioindicators. The use of APTI has therefore become an important component of vegetation-based air-quality assessment [21-23].

Douala provides an important setting for examining these interactions. The city is Cameroon's major economic and port centre and has experienced rapid urban expansion, increasing traffic, industrial activity, construction and other anthropogenic pressures. Previous studies have documented particulate pollution in Douala and identified traffic and other urban activities as important contributors [24-26]. However, most local studies have focused on atmospheric concentrations and human health, while considerably less attention has been given to the biological consequences of particulate deposition on urban vegetation.

Psidium guajava L. is particularly relevant in this context because it is widely cultivated in tropical environments and contributes to household nutrition and urban food systems. At the same time, its leaves provide an accessible biological surface for monitoring particulate deposition. The species can therefore occupy a dual position as both an ecosystem component exposed to pollution and a potential bioindicator of environmental stress.

The present study builds on an integrated assessment of particulate pollution in Douala by linking atmospheric PM concentrations and source characteristics with foliar deposition and plant physiological responses. The specific objectives were to characterize the spatial and temporal dynamics of PM2.5 and PM10, examine meteorological influences on particulate concentrations, identify the elemental composition and major sources of PM2.5, quantify particulate deposition on P. guajava leaves, determine the physiological and biochemical responses of the plant to deposited dust, and evaluate plant sensitivity using APTI.

The study is framed within One Health because air quality, plant health, ecosystem integrity, food systems and human wellbeing are interconnected. Current One Health frameworks explicitly recognize people, plants, animals and ecosystems as interdependent components of health and identify air pollution as an environmental threat requiring integrated responses [27].

Materials and Methods

Study Area

The study was conducted in Douala, Cameroon, within three contrasting locations representing different urbanization and land-use conditions – Figure 1: PK14 (Site 1- N04o04.6716'; E009o47.5021'), Entrée Kotto (Site 2- N04o05.5612'; E009o44.9215') and Lendi (Site 3- N04o06.5177'; E009o46.1527'). PK14 represents a highly urbanized commercial environment characterized by intense traffic and human activity. Entrée Kotto represents a residential environment influenced by traffic, household activities and other localized emission sources. Lendi represents a more suburban/peri-urban environment with comparatively lower and more variable anthropogenic pressure.

These locations were selected to capture a pollution gradient while remaining within the broader Douala urban system. The study therefore provides a spatial comparison of contrasting micro-environments rather than a city-wide statistical representation of all of Douala.

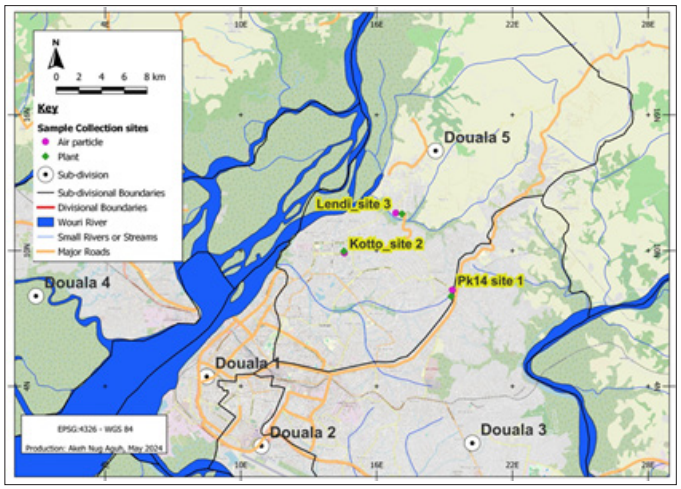


Figure 1: Map of the Three Sampling Sites in Douala V

Ambient particulate matter monitoring

Ambient $PM_{2.5}$ and PM10 concentrations were monitored from April to November 2023. Measurements were conducted at the three study sites using portable air-quality monitoring equipment. The monitoring period covered both rainy and dry-season conditions.

The atmospheric measurements showed substantial temporal variability. Hourly $PM_{2.5}$ concentrations ranged from approximately 2.0 to 120 μg m^{-3}, while PM_{10} ranged from 3.3 to 190 μg m^{-3}. Daily PM2.5 concentrations ranged from 6.5 to 55 μg m^{-3} and PM10 from 10 to 88 μg m^{-3}.

Estimated annual $PM_{2.5}$ concentrations were approximately 31 μg m^{-3} at PK14, 20 μg m^{-3} at Entrée Kotto and 17μg m^{-3} at Lendi, with an overall estimate of approximately 23 μg m^{-3}. The corresponding relative-risk estimates for short-term PM2.5 exposure were 1.013, 1.004 and 1.002 at PK14, Entrée Kotto and Lendi, respectively.

The mean $PM_{2.5}/PM_{10}$ ratio was approximately 0.62, indicating a substantial fine-particle component in the ambient aerosol.

Meteorological Measurements

Temperature, relative humidity, precipitation and wind speed were recorded alongside particulate concentrations. Pearson correlation and regression analyses were used to examine relationships

between meteorological parameters and PM concentrations. Granger causality analysis was additionally used to evaluate whether previous meteorological conditions provided predictive information for subsequent PM_{10} concentrations.

The thesis emphasizes that the term "causality" in this analysis refers to predictive temporal association rather than mechanistic causation.

Elemental Characterization of $PM_{2.5}$

A total of 72 $PM_{2.5}$ filter samples were collected over the eight-month atmospheric sampling period. Elemental characterization was conducted using energy-dispersive X-ray fluorescence (EDXRF). The analytical procedure included calibration with reference materials, field blanks and replicate analyses. Mean analytical precision from repeated analysis was approximately 1–10%.

The elemental dataset included sulphur (S), chlorine (Cl), potassium (K), calcium (Ca), titanium (Ti), vanadium (V), iron (Fe), bromine (Br), barium (Ba) and silicon (Si), with additional elements initially assessed during the analytical procedure.

Elements were screened according to analytical precision and detection-limit criteria. Copper was excluded because of poor analytical precision, while zinc and nickel were excluded from the final source-apportionment dataset because of detection-limit limitations.

Positive Matrix Factorization

Positive Matrix Factorization (PMF) was applied to the elemental composition dataset to identify major sources of $PM_{2.5}$. PMF was selected because it provides non-negative source contributions and does not require complete prior specification of source profiles [1,28]. Multiple factor solutions were evaluated and model robustness was examined using Bootstrap, displacement (DISP) and Bootstrap–DISP analyses. The final interpretation resolved six major source categories:

- Vehicular/Traffic Emissions;
- Industrial Emissions;
- Biomass Burning;
- Secondary Sulphate Aerosols;
- Resuspended Soil and Road Dust;
- Shipping/Heavy-Fuel-Oil Combustion.

The identification of a shipping-related contribution is particularly relevant because Douala is a coastal port city, and vanadium-rich signatures can be associated with heavy-fuel-oil combustion.

Plant Sampling

Plant sampling was conducted monthly over a 12-month period from December 2022 to November 2023. Mature leaves were collected from the same selected P. guajava trees at each site to reduce variation associated with differences among individual trees.

Leaves were collected from comparable canopy positions during the early morning, approximately 06:30–10:00 h, at heights of approximately 0.6–2.5 m. Between approximately 30 and 50 leaves were collected per site per month.

Foliar Dust-Load Determination

Foliar dust was quantified gravimetrically following the approach of [18]. Approximately 10 g of fresh leaves were weighed before washing (M_1), carefully washed with distilled water and gently brushed to remove surface particles, air-dried for approximately four hours and reweighed (M_2).

Dust load was calculated as:

$$\textbf{Dust Load} = \left[\frac{(M1-M2)}{M1}\right] \textbf{x } 100 \quad (1)$$

Pearson correlation and simple linear regression were used to evaluate relationships between dust load and plant physiological variables. One-way ANOVA was used to test whether mean foliar dust load differed among the three sites, with $\alpha = 0.05$.

Biochemical and physiological Measurements

Four plant indicators were assessed: Total chlorophyll, relative water content (RWC), leaf extract pH, and ascorbic acid (AsA). RWC was calculated using fresh weight, turgid weight and dry weight:

$$\textbf{RWC}\ (\%) = \frac{FW-DW}{TW-DW} \textbf{ x } 100 \quad (2)$$

The biochemical analyses were conducted at the Agroecological Laboratory, Department of Agronomic and Applied Molecular Sciences, Faculty of Agriculture and Veterinary Medicine, University of Buea.

Air Pollution Tolerance Index

APTI was calculated from the measured values of ascorbic acid, total chlorophyll, RWC and leaf extract pH following the established formulation of [18].

The resulting values were interpreted using the classification framework applied in the thesis: APTI values of 30–100 indicate tolerant species, 17–29 intermediate species, 1–16 sensitive species and values below 1 very sensitive species [20].

Results

Ambient particulate pollution

Particulate pollution showed pronounced temporal and spatial variability across Douala. Hourly $PM_{2.5}$ concentrations ranged from 2.0 to 120 μg m^{-3} and PM_{10} from 3.3 to 190 μg m^{-3}. Daily concentrations ranged from 6.5–55 μg m^{-3} for PM2.5 and 10–88 μg m^{-3} for PM_{10}.

The estimated annual $PM_{2.5}$ concentrations followed the pattern PK14 > Entrée Kotto > Lendi (as seen in Figure 2), with values of approximately 31, 20 and 17 μg m^{-3}, respectively. The corresponding overall estimate was approximately 23 μg m^{-3}.

Distinct diurnal peaks were observed, particularly around the morning traffic period (approximately 07:00–09:00) and afternoon/evening activity period (approximately 17:00–21:00). The peaks were most pronounced at PK14 and Entrée Kotto and least pronounced at Lendi.

The PM2.5/PM10 ratio averaged approximately 0.62, indicating substantial fine-particle dominance within the measured particulate mixture.

Meteorological Influences

Meteorological influences differed among sites rather than following a single city-wide pattern.

At PK14, relative humidity showed the strongest relationship among the meteorological variables considered, explaining approximately 27.7% of PM2.5 variability ($R^2 = 0.2767$) and 22.8% of PM10 variability ($R^2 = 0.2282$).

At Entrée Kotto, temperature showed a strong negative relationship with PM10 (R^2 = 0.7995), while precipitation showed a strong positive association with PM10 (R^2 = 0.6805). The latter relationship was counter to the expected rainfall scavenging effect and suggests the influence of coincident local emission activity. Wind speed showed a moderate negative association with PM10 (R^2 = 0.3197).

At Lendi, meteorological relationships were generally weak. For example, wind speed explained only approximately 0.16% of PM2.5 variability, while temperature explained approximately 0.36% of the variability in both PM2.5 and PM10. These findings demonstrate that meteorological effects were strongly site-dependent and interacted with local emission sources.

Elemental Composition and Source Apportionment

The elemental composition of PM2.5 showed a mixture of crustal, combustion and marine/port-related signatures. Fe, Si and S were among the most abundant measured elements, with mean surface concentrations of approximately 1400, 1100 and 810 ng cm^{-2}, respectively.

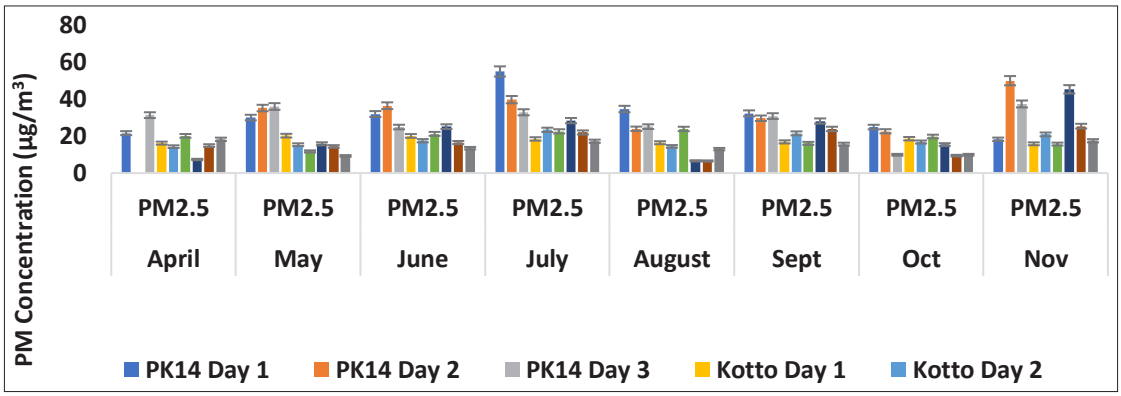
PMF produced a stable six-factor solution. The resolved factors corresponded to traffic emissions, industrial emissions, biomass burning, secondary sulphate aerosols, resuspended soil/road dust and shipping/heavy-fuel-oil combustion.

The source profile was therefore distinctly mixed rather than attributable to a single dominant urban activity. The shipping contribution is especially relevant to Douala because of the city's proximity to port activities and the associated vanadium-rich combustion signature.

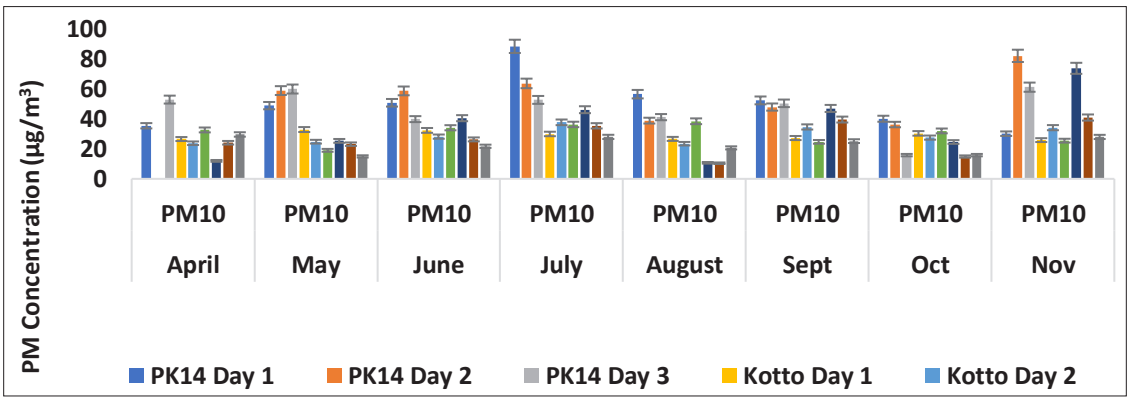
Foliar Dust Deposition

Dust deposition on P. guajava leaves ranged from 0.10 to 3.93% during the sampling period.

PK14 had a mean dust load of 0.89%, a median of 0.61% and a standard deviation of 1.08%, with a maximum of 3.93%. Entrée Kotto had a mean of 0.91%, median of 0.45% and standard deviation of 1.01%, with a maximum of 2.82%. Lendi had the lowest mean value, 0.75%, with a median of 0.38%, standard deviation of 0.83% and maximum of 2.42%.



(a)



(b)

Figure 2: Spatiotemporal Variation of PM2.5 and PM10 Concentrations Across PK14, Entrée Kotto and Lendi.

Importantly, although the descriptive values suggest greater episodic deposition at PK14, the differences among sites were **not statistically significant: F(2,30) = 0.085, p = 0.919.**

This result indicates that broad site classification alone did not explain foliar dust deposition. Localized emission sources, road proximity, construction activity, wind conditions and temporal variability likely contributed substantially to the observed deposition patterns.

Seasonal variation was more apparent than the overall site effect. PK14 experienced its largest dust loads during the dry season, particularly September–November, culminating in the maximum value of 3.93% in November. Entrée Kotto also showed elevated values during the later part of the sampling period, whereas Lendi generally maintained lower and more stable deposition.

Dust Load and Total Chlorophyll Response

The relationship between leaf dust load and total chlorophyll content was examined using Pearson's correlation and simple linear regression (Fig. 3). The scatterplots showed a generally positive association between dust load and total chlorophyll at the study sites, although the strength of the relationship varied among sites. At Entrée Kotto, the relationship was positive and statistically significant, with the regression model explaining 71.4% of the variation in total chlorophyll ($R^2 = 0.714$, $F = 12.490$, $p = 0.017$). The regression coefficient ($\beta = 1.607$) indicates an increase in total chlorophyll

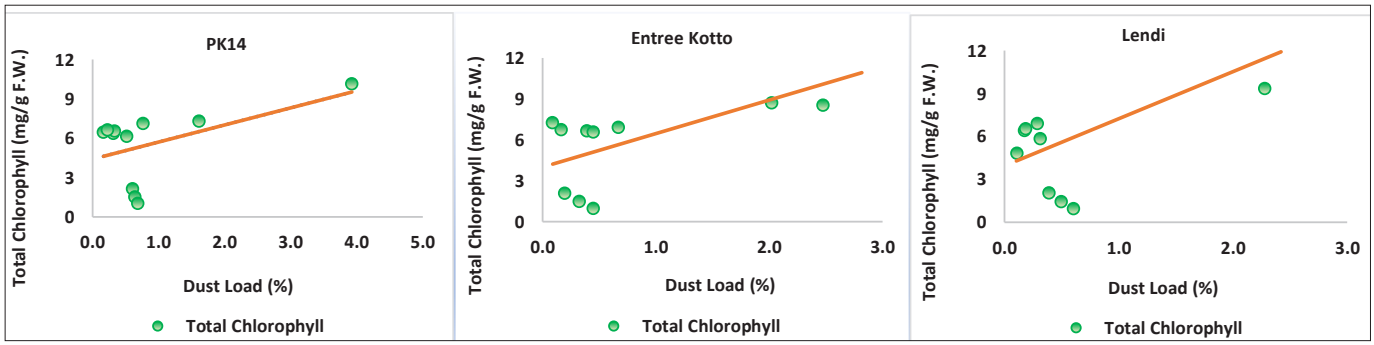


Figure 3: Correlation Between Dust Load Against Total Chlorophyll Content for the Three Sites

with increasing dust load within the observed range. A positive regression relationship was also recorded at Lendi ($R^2 = 0.589$, $F = 7.178$, $p = 0.044$), although the proportion of variation explained by the model was lower. At PK14, the scatterplot showed a positive tendency, but the Pearson correlation was not statistically significant ($r = 0.50$, $p = 0.10$).

The contrasting responses among sites suggest that the effect of dust deposition on chlorophyll was not uniform across the observed exposure range. Moderate dust deposition was associated with increased chlorophyll at Entrée Kotto and Lendi, which may indicate a compensatory physiological response to reduced light availability at the leaf surface. Such an adjustment is consistent with the possibility that plants can initially respond to moderate particulate stress through physiological acclimation. However, the absence of a significant relationship at PK14, despite its higher maximum dust load of 3.93%, suggests that this compensatory response may become less consistent under greater particulate exposure. The observed pattern therefore provides evidence for a possible threshold-dependent response, although a formal nonlinear or breakpoint model was not tested in this study.

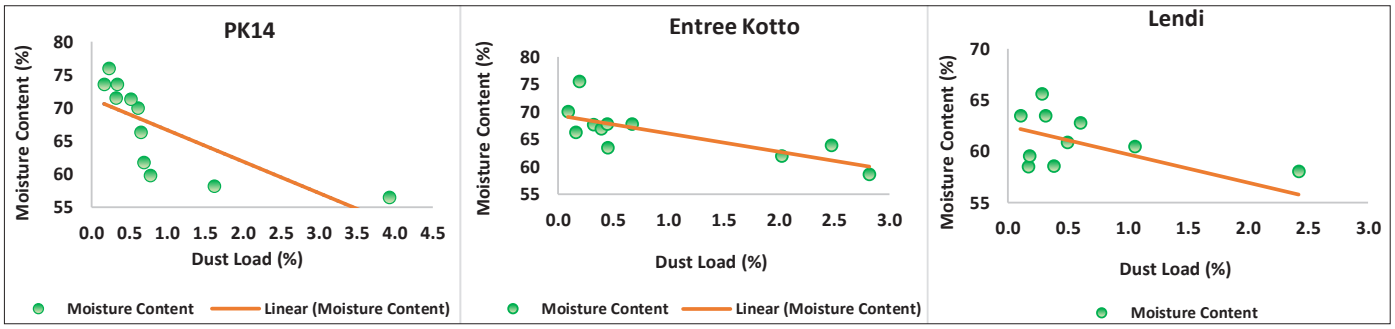


Figure 4: Correlation Between Dust Load and Relative Water Content for all Three Sites

A strong inverse relationship was observed between leaf dust load and relative water content (RWC) across the three study sites (Fig. 4). Pearson's correlation coefficients were negative at PK14 ($r = -0.74$, $p = 0.01$), Entrée Kotto ($r = -0.75$, $p = 0.01$), and Lendi ($r = -0.67$, $p = 0.03$), indicating that leaves carrying greater amounts of deposited dust generally had lower relative water content. The scatterplots therefore show a consistent decline in leaf water status as dust deposition increased.

The linear regression analysis supported this pattern. Dust load explained 61.7% of the variation in moisture content at PK14 ($R^2 = 0.617$, $F = 8.046$, $p = 0.036$), 86.5% at Entrée Kotto ($R^2 = 0.865$, $F = 31.935$, $p = 0.002$), and 65.4% at Lendi ($R^2 = 0.654$, $F = 9.430$, $p = 0.028$). The corresponding regression coefficients were negative, indicating a decline in leaf moisture content with increasing dust load. The strongest model fit occurred at Entrée Kotto, where dust load accounted for more than four-fifths of the observed variation in RWC.

The consistent negative relationships across all three sites indicate that water status was one of the clearest physiological responses associated with particulate deposition in P. guajava. Increased dust accumulation on the leaf surface may interfere with normal stomatal functioning and gas exchange, potentially contributing to reduced water regulation under particulate stress. The response was particularly evident at Entrée Kotto, although significant negative relationships were also present at PK14 and Lendi. Thus, unlike the chlorophyll response, which showed evidence of an initial positive association at some sites, RWC declined consistently as dust deposition increased.

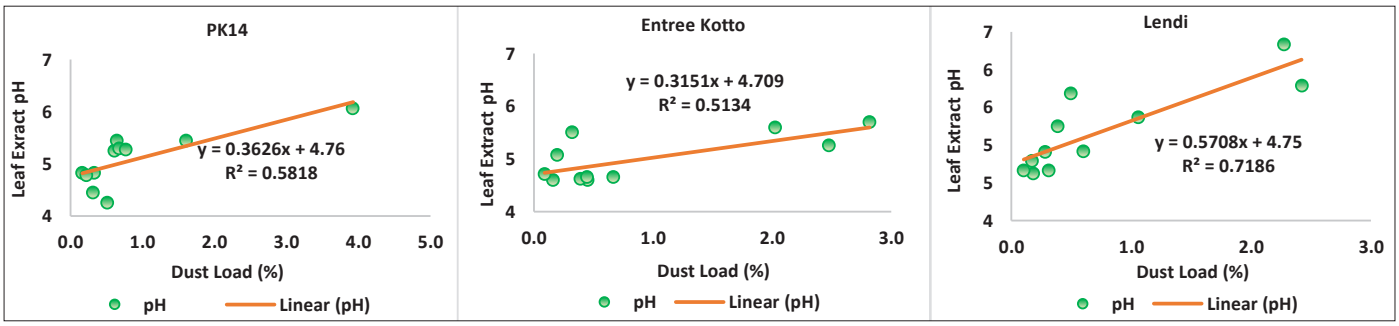


Figure 5: Correlation Between Dust Load and Leaf Extract pH for all Three Sites

Dust Load and Leaf Extract pH

Leaf extract pH showed a significant positive association with dust load at all three study sites (Fig. 5). Pearson's correlation analysis gave $r = 0.76$ ($p < 0.01$) for PK14, $r = 0.72$ ($p = 0.01$) for Entrée Kotto, and $r = 0.85$ ($p < 0.01$) for Lendi. The scatterplots therefore indicate a consistent increase in leaf extract pH with increasing dust deposition, with the strongest correlation observed at Lendi.

The linear regression analysis similarly indicated strong relationships between dust load and leaf extract pH. Dust load explained 85.6% of the variation in pH at PK14 ($R^2 = 0.856$, $F = 29.627$, $p = 0.003$), 86.2% at Entrée Kotto ($R^2 = 0.862$, $F = 31.129$, $p = 0.003$), and 90.5% at Lendi ($R^2 = 0.905$, $F = 47.408$, $p = 0.001$). These results indicate that variation in leaf extract pH was strongly associated with variation in dust deposition across all three environments.

The increase in leaf extract pH with dust load may reflect the contribution of deposited particulate material to the chemical environment of the leaf surface and tissues. The seasonal results in the thesis also showed higher pH during the dry season, when dust accumulation was generally greater. Within the context of the other physiological responses, the increase in pH may represent part of the biochemical adjustment of P. guajava to particulate stress. However, the present analysis demonstrates an association between dust load and pH rather than establishing a direct causal mechanism.

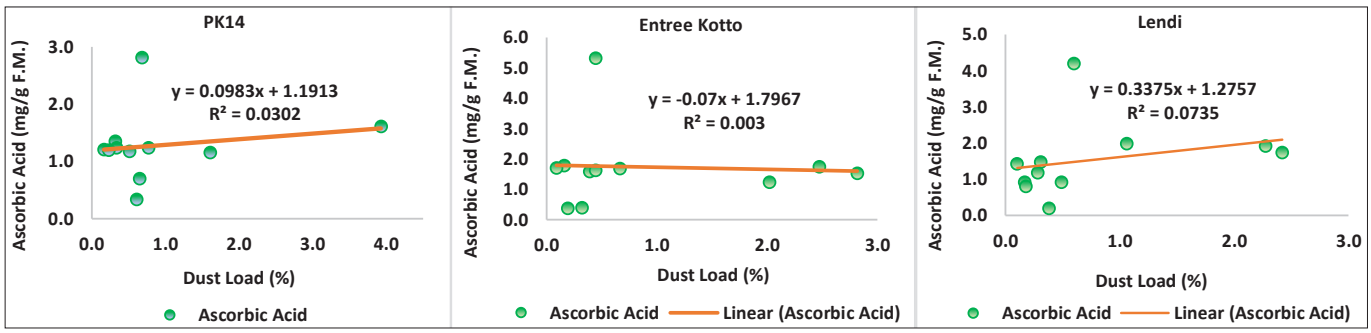


Figure 6: Correlation Between Dust Load against Ascorbic Acid for all Three Sites

Dust Load and Ascorbic Acid

In contrast to RWC and leaf extract pH, the relationship between dust load and ascorbic acid (AsA) was weak and inconsistent among the three sites (Fig. 6). Pearson's correlation coefficients were $r = 0.17$ ($p = 0.61$) at PK14, $r = -0.05$ ($p = 0.80$) at Entrée Kotto, and $r = 0.40$ ($p = 0.30$) at Lendi. None of these correlations was statistically significant, indicating that variation in dust load was not consistently associated with variation in leaf AsA concentration. The regr regression results were similarly variable. For the pooled regression summary reported in the thesis, dust load explained only 11.8% of the variation in AsA ($R^2 = 0.118$, $F = 0.668$, $p = 0.451$), with a regression coefficient of $\beta = -0.052$. Site-specific regression results showed R^2 values of 0.624 at PK14 ($F = 8.301$, $p = 0.035$), 0.118 at Entrée Kotto ($F = 0.668$, $p = 0.451$), and 0.491 at Lendi ($F = 4.815$, $p = 0.080$). The overall pattern therefore indicates that the relationship between dust deposition and AsA was less consistent than the responses observed for RWC and pH.

The weak correlation between dust load and AsA suggests that AsA concentration did not respond proportionally to the amount of particulate material deposited on the leaves. This may indicate that antioxidant responses were influenced by additional environmental or physiological factors beyond dust load alone. The seasonal increase in AsA observed during the dry period in the thesis nevertheless suggests that antioxidant metabolism may be involved in the broader response of P. guajava to environmental stress. Thus, while AsA may contribute to the plant's stress-response system, the present correlation and regression analyses do not provide sufficient evidence to attribute changes in AsA directly to increasing dust deposition.

Air Pollution Tolerance Index

APTI values ranged from **6.0 to 9.7**, placing all observed values within the **sensitive** category.

Entrée Kotto generally showed the highest and more stable values, including 9.3 in February and 9.1 in July. PK14 showed comparatively stable values ranging from approximately 7.1 to 9.0. Lendi displayed the greatest temporal fluctuation, with a minimum

of 6.0 in December and higher values later in the year, including 9.7 in September.

These patterns indicate that P. guajava did not behave as a pollution-tolerant species. Instead, its physiological responses were consistent with a sensitive species capable of measurable biochemical adjustment under changing pollution pressure.

Discussion

From Atmospheric Pollution to Biological Exposure

The atmospheric measurements demonstrate that particulate pollution in Douala is spatially heterogeneous and influenced by both local emissions and meteorological conditions. The higher estimated annual PM2.5 concentration at PK14 compared with Lendi is consistent with the greater intensity of traffic and commercial activity at PK14. Similar associations between urban activity and particulate concentrations have been reported in Douala and other African cities [24-26].

The relatively high PM2.5/PM10 ratio of approximately 0.62 further indicates that fine particles constitute an important fraction of the particulate burden. Fine particles are of particular concern because they can remain suspended for longer periods and carry chemically reactive constituents [3].

However, atmospheric concentration alone does not establish biological exposure. The foliar measurements provide the missing biological pathway by demonstrating that airborne particulate pollution was physically transferred to plant surfaces.

This distinction is important. The study therefore moves from:
Ambient PM → elemental composition → emission sources → foliar deposition → physiological response.
This integrated sequence strengthens the interpretation of plant biomarkers as indicators of environmental exposure rather than simply indicators of generic plant stress.

Source Complexity and Implications for Plant Exposure

The six-factor PMF solution demonstrates that particulate pollution in Douala is generated by a combination of traffic, industrial activities, biomass burning, secondary aerosol formation, road/crustal dust and shipping.

Such source diversity has important implications for plant responses because the biological effect of particulate deposition depends not only on mass but also on particle composition. Metals and combustion-derived components can participate in oxidative processes, while mineral particles can alter leaf-surface properties and interfere with light interception and stomatal function [2,3].

The identification of a shipping-related component also distinguishes Douala from many inland urban environments. Port-related combustion introduces an additional source of fine particulate pollution, particularly relevant given the contribution of vanadium and other combustion-associated elements.
The plant therefore experiences a chemically heterogeneous particulate mixture rather than a single uniform dust source.

Foliar Deposition was Spatially Heterogeneous but not Statistically Different Among Sites

The observed dust-load range of 0.10 - 3.93% demonstrates substantial exposure of guava foliage to deposited PM. Nevertheless, the absence of a statistically significant difference among sites is an important result.

The descriptive pattern PK14 > Entrée Kotto > Lendi at peak exposure should therefore not be interpreted as evidence that urban classification alone determines deposition. The ANOVA result, $\mathbf{F(2,30) = 0.085, p = 0.919}$, indicates considerable within-site variability.

This finding is scientifically important because deposition on vegetation is influenced by leaf traits, canopy position, particle characteristics, wind, rainfall, road proximity and local activities [6,8,29]. The results suggest that micro-environmental exposure may be more important than a simple urban–residential–suburban classification.

The seasonal pattern nevertheless supports an important climatic influence. The highest deposition occurred toward the end of the dry period, when reduced rainfall and intensified human activity favour particle accumulation and resuspension. Rainfall can remove deposited particles through wash-off, although its effectiveness depends on rainfall intensity, leaf characteristics and the timing of subsequent emissions [30].

A Threshold-Dependent Chlorophyll Response

One of the most important findings was the positive association between moderate dust exposure and chlorophyll content.

At Entrée Kotto, the regression coefficient of 1.607 ($p = 0.017$) indicates that increasing dust load within the observed moderate exposure range was associated with increased chlorophyll. A comparable positive relationship was observed at Lendi ($\beta = 1.607$, $p = 0.028$).

This finding initially appears contradictory because particulate deposition can reduce light interception and interfere with gas exchange. However, plants can respond to moderate stress through compensatory mechanisms, including adjustments in pigment concentration and photosynthetic machinery [14,31].

The result is consistent with the concept of hormesis, in which mild stress stimulates an adaptive response before stronger exposure becomes inhibitory [11,13].

Nevertheless, the present study should not claim that hormesis was mechanistically demonstrated. The data show an **observed threshold-dependent response consistent with hormetic behaviour.** The underlying molecular mechanisms were not directly measured.

The apparent threshold around 2.4% is particularly relevant. Below this range, chlorophyll responses suggest compensatory adjustment. At higher loads, particularly the 3.93% maximum at PK14, this apparent benefit was no longer maintained. Similar transitions from stimulation to inhibition have been documented in plants exposed to increasing pollutant or dust stress [10,14].

Water Status Emerged as the Dominant Physiological Constraint

In contrast to the chlorophyll response, RWC showed a remarkably consistent negative association with dust load at all three sites.

The correlation of $\mathbf{r = -0.74}$ across the study is particularly important because it indicates that increasing foliar dust was closely associated with declining leaf water status. The site-specific regression results reinforce this relationship, with dust explaining 61.7%, 86.5% and 65.4% of RWC variability at PK14, Entrée Kotto and Lendi, respectively.

Particulate deposition can alter leaf-surface conductance and physically interfere with stomatal functioning. Such changes can disrupt transpiration and gas exchange and ultimately reduce photosynthetic performance [32-34].

The strength and consistency of the RWC response suggest that hydration status may provide a more reliable early-warning indicator of sustained dust stress than chlorophyll alone.

This finding also changes the interpretation of the apparent chlorophyll stimulation. An increase in chlorophyll under moderate exposure should not be interpreted as evidence that the plant is unaffected. The simultaneous decline in RWC demonstrates that physiological stress was already developing even while chlorophyll was being maintained or increased.

Leaf pH Indicates Biochemical Adjustment

Leaf extract pH increased significantly with dust load across all sites. The strongest relationship was observed at Lendi ($r = 0.85$, $p < 0.01$), followed by PK14 and Entrée Kotto.

The pH response may reflect chemical interactions between deposited particles and leaf surfaces as well as physiological adjustment within the plant. Previous work has identified changes in leaf pH as a useful component of pollution-response assessment [19,21].

Because pH is incorporated into APTI, its response also contributes to the integrated assessment of plant sensitivity.

Ascorbic Acid Provided Weaker Evidence of Compensation

Unlike RWC and pH, AsA did not show a consistent relationship with dust load. This is important because AsA is commonly considered an important antioxidant component of plant defence against oxidative stress [16,17,35].

The weak and inconsistent correlations observed here suggest that the AsA response of P. guajava was influenced by factors other than dust load alone. Nutrient status, seasonal physiology, microclimate and the chemical composition of deposited particles may all contribute to antioxidant regulation.

Thus, the absence of a strong AsA–dust relationship should not be interpreted as absence of oxidative stress. Rather, it indicates that AsA alone did not provide a sufficiently consistent measure of particulate stress in this system.

APTI identifies P. Guajava as a Sensitive Bioindicator

The APTI results provide an important synthesis of the individual biomarkers.

All values fell within the sensitive category, with a range of 6.0–9.7. This is consistent with the physiological evidence showing that P. guajava responds measurably to particulate exposure rather than maintaining a stable high-tolerance phenotype.

The relatively higher and more stable APTI at Entrée Kotto should therefore not be interpreted as evidence that the species is pollution-tolerant. Rather, it indicates that the plants at this site maintained a comparatively better physiological balance during the monitoring period.

PK14 displayed comparatively stable but lower APTI values, consistent with persistent exposure associated with traffic and urban activity. Lendi showed greater temporal fluctuations, suggesting a less stable physiological response under changing pollution pressure. This distinction is important for urban greening. A plant that is sensitive may be highly useful for **biomonitoring**, but it may be a poor candidate for use as a pollution sink in heavily polluted locations. APTI should therefore be interpreted alongside plant performance rather than as a simple measure of survival alone [20,23].

One Health Significance

The central contribution of this study is to demonstrate that particulate pollution in a rapidly urbanizing African city can be traced across interconnected environmental and biological compartments.

The pathway identified here is:

Urban Activities → atmospheric PM → chemical mixture → foliar deposition → plant physiological stress → potential productivity consequences → implications for urban food systems and human wellbeing.

This pathway fits naturally within the One Health framework, which recognizes the interdependence of human, animal, plant and ecosystem health and calls for integrated approaches to environmental threats such as air pollution.

The implications are particularly important for urban agriculture. P. guajava is not simply ornamental vegetation; fruit production contributes to household nutrition, livelihoods and urban food systems. Consequently, chronic particulate exposure may have consequences extending beyond individual plant physiology to food-production stability.

Vegetation also provides an environmental service by intercepting particulate matter. However, the present results illustrate an important trade-off: the same vegetation that removes particles from the atmosphere is itself exposed to those particles. Vegetation-based air-quality interventions therefore need to consider species sensitivity, pollutant intensity and long-term plant performance rather than assuming that all urban vegetation provides equivalent mitigation.

This supports a more integrated approach to urban greening in which air-quality management, biodiversity, urban agriculture, environmental health and public health are considered together.

Implications for Climate-Resilient Urban Planning

The findings support three practical directions.

First, **pollution monitoring should include biological indicators**. Conventional PM monitoring remains essential, but plant biomarkers can provide relatively inexpensive information on biological exposure where continuous monitoring infrastructure is limited.

Second, **urban vegetation should be selected according to pollution context.** Sensitive species such as P. guajava can be valuable for biomonitoring, whereas heavily polluted corridors may require species demonstrating greater tolerance and particulate-retention capacity [20,36].

Third, **urban planning should address pollution at source**. The PMF results indicate that traffic, industry, biomass burning, road dust, secondary aerosols and shipping all contribute to particulate pollution. Vegetation alone cannot compensate for uncontrolled emissions. Effective management therefore requires source control combined with appropriately designed green infrastructure [].

Conclusions

This study demonstrates that particulate pollution in Douala extends beyond atmospheric concentrations to measurable biological exposure and physiological responses in Psidium guajava.

Ambient PM2.5 and PM10 concentrations showed substantial spatial and temporal variability, while elemental characterization and PMF demonstrated that pollution originated from a combination of traffic, industrial activity, biomass burning, secondary aerosol formation, road/crustal dust and shipping.

Foliar dust deposition ranged from 0.10 to 3.93%, although differences among sites were not statistically significant. The physiological responses were more informative than the site-level dust comparison. Moderate dust exposure was associated with increased chlorophyll at Entrée Kotto and Lendi, suggesting an adaptive response consistent with hormetic behaviour. However, this apparent compensation occurred alongside a strong and consistent decline in RWC with increasing dust load.

The results therefore indicate a transition from **compensation under moderate stress to physiological constraint under higher exposure**. The strongest evidence of this transition was provided by the RWC response, while the inconsistent AsA response suggests that antioxidant adjustment alone was insufficient to buffer prolonged particulate stress.

APTI values of 6.0–9.7 classified P. guajava as pollution-sensitive throughout the study. The species should consequently be viewed primarily as a useful **bioindicator of particulate pollution rather than a pollution-tolerant urban greening species.**

From a One Health perspective, the findings demonstrate how atmospheric pollution can move across the environment–plant–food-system interface. Protecting urban air quality is therefore simultaneously an environmental, ecological, agricultural and human wellbeing priority. Integrating plant-based biomonitoring with conventional air-quality monitoring and source-oriented pollution control could provide a practical strategy for strengthening environmental surveillance in rapidly growing African cities.

Statements and Declarations

Authors' Contributions: Credit

Aguh Akeh Nug: Conceptualization, Methodology, Investigation, Formal analysis, Writing - Original draft, Writing - Review & Editing.

Johan Boman: Methodology, Resources, Supervision, Data curation, Writing - Review & Editing, Validation.

Tening Aaron: Supervision, Investigation, Writing - Review & Editing, Resources

Ngwabie Martin: Supervision, Writing - Review & Editing, Resources

Data Availability: The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Ethics Approval: not applicable.

Funding: the author(s) received no financial support for the research. the study is part of an ongoing phd research program of the first author at the department of agricultural and environmental engineering in the college of technology, university of bamenda, cameroon.

Declaration of Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Diversity and Inclusion Statement

Our research team is committed to fostering an inclusive and diverse environment that values and respects the unique perspectives and contributions of all individuals. We believe that diversity in backgrounds, experiences, and ideas enhances the quality and impact of our research.

We recognize the importance of diverse viewpoints in addressing complex environmental challenges and are committed to integrating these perspectives into our research on air pollution and public health. By embracing diversity and inclusion, we aim to advance scientific knowledge and promote sustainable solutions that benefit all communities.

Citation Diversity Statement

In conducting this research, we are committed to promoting diversity and inclusion through our citation practices. We strive to acknowledge and include a broad spectrum of voices and perspectives, particularly those from underrepresented groups in environmental science and public health.

We recognize that diverse citations enhance the richness and depth of our work, and we actively seek to include contributions from researchers of various backgrounds, genders, ethnicities, and career stages. By doing so, we aim to foster a more inclusive and equitable academic environment.

Our citation practices reflect our dedication to valuing all contributions and ensuring that our research is informed by a wide array of viewpoints. We believe that this approach not only strengthens our work but also supports the broader goal of advancing diversity and inclusion within the scientific community.

Competing Interests: The authors declare no competing interests.

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