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Elemental and carbonaceous composition of PM_{10} and its oxidative potential in schools in Luanda

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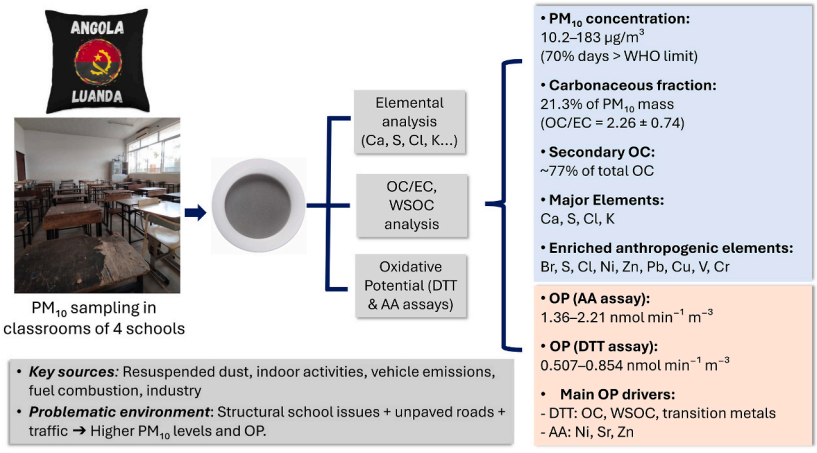
HIGHLIGHTS

- PM_{10} levels in Luanda schools often exceeded WHO guidelines, especially on weekdays.
- Carbonaceous material made up 21.3 % of PM_{10}, with a high OC/EC ratio of 2.26 ± 0.74.
- Mineral dust, traffic, and industrial activities were key sources of elemental PM_{10}.
- Oxidative potential of PM_{10} was driven by OC, WSOC, and transition metals.
- Structural upgrades and dust control are needed to improve school air quality.

GRAPHICAL ABSTRACT



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ABSTRACT

Chemical speciation and oxidative potential (OP) analysis of airborne particles in African schools has not been previously conducted. In this study, daily atmospheric particulate matter (PM_{10}) sampling was carried out in classrooms of four primary schools in Luanda, Angola. Samples were analysed for elemental composition, organic and elemental carbon (OC and EC) and water-soluble organic carbon (WSOC). OP was measured using two acellular assays: dithiothreitol (DTT) and ascorbic acid (AA). PM_{10} concentrations ranged from 10.2 to 183 µg m^{-3}, exceeding the WHO guideline on ~70 % of days, with weekday averages (61.0 µg m^{-3}) more than twice those recorded on Saturdays (26.2 µg m^{-3}). Carbonaceous constituents accounted for 21.3 % of PM_{10} mass, with a consistent OC/EC ratio of 2.26 ± 0.74. On average, 77 % of OC was estimated to be secondary, while WSOC/OC ratios ranged from 0.15 to 0.90, averaging 0.42 ± 0.18. The most abundant elements were Ca, S, Cl, and K,

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with the highest concentrations observed in a school affected by structural issues and proximity to an unpaved road. Enrichment factor analysis revealed extremely high anthropogenic contributions for Br, S, Cl, Ni, Zn, Pb, Cu, V, and Cr, while correlations between elements indicated major sources such as resuspended mineral dust, vehicular emissions, fuel combustion, and industrial activities, with additional contributions from road dust, construction sites, and sea spray. Average OP^{AA} values ranged from 1.36 to 2.21 nmol min^{-1} m^{-3}, while OP^{DTT} values spanned from 0.507 to 0.854 nmol min^{-1} m^{-3}. OC, WSOC, and several transition metals were key contributors to OP^{DTT}, whereas OP^{AA} showed significant correlations only with Ni and Sr.

1. Introduction

Particulate matter with an equivalent aerodynamic diameter of 10 μm or less (PM_{10}) is a significant environmental pollutant with adverse effects on human health, principally in urban settings (Broomandi et al., 2023; Madaniyazi et al., 2024; Maji et al., 2017; Yorifuji et al., 2015). PM_{10} varies in composition depending on both outdoor and indoor sources and understanding its elemental and carbonaceous makeup is crucial for assessing health risks. The elemental composition of outdoor PM_{10} can reveal the presence of non-metals, metals or metalloids such as silicon (from soil dust), copper and zinc (from brake and tyre wear), sulphur (from combustion sources), and various trace constituents, whose presence or relationship with other chemical species may indicate specific sources (Lin et al., 2015; Maring et al., 2023). Carbonaceous components include organic carbon (OC) from vehicle emissions and biomass burning, and elemental carbon (EC) from diesel engines and industrial combustion. Indoor PM_{10}, while also influenced by outdoor air quality, has unique sources such as smoking, cleaning activities, food preparation, building materials, printers and copiers, among others (Kumar et al., 2023; Sadrizadeh et al., 2022; Zhang et al., 2021). The health risks associated with PM_{10} are largely determined by its composition, as metals and carbonaceous particles can irritate the respiratory system, contribute to cardiovascular diseases, and increase the risk of cancer (Hwang et al., 2017; Lamas et al., 2023; Shrivastav et al., 2024). Furthermore, the interaction between indoor and outdoor PM_{10} can exacerbate exposure, especially in poorly ventilated spaces, making it essential to monitor and control this pollutant to reduce its impact on public health (Kumar et al., 2023; Tran et al., 2020).

The oxidative potential (OP) of airborne PM is increasingly recognised as a key health-relevant metric, reflecting the ability of this pollutant to induce oxidative stress and contribute to adverse health effects. The OP of PM depends on its chemical composition, with transition metals and organic compounds playing a crucial role in enhancing the potential for harmful reactions in the body (Bates et al., 2019). Different extracellular assays have been developed to quantify the OP of PM, each relying on distinct mechanisms and thereby exhibiting varying sensitivities to PM components. The dithiothreitol (DTT) assay is widely used as it measures the redox activity of organic compounds and transition metals through electron transfer to oxygen, producing reactive oxygen species (ROS). The ascorbic acid (AA) assay, in contrast, primarily reflects the catalytic activity of transition metals that deplete antioxidants in the respiratory tract lining fluid. Electron paramagnetic resonance (EPR) provides direct detection of radical formation, offering high specificity but requiring more complex instrumentation. Since these assays differ in their response to various PM components, comparisons across studies must be interpreted with caution (Bates et al., 2019; Shahpoury et al., 2022). Although the OP of outdoor PM has been investigated in different regions around the world (e.g., Farahani et al., 2022), comprehensive studies on indoor OP are lacking (Yang et al., 2021). Given that individuals spend a significant portion of their time in confined spaces, understanding the OP of indoor PM is crucial for assessing potential health risks, particularly given the diversity of sources.

Over 95 % of schools across Africa are situated in regions where air pollution levels vastly exceed the air quality guidelines set by the World Health Organisation (Fisher et al., 2021). In rapidly urbanising cities like Luanda, Angola, air quality has become a growing concern, especially in school environments where children - vulnerable populations - are exposed to airborne pollutants for extended periods (Alves et al., 2025). Among air pollutants in African schools, PM_{10} is particularly worrying (Kalisa et al., 2023a). Studies have shown that exposure to atmospheric particles in educational facilities can contribute to attention-deficit/hyperactivity disorders (ADHD) and absenteeism, exacerbate pre-existing conditions such as asthma and rhinitis, and increase the prevalence of other respiratory diseases (Annesi-Maesano et al., 2012; Arikan and Tekin, 2023; Donzelli et al., 2019; Marcon et al., 2014; Were et al., 2020; Zhang et al., 2022). While numerous studies have examined PM in school environments in developed countries (e.g., Baloch et al., 2020), the air quality in educational institutions across Africa remains largely overlooked. The few studies with PM measurements in schools across the African continent (deSouza et al., 2017; Ite et al., 2019; Kalisa et al., 2023b; Khadidja et al., 2019; Were et al., 2020), have focused solely on obtaining the concentrations of this pollutant, but none of them conducted a chemical characterisation or assessed its OP.

This study aims to characterise the elemental and carbonaceous composition of PM_{10} in various schools in Luanda, focusing on its OP and the implications for public health. By analysing the elemental and carbonaceous composition, it is intended to provide a comprehensive understanding of the pollution profile in these environments and underscore the need for effective air quality management in urban schools within a country lacking air quality monitoring and legislation.

2. Methodologies

2.1. Sampling

Sampling was performed at four primary schools in Luanda from September 11 to November 4, 2023: School 1138 at Largo das Escolas (−8.831° S, 13.241° W), School 1603 in the Neves Bendinha neighbourhood (−8.839° S, 13.259° W), School 1116 in the Cassenda neighbourhood (−8.846° S, 13.229° W), and School 1207 (formerly School 8) in Ingombota (−8.813° S, 13.242° W). The features of each school are displayed in Table S1 (Supplementary Material). The selection of schools was performed in close collaboration with the Angolan Ministry of Education. In addition to representativeness, one of the criteria considered was ensuring safety conditions and the availability of electricity. In each school, gravimetric samplers were installed in two classrooms, over one week in each one, from Monday to Saturday. Sampling was carried out for 24-h periods, starting between 7:30 and 8:00, with a low-volume equipment (2.3 m^3 h^{-1}) from TECORA (model Echo PM), equipped with quartz fibre filters of 47 mm in diameter (Pallflex®) and a PM_{10} size selective inlet.

Although an outdoor PM_{10} sampler was deployed to assess contributions from outdoor sources, technical issues during the campaign - specifically a malfunction in flow control - rendered the outdoor measurements unreliable. As a result, the outdoor filter data were excluded from the analysis. Consequently, quantitative assessment of indoor versus outdoor contributions, such as indoor/outdoor (I/O) ratios or source apportionment using statistical models, was not possible. This limitation is acknowledged and should be considered when interpreting the findings.

2.2. Analytical determinations

The quartz fibre filters were calcined in a muffle furnace at 500 °C for 6 h to eliminate potential organic contaminants. The filters were weighted before and after sampling on an analytical balance with an accuracy of 1 μg (Radwag 5/2Y/F) after conditioning in a room at 20 °C and 50 % relative humidity for 48 h.

Elemental analysis was carried out by Energy Dispersive X-Ray Fluorescence (ED-XRF) using an ARL Quant'x Spectrometer (Thermo Fisher Scientific, UK) with a Si(Li) detector. A thorough description of this analysis can be found in Chiari et al. (2018). Following the elemental determination, the same filters were ultrasonically extracted with ultrapure water for the quantification of water-soluble organic carbon (WSOC) in a TOC-L CSH analyser (Shimadzu), which employs a 680 °C combustion catalytic oxidation method. WSOC was determined as non-purgeable organic carbon (NPOC). To quantify NPOC, an aliquot of the water extract was diluted 1:2 with ultrapure water, acidified with 1 M HCl (PanReac AppliChem) and purged with pure air to eliminate dissolved inorganic carbon and volatile organics. The analyses were performed in triplicate and average WSOC levels were obtained. A standard solution of potassium hydrogen phthalate (PanReac AppliChem) was used for calibration. Blanks were also included in the analytical runs. All samples presented concentrations above the method detection limit.

A thermo-optical transmission technique was employed to quantify the carbonaceous content of the PM_{10} samples. This method differentiates OC from EC by progressively heating small circular sections of a filter in an inert nitrogen environment (100 %) to vaporise the OC. Following this, oxidation occurs in a controlled atmosphere with 4 % oxygen and 96 % nitrogen to measure EC. Both OC and EC are quantified as CO_2 using a non-dispersive infrared analyser (NDIR, Licor LI-7000). The temperature program followed the EUSAAR-2 protocol, and all analyses were performed in duplicate. Additional details on the analytical procedure are described in Pio et al. (2011).

2.3. Oxidative potential

Pieces of each PM_{10} filter were extracted with 12 mL of Milli-Q ultrapure water for 30 min in an ultrasonic bath. The extracts were filtered through 0.2 μm pore size PVDF syringe filters from Whatman™ to remove insoluble material and then used to determine the OP using the DTT and AA assays. For the DTT assay, 3 aliquots of 0.45 mL of the extracts were incubated at 37 °C with 90 μL of 0.1 M potassium phosphate buffer (pH 7.4) and 60 μL of 1 mM DTT. After 15, 30, and 45 min in a 222DS benchtop shaking incubator from Labnet, 0.5 mL of trichloroacetic acid (10 % w/v) were added to each aliquot to stop the reaction. Subsequently, 2 mL of Tris–EDTA (0.4 M Tris with 20 mM EDTA) and 50 μL of 10 mM 5,5′-dithiobis-2-nitrobenzoic acid (DTNB) were added, and the absorbance of the solution was measured at 412 nm in a UV–Vis spectrometer (SPECORD 50 PLUS). For the AA assay, aliquots of 1.5 mL of the PM_{10} extracts were incubated with 1.35 mL of 0.1 M potassium phosphate buffer (pH 7.4) and 150 μL of 2 mM AA at 37 °C. After adding ascorbic acid, the absorption at 265 nm was recorded at specific time intervals (15, 30 and 45 min) to determine the AA depletion rate. Blank filters were analysed using the same procedures as those applied to PM_{10} samples. The oxidative potential (OP^{DTT} and OP^{AA}) was expressed as the DTT or AA consumption rate per sampled volume or mass of PM_{10} (nmol min^{-1} m^{-3} or nmol min^{-1} μg^{-1}, respectively).

3. Results and discussion

3.1. PM_{10} concentrations and carbonaceous constituents

PM_{10} concentrations in Luanda schools ranged from 10.2 to 183 μg m^{-3}, exceeding the WHO guideline of 45 μg m^{-3} on approximately 70 % of the days. The highest values were recorded at School 1603, which, in addition to having structural problems (cracked walls, peeling paint), is surrounded by unpaved roads. The lowest values were recorded at school 1207, whose access road is paved and has the lowest occupancy rate. The minimum concentrations were observed in this school on two days when, due to meetings between some teachers and the school administration, the students were relocated to another room, leaving the space unoccupied. The global average for weekdays with occupancy (61.0 μg m^{-3}) was more than twice that recorded in the absence of students on Saturdays (26.2 μg m^{-3}). PM_{10} levels surpassing the WHO guideline have also been reported for schools in Brazzaville, Republic of Congo (Nsompi et al., 2023), Nairobi, Kenya (deSouza et al., 2017), Durban, South Africa (Reddy et al., 2012), and Akwa Ibom State, Nigeria (Ite et al., 2019).

It should be noted that meteorological factors such as wind speed, temperature, and humidity, which can significantly influence PM dispersion and secondary formation, were not directly analysed in the present study. However, this work is part of a broader research project, and a companion manuscript (Silva et al., 2025) specifically investigates the relationship between ambient PM concentrations and meteorological parameters using a co-located meteorological station and low-cost air quality monitoring systems. The results of that study provide detailed insights into the influence of local meteorology on PM_{10} and $PM_{2.5}$ levels in Luanda, and are complementary to the findings presented here.

Globally, for the four schools, total carbon (TC = EC + OC) accounted for 21.3 % of the PM_{10} mass (Fig. 1). This carbonaceous content is lower than that reported for primary schools in the Portuguese cities of Aveiro (31.9 %, Alves et al., 2014a) and Lisbon (36.8 %, Faria et al., 2020), and in São Paulo, Brazil (32.0 %, Pereira et al., 2019), suggesting that particulate matter in Luanda is more enriched in mineral matter and other inorganic constituents. The ratio between OC and EC was relatively constant across the various samples, with a value of 2.26 ± 0.74. The lowest values (average = 1.63) were obtained in school 1138. The strong correlation between OC and EC ($r = 0.995$) observed in this establishment suggests a common source (Hama et al., 2022), most likely infiltration of emissions from vehicular traffic, given its close proximity to one of Luanda's busiest thoroughfares, Ho Chi Minh Avenue. The OC/EC ratio is often used to help identify the sources of carbonaceous particles in the atmosphere. A higher OC/EC ratio typically suggests a stronger influence of organic sources, such as biomass burning, cooking emissions, bioaerosols or secondary organic aerosol formation, while a lower ratio indicates a dominance of primary combustion sources, like vehicle emissions. Pio et al. (2011) compiled extensive measurement databases from various locations across Europe, concluding that a ratio between 0.3 and 0.4 is representative of emissions from combustion vehicles. Highly variable ratios up to 61.8, dependent on equipment and biofuels, have been reported for residential biomass combustion (Vicente and Alves, 2018). Even higher ratios, on the order of tens or hundreds, have been observed in particles emitted from the chimneys of various types of restaurants (Alves et al., 2014b).

To distinguish primary organic carbon (POC), which is directly emitted, from secondary organic carbon (SOC), which forms through photochemical reactions involving gaseous precursors or by condensation of semi-volatile gases on pre-existing particles, the EC tracer method was applied (Yoo et al., 2022, and references therein):

$$POC = (OC/EC)_{pri} \times EC + OC_{non-comb} \quad (1)$$

$$SOC = OC_{total} - (OC/EC)_{pri} \times EC \quad (2)$$

where $OC_{non\text{-}comb}$ stands for the OC released from non-combustion emission sources. To estimate $(OC/EC)_{pri}$, regression analysis was performed, deriving the linear equation between OC and EC from the lowest 20 % OC/EC values recorded during the measurement period ($OC = 0.45 \times EC + 0.06$, $r^2 = 0.91$). Using an $(OC/EC)_{min}$ value of 0.45 (regression slope), it was estimated that, on average, a significant

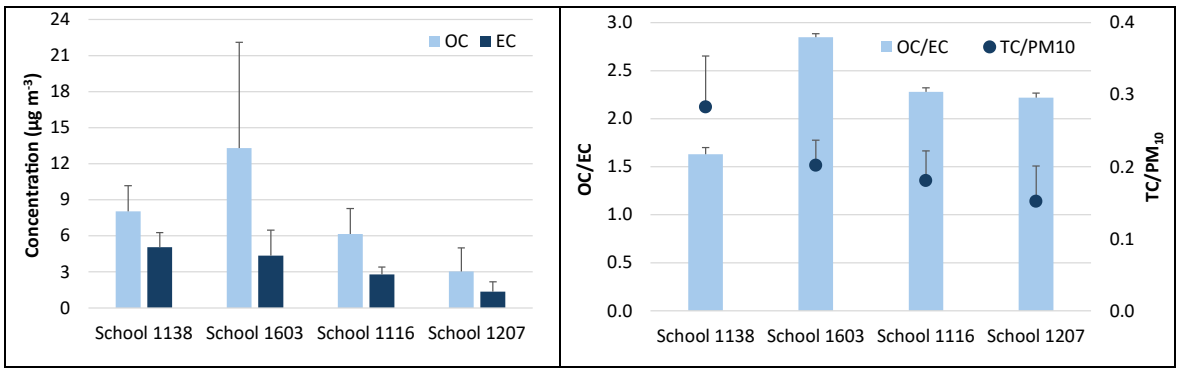

Fig. 1. Organic and elemental carbon (OC and EC) concentrations, and OC-to-EC and total carbon (TC = OC + EC)-to-PM_{10} ratios.

fraction (77 %) of OC in Luanda's primary schools is secondary, while only a minor portion (23 %) is primary. Wang et al. (2021) estimated that SOC concentrations in a dormitory at Nankai University, China, accounted for 53.5 % of OC. The high secondary contribution to OC was attributed to volatile organic compounds (VOCs) from specific sources, whose emissions are enhanced at indoor temperatures typically above 20 °C. The high SOC percentage in the present study seems to contradict the small peaks of the more volatile organic carbon fraction that evolve at the lowest temperature in the EUSAAR2 protocol (OC1). However, SOC can include a lot of oxidised, less volatile compounds, especially indoors, where ageing is slower, but still present. These oxidised species often desorb at higher temperatures in a thermo-optical analysis, not necessarily as OC1. In indoor environments (e.g., classrooms), sources such as cleaning products, human emissions, furniture, and plastics emit continuously VOCs that generate low-volatility or semi-volatile products. These condense to form SOC that thermally evolves at higher temperatures. Furthermore, the indoor surface interfaces provide reaction and storage spaces for VOCs and semi-volatile VOCs (SVOCs), as demonstrated by diverse cleaning and controlled open-close window experiments (You et al., 2022). VOC and SVOC sorption on indoor surfaces increase their residence time indoors, and facilitate the heterogeneous reactions of polar compounds under high relative humidity conditions, such as those recorded in the classrooms of Luanda's schools (Alves et al., 2025).

WSOC/OC ratios ranged from 0.15 to 0.90, averaging 0.39 ± 0.17. Regardless of the school, the highest ratios were consistently observed on Saturdays, when no classes were held. During weekdays, activities inside and around schools (such as human presence, movement, cleaning, and traffic during drop-off/pick-up) increase primary OC emissions, especially hydrophobic fractions (e.g., from combustion or resuspension of particles). On Saturdays, these human-related emissions are minimised, leading to a relative increase in the WSOC fraction, which is more associated with more water-soluble aged particles. The WSOC/OC ratio can be used as an indicator of emission sources and atmospheric processing of organic aerosols. Low WSOC/OC (<0.3–0.5) have been associated with primary emissions such as traffic, biomass burning (fresh emissions), and cooking aerosols (Kawichai et al., 2024; Li et al., 2015; Saarikoski et al., 2008). High WSOC/OC (>0.5–0.8) indicates secondary organic aerosol (SOA) formation via photochemical ageing or oxidation (Bhowmik et al., 2021). Biomass burning emissions can also produce high WSOC fractions after atmospheric aging (Ramya et al., 2023).

Recent studies have begun to explore the characteristics of WSOC, sources, and effects within indoor environments. Webb et al. (2025) examined the dynamics of gas-phase and particle-phase WSOC in a residential setting. The research found that indoor gas-phase WSOC concentrations were substantially higher than outdoor levels, with ethanol identified as a major contributor. The study also highlighted those activities such as surface cleaning and the introduction of VOCs significantly elevated WSOC concentrations indoors. In a review article, Duarte and Duarte (2021) emphasised the limited understanding of indoor WSOC compared to outdoor scenarios. The authors discussed the origins, mass contributions, and health effects of WSOC in indoor air particles, underscoring the challenges in chemical characterisation and the need for further research to elucidate its role in indoor air quality. These studies collectively suggest that indoor WSOC originates from various sources, including human activities and chemical reactions within indoor environments. Given its potential health implications, there is a pressing need for more targeted research to fully understand the sources, transformations, and effects of WSOC in indoor air.

Although teachers were asked to complete activity logs and occupancy diaries during the sampling campaign, the records were not carried out systematically and contained several omissions and inconsistencies, which precluded their use in the analysis. This represents a limitation of the study, as direct evidence linking specific indoor activities to WSOC levels was not available. Nevertheless, our interpretation is supported by previous research identifying cleaning products, human emissions, furniture, and plastics as important indoor sources of VOCs and semi-volatile compounds that contribute to WSOC formation (Webb et al., 2025; You et al., 2022). Future studies should integrate PM chemical analysis with VOC monitoring and systematic activity logging to better characterise WSOC sources in classroom environments.

3.2. PM_{10}-bound elements

The most abundant elements were Ca, S, Cl, and K (Fig. 2). As observed for PM_{10}, the highest levels were recorded at school 1603 (Table S2), which has structural issues, degraded furniture, and is located next to an unpaved street. Ratios greater than one between days with and without classes for most of the elements indicate that daily activities contribute to the emission of these chemical constituents. Pb and Ni constitute an exception, with ratios close to 1, suggesting that the measured concentrations are not significantly influenced by activities in the classrooms.

The enrichment factor (EF) is a commonly used metric for evaluating how much the presence of an element in a sampling medium has increased relative to its average natural abundance due to anthropogenic activities. It is the ratio between the concentration of the chemical species (X) and that of a reference element (R), both for the sample and for the upper continental crust ($EF = (X/R)_{sample}/(X/R)_{UCC}$). In this study, Fe was adopted as the reference element, and the composition of the crust was obtained from Wedepohl (1995). Six categories of contamination based on the EF are recognised (Boga et al., 2021): <1 indicates background concentration, 1–2 signifies depletion to minimal enrichment, 2–5 denotes moderate enrichment, 5–20 represents significant enrichment, 20–40 indicates very high enrichment, and >40 signifies extremely high enrichment. In the present study, Br, S, Cl, Ni, Zn, Pb, Cu, V, and Cr showed extremely high enrichments, emphasising their anthropogenic origin (Fig. S1). On the opposite extreme, K was

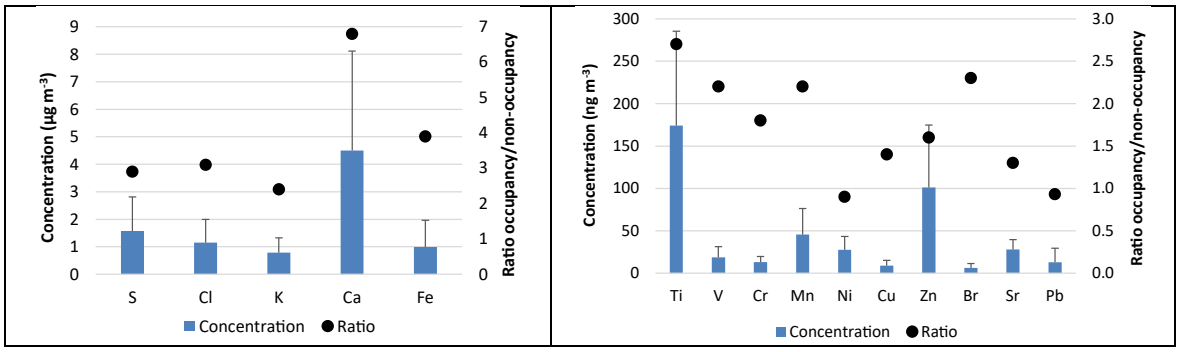

Fig. 2. Concentrations of PM_{10}-bound elements and ratios between days with and without classes in primary school classrooms in Luanda.

detected at levels like that of the Earth's crust (EF = 1), without any additional human-made influence. Moderate enrichments were found for Ti, Mn, Sr and Ca.

A very strong correlation between V and Mn (r = 0.98) suggests a common or closely related source, as both elements are emitted during the combustion of diesel and fuel oil, particularly from ships and older vehicles (Coufalík et al., 2019). Mn is also used as an additive in some gasoline formulations, such as MMT (methylcyclopentadienyl manganese tricarbonyl), explaining its presence in traffic-related emissions (Oudijk, 2010). A notable correlation was found between Mn and Fe (r = 0.93), as both are abundant in mineral dust, which can resuspend indoors due to student activity, cleaning, or ventilation. These elements may also originate from road dust contaminated by vehicle emissions, brake and tyre wear, and industrial sources like steel production, welding, or cement plants. They can enter indoor environments via foot traffic or infiltrated air. While some chalk and classroom materials may contain minor levels of Fe and Mn (Maruthi et al., 2017), this is typically a lesser source unless specific materials are particularly rich in these metals. Additionally, the corrosion of metallic structures like window frames, desks, and pipes may contribute to indoor Fe and Mn levels (Dwivedi et al., 2017; Frenck et al., 2021). Trace amounts of Mn and Fe in some fuels can also be emitted and transported indoors (Coufalík et al., 2019). Interestingly, K and V were strongly correlated, as were other elements typically associated with mineral dust, such as Ca (r = 0.95), Ti (r = 0.94), Fe (r = 0.94), and Mn (r = 0.90). The excellent correlations between these elements suggest that resuspended soil and mineral dust are the dominant sources. However, the elevated EF of V implies that anthropogenic pollutants may be associated with - or adsorbed onto - soil particles. Ti, commonly present in clay minerals and oxides, further supports the association with soil and mineral dust. Likewise, Fe and Mn are abundant in geological materials, particularly in silicates and oxides, reinforcing the crustal origin of these elements. In the Angolan capital, two dominant geological formations are present: the "Luanda" and the "red sands". The geochemistry of street dust from the "Luanda" formation exhibits complex lithological variations, encompassing ferruginous sands with coarse quartz grains, fine sand coated with clay, diverse types of marl, shell limestone, and grey-greenish clays. Street dust from the "red sands" formation mainly includes fine to medium-sized quartz grains, minor amounts of kaolinite and illite, and relatively elevated concentrations of hematite and goethite, which coat the quartz grains and occasionally form ferruginous nodules (Ferreira-Baptista and De Miguel, 2005). Disturbances from student activity, cleaning, and foot traffic can resuspend dust that can partially mimic the composition of these geological formations, increasing PM_{10} levels indoors. Deteriorating walls, floors, and chalk can also contribute. Road dust, especially from brake wear, road abrasion, and particle resuspension, can enrich Ca and Fe levels (Casotti Rienda and Alves, 2021). Mn and V are linked to fuel additives, brake wear, and oil combustion. Cement plants, metallurgical industries, and nearby construction activities can also contribute to indoor Ca, Fe, Mn, and V in PM_{10} (Calvo et al., 2013). Luanda's coastal location may contribute additional calcium (Ca) from sea spray aerosol. However, mineral dust and anthropogenic sources (e.g., cement industry) are likely the primary contributors.

The strong correlations between Ti and V (r = 0.95), Cr (r = 0.87), Fe (r = 0.93), and Mn (r = 0.92) further suggest shared sources or similar atmospheric behaviours. These elements are often associated with industrial emissions, vehicular exhaust, and combustion processes (Calvo et al., 2013). They attach to PM_{10} particles, which can remain airborne and infiltrate indoor environments. Luanda is surrounded by an industrial belt, which, among other activities, includes an oil refinery, a cement plant, and a smelter. Together with urban dust from construction sites or roads (Vanegas et al., 2021), these industrial activities can contribute to Ti, Cr, Fe and Mn. Fe, Cr and Mn are also linked to brake and tyre wear (Grigoratos and Martini, 2014) and Ti is found in vehicle coatings and brake components (Schauerte, 2003). V is a known marker of heavy fuel oil combustion, which may be tied to diesel vehicle emissions (Shafer et al., 2012). In Luanda, both ship and vehicle traffic can contribute to V emissions. The Port of Luanda is responsible for handling about 80 % of Angola's exports and imports. It is situated along the coastline, directly adjacent to the Luanda downtown area, and has 2738 m of docking quay, divided into seven terminals, and a logistics platform supporting the oil industry (PPIAF and WBG, 2005). As of early 2015, Luanda had approximately 1.75 million registered vehicles, with a significant portion being diesel-powered. In the mornings, about 59,340 vehicles enter Luanda's city centre, facing a parking supply of 18,711 spots, leading to issues like traffic jams, illegal parking and elevated emissions (Fortunado, 2015).

3.3. *Oxidative potential*

The oxidative potential of PM is a key factor in determining its health impacts, as it reflects the ability of airborne particles to induce oxidative stress (He and Zhang, 2023). The OP results of PM_{10} assessed at four primary schools in Luanda, using two assays, OP^{AA} and OP^{DTT}, are displayed in Table 1. The results revealed variations between the sampled locations, suggesting that environmental conditions, pollution sources, and school infrastructure influence the oxidative potential of the samples. On average, OP^{AA} values varied from 1.36 to 2.21 nmol min^{-1} m^{-3}, while OP^{DTT} values spanned from 0.507 to 0.854 nmol min^{-1} m^{-3}. School 1138 exhibited the highest OP^{AA} values, whereas School 1116 recorded the highest OP^{DTT}, indicating that different chemical constituents may be driving OP in each location. Schools 1603 and 1116, which displayed higher OP^{DTT} values, have structural deficiencies (peeling paint, visible cracks), suggesting a possible link between oxidative activity and indoor degradation. Regarding mass-normalised OP, School 1207 had the highest OP^{AA} average (0.060 nmol min^{-1} μg^{-1}), with values ranging from 0.024 to 0.167, whereas School 1603 had the lowest (0.024 nmol min^{-1} μg^{-1}). For OP^{DTT}, School 1207 again showed the highest mass-normalised average (0.022 nmol min^{-1} μg^{-1}), with a wide

Table 1
Average, maximum, and minimum OP levels at the schools studied. OP is expressed in volume (nmol min^{-1} m^{-3}) and mass (nmol min^{-1} μg^{-1}) normalised units.

	OP^{AA} nmol min^{-1} m^{-3}		OP^{DTT} nmol min^{-1} m^{-3}		OP^{AA} nmol min^{-1} μg^{-1}		OP^{DTT} nmol min^{-1} μg^{-1}	
Site	Average	min - max	Average	min - max	Average	min - max	Average	min - max
School 1138	2.21	1.07–4.09	0.507	0.146–1.14	0.049	0.052–0.103	0.011	0.003–0.029
School 1603	1.36	0.723–2.27	0.822	0.405–1.53	0.024	0.005–0.068	0.013	0.005–0.031
School 1116	1.72	0.749–3.55	0.854	0.381–1.84	0.034	0.015–0.076	0.017	0.008–0.047
School 1207	1.52	0.430–5.06	0.618	0.009–1.40	0.060	0.024–0.167	0.022	0.001–0.046

range from 0.001 to 0.046, while School 1138 had the lowest average (0.011 nmol min^{-1} μg^{-1}). The wide ranges observed across the sampling period, in both volume-based and mass-based OP values, suggest that local environmental factors, such as pollution sources and atmospheric conditions, may strongly influence OP levels at each site. Despite the growing body of research on OP in recent years, a notable knowledge gap remains in its assessment in school environments, where children spend a considerable amount of time. Due to this lack of reference data in the literature, direct comparisons with previous studies were not feasible, reinforcing the need for further investigations into the oxidative potential of indoor PM in educational settings. As far as we are aware, the only study reporting indoor OP values in Africa is that of Segakweng et al. (2025), who collected size-segregated PM samples from three houses in Jouberton, a low-income urban settlement in the northeastern interior of South Africa, situated within the country's largest industrialised region. The researchers reported mean OP^{DTT} values of 0.061 nmol min^{-1} μg^{-1} and 0.011 nmol min^{-1} μg^{-1} for PM_1 and $PM_{1\text{-}10}$, respectively.

Spearman correlation coefficients between OP^{DTT}, OP^{AA} and PM_{10} are reported in Table 2. A significant correlation was observed between OP^{DTT} and OP^{AA} ($r = 0.526$, $p < 0.01$), suggesting comparable sensitivity between these two assays. This finding aligns with prior research on ambient PM, for which similar correlations have been reported (Calas et al., 2019; Clemente et al., 2023; Gómez-Sánchez et al., 2024; Pietrogrande et al., 2021). No correlation between OP values and PM_{10} concentrations was observed in this study, consistent with previous findings suggesting that toxicity depends more on particle composition than on concentration alone (Gómez-Sánchez et al., 2024; Yang et al., 2024).

Table 2
Spearman correlation coefficients between volume normalised OP measurements and the concentration of PM_{10}-bound chemical components.

	OP^{AA} (nmol min^{-1} m^{-3})	OP^{DTT} (nmol min^{-1} m^{-3})
OP^{AA}	1	0.526**
OP^{DTT}	0.526**	1
PM_{10}	0.185	0.295
Carbonaceous compounds		
OC	0.204	0.302*
EC	0.227	0.139
WSOC	0.286	0.490**
Elements		
S	0.185	0.257
Cl	−0.098	0.330*
K	0.158	0.335*
Ca	0.140	0.281
Ti	0.142	0.368*
V	0.245	0.433**
Cr	0.221	0.332*
Mn	0.168	0.489**
Fe	0.105	0.300
Ni	0.394**	0.305*
Cu	0.079	0.102
Zn	0.322*	0.359*
Br	−0.089	0.115
Sr	0.343*	0.501**
Pb	0.158	0.060

Significant correlation coefficients at the p-level <0.05 and 0.01 are marked with * and **, respectively. OC: organic carbon; EC: elemental carbon; WSOC: water-soluble organic carbon.

Additionally, the correlation analysis (Table 2) revealed significant associations between volume-normalised OP^{AA} and OP^{DTT} and the concentration of various carbonaceous compounds and elements. OP^{DTT} exhibited stronger correlations with a broader range of PM-bound species compared to OP^{AA}, particularly with OC, WSOC and several elements known to drive oxidative stress. Among the carbonaceous compounds, WSOC showed the strongest correlation with OP^{DTT} ($r = 0.490$, $p < 0.01$), suggesting that the soluble fraction of OC plays a key role in redox reactions. This association has been consistently observed in several outdoor studies, where OP^{DTT} often showed particularly strong correlations with WSOC concentrations (Bates et al., 2019; Gómez-Sánchez et al., 2024; Li et al., 2025; Wang et al., 2018). Organic carbon also correlated strongly with OP^{DTT} ($r = 0.302$, $p < 0.05$). This confirms its role as a major driver of oxidative potential, as previously highlighted by He et al. (2021), who found that organic matter, largely of indoor origin, significantly contributes to PM OP.

Potassium ($r = 0.335$, $p < 0.05$) and chlorine ($r = 0.330$, $p < 0.05$) exhibited significant positive correlations with OP^{DTT}. Although strong correlations with chemical components do not necessarily imply direct redox activity, these associations probably reflect the contribution of specific emission sources, such as biomass burning. As previously highlighted by Calas et al. (2019) and Kurihara et al. (2022), correlations between OP and chemical species should be interpreted with caution, since covariations among multiple components, including those not analysed, are often induced by common sources. Several transition metals also showed significant positive correlations with OP^{DTT}, consistent with their established role in catalysing oxidative processes. Manganese showed one of the highest correlations with OP^{DTT} ($r = 0.489$, $p < 0.01$), confirming its importance in reactive oxygen species generation. This finding is consistent with Guo et al. (2019), who reported a similar association in a study assessing OP^{DTT} in samples collected from various indoor environments, including offices, homes (bedrooms, living rooms, and storerooms), and laboratories. The authors pointed out that transition metals (Cu, Mn, and Fe) may act as catalysts during oxidation processes, inducing $^{\bullet}OH$ formation through the concomitant consumption of DTT. Among the transition metals, vanadium ($r = 0.433$, $p < 0.01$), strontium ($r = 0.501$, $p < 0.01$), nickel ($r = 0.305$, $p < 0.05$), chromium ($r = 0.332$, $p < 0.05$), titanium ($r = 0.368$, $p < 0.05$), and zinc ($r = 0.359$, $p < 0.05$) also demonstrated significant correlations with OP^{DTT}. OP^{AA} displayed significant correlations with nickel ($r = 0.394$, $p < 0.01$), strontium ($r = 0.343$, $p < 0.05$) and zinc ($r = 0.322$, $p < 0.05$). These findings are consistent with previous research reviewed by He and Zhang (2023), which identified organic compounds, trace metals, and humic-like substances, key components of OC and WSOC, as major contributors to OP. The authors also emphasised that in non-residential indoor environments, where household activities such as cooking and cleaning are not significant sources, indoor PM is largely influenced by outdoor air pollution, and transition metals may remain the dominant contributors to OP. A comparative consideration of the mechanistic sensitivities of the assays helps explain these patterns. The DTT assay is known to respond to both water-soluble organic compounds and a wide spectrum of transition metals through electron

transfer reactions that promote the formation of reactive oxygen species. This broader reactivity is consistent with the significant associations observed here between OP^{DTT} and both carbonaceous species (OC, WSOC) and several redox-active elements (Mn, V, Ni, Cr, Ti, Zn). In contrast, the AA assay is more selective to specific transition metals, particularly Cu and Fe, which catalyse antioxidant depletion in the respiratory tract lining fluid. In our dataset, OP^{AA} showed comparatively fewer and narrower associations, mainly with Ni, Sr and Zn, highlighting its more limited sensitivity to PM components. These mechanistic differences between assays reinforce the need to apply multiple OP metrics in parallel, as each captures a distinct fraction of the oxidative activity of PM.

Although toxicological thresholds for OP are not yet established, contextual comparisons with other indoor environments provide insight into the potential health risks. The volume-normalised OP^{DTT} values measured in this study (0.507–0.854 nmol min^{-1} m^{-3}) are within the same order of magnitude as those reported in indoor environments in Asia and Europe, where associations with respiratory inflammation and impaired lung function have been observed (He et al., 2021; He and Zhang, 2023; Janssen et al., 2015; Marsal et al., 2023; Santibáñez et al., 2024, 2025). Similarly, the OP^{AA} values (1.36–2.21 nmol min^{-1} m^{-3}) are comparable to or higher than those observed in other non-residential indoor settings, indicating a substantial oxidative burden. Recent work in South African households also reported measurable indoor OP^{DTT} (Segakweng et al., 2025), reinforcing that indoor environments across Africa can contribute significantly to oxidative stress exposure. Given that schoolchildren spend a considerable proportion of their daily time indoors and are particularly susceptible to oxidative damage due to their developing respiratory and immune systems, these findings highlight the need for targeted interventions to reduce exposure in educational settings.

Comparing OP^{AA} and OP^{DTT} highlights the importance of using multiple assays to capture the full spectrum of oxidative activity in PM, reinforcing the distinct oxidative properties of different PM constituents. Given that OP is increasingly recognised as a more health-relevant metric than PM mass alone, understanding the contributions of different chemical constituents is essential for developing targeted air quality interventions. As people spend the majority of their time indoors, minimising exposure to oxidative stress in indoor environments is especially crucial. A study by Yang et al. (2021) assessing the OP of $PM_{2.5}$ in indoor and outdoor environments in Nanjing, China, found that indoor OP levels exceeded outdoor levels in 40 % of cases during summer and 67 % during winter. These variations were attributed to differences in $PM_{2.5}$ composition and environmental factors such as temperature, humidity, and seasonal changes. Previous research has highlighted that air purifiers can significantly reduce both PM mass concentrations and OP indoors, leading to measurable improvements in respiratory health outcomes (He et al., 2021), underscoring the importance of indoor air quality management as a key strategy for protecting public health.

Spearman rank correlations between the chemical composition of PM_{10} and particle-mass-normalised oxidative potential (OP_m) were calculated. OP_m was chosen because it is an informative metric when determining the role of chemical composition on OP (Campbell et al., 2021). However, collinearity among predictors was observed in the dataset, prompting the use of Partial Least Squares Regression (PLSR) to address this issue. Separate PLSR models were constructed for each OP assay, using both mass- and volume-normalised data (OP_m and OP_v), to identify the most specific chemical markers associated with each assay's response. The performance metrics for all models are summarised in Table 3.

The performance indicators show that the PLSR models explain between 23 % and 35 % of the variance in OP and perform significantly better than chance ($p < 0.05$ in a permutation test). This indicates that the models capture a real and statistically significant relationship, even though they explain only a modest share of the variance. Considering the complexity of the system and the relatively small sample size ($n = 43$), the observed level of model performance can be considered reasonable. However, it also suggests that OP may be influenced by factors not represented in the current dataset.

Table 3
Performance assessment of PLSR models for all assays, using both mass-normalised and volume-normalised data. Model significance was evaluated using p-values obtained from permutation tests.

Assay	Optimal number of LVs	Variance explained (%)		R^2CV	p-value	Permutation test pass
		X	Y			
OP_m^{AA}	2	66.2	56.6	0.30	0.001	Yes
OP_V^{AA}	3	71.6	69.0	0.35	0.001	Yes
OP_m^{DTT}	3	71.8	60.0	0.23	0.001	Yes
OP_V^{DTT}	2	67.4	55.2	0.27	0	Yes

LVs – latent variables; X – predictor block (chemical composition); Y – response block (AA and DTT oxidative potential assays, mass- and volume-normalised); R^2CV - Real cross-validated $R.^2$.

As shown in Fig. 3, the models identified a limited number of variables as key predictors of each OP assay (AA and DTT), as indicated by their Variable Importance in Projection (VIP) scores. The results indicate that some influential predictors were shared between mass- and volume-normalised data. For instance, DTT, Ni, and Cl were identified as important in the mass-normalised AA dataset, whereas AA, Sr, and WSOC were prominent in the volume-normalised dataset. Consistent with the correlation analysis, fewer variables were deemed significant in the AA models for both normalisation schemes, suggesting either limited assay sensitivity or the contribution of unmeasured components. In addition, the variables highlighted as important by the PLSR models did not always correspond with those identified through statistical correlation. For example, in the mass-normalised AA model, only Ni was identified as important by both approaches. A similar pattern was observed in the mass-normalised DTT model, where only 4 of 11 variables were consistently identified as important across both methods.

These results are consistent with findings from a previous study (Campbell et al., 2021), which showed that univariate analyses (Spearman correlation in that study) and multivariate approaches often highlight different subsets of variables, reflecting the diverse chemical sensitivities of each assay. Campbell et al. (2021) also reported that mass-normalised data tend to provide a more nuanced view of the compositional drivers and sources of OP compared with volume-normalised data. In the present analysis, the variables identified as important varied depending on the normalisation approach and the statistical method employed (correlation vs. PLSR), further supporting the idea that different assays and data treatments capture distinct aspects of the OP signal. Moreover, the limited sample size and potential noise in the dataset likely constrained the models' ability to detect broader patterns.

4. Conclusions

This study provides a comprehensive assessment of PM_{10} concentrations and chemical composition in schools in Luanda, highlighting the significant impact of indoor and outdoor sources on air quality. PM_{10} levels frequently exceeded the WHO guideline of 45 μg m^{-3}, particularly at classrooms with structural deficiencies and proximity to unpaved roads. The presence of students contributed significantly to PM_{10} levels, with weekday concentrations more than double those recorded on Saturdays when schools were unoccupied.

Carbonaceous material accounted for 21.3 % of PM_{10}, with an OC/EC ratio of 2.26 ± 0.74, suggesting the influence of mixed sources, including vehicle emissions, biomass burning, and secondary organic aerosol formation. The application of the EC-tracer method indicated

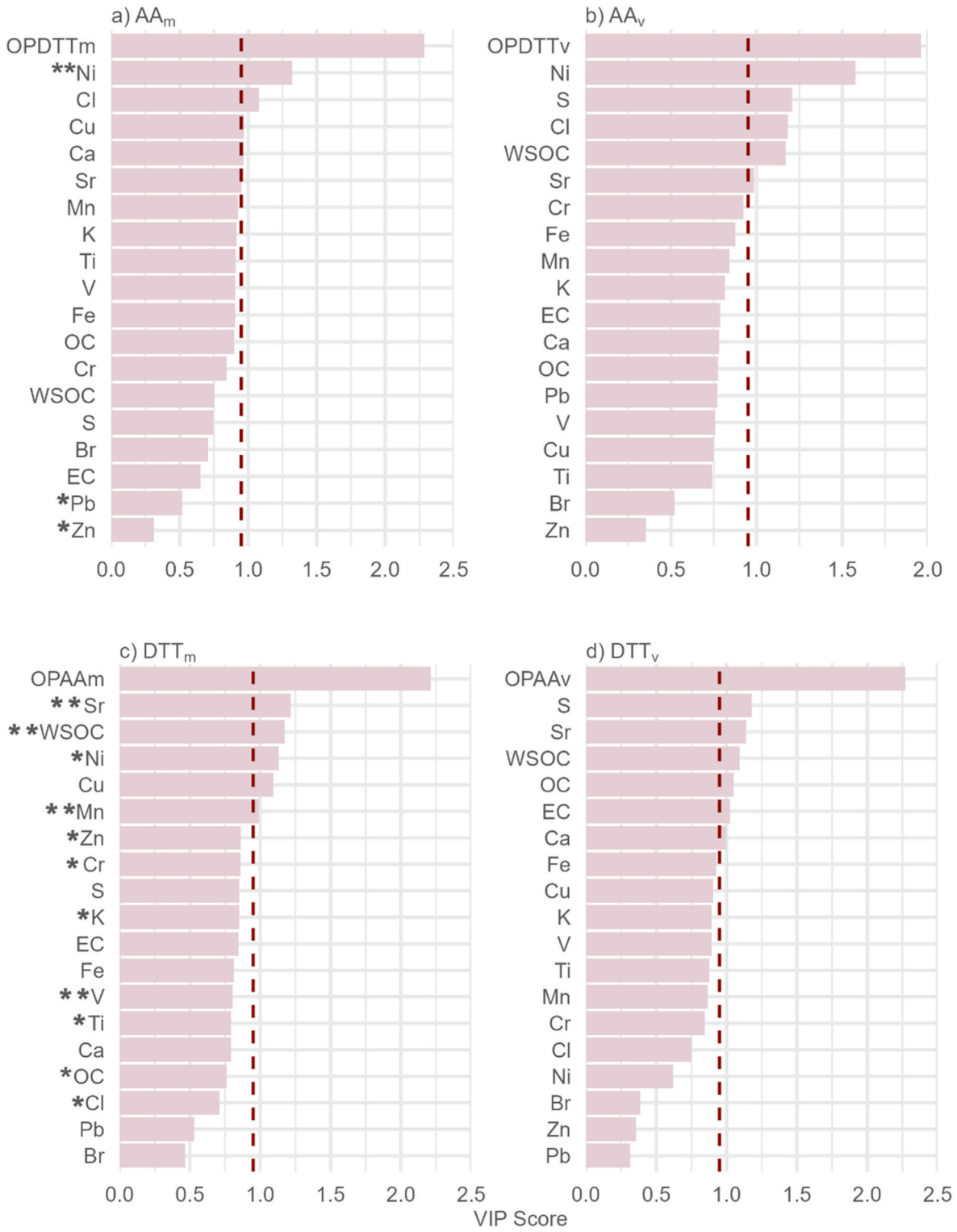

Fig. 3. PLSR models of OP as defined by VIP for each model. Variables/predictors with VIP >0.95 have strong influence on OP. The * indicates significant positive correlation from the Spearman test of the feature with the assay previously reported.

that a substantial fraction (77 %) of OC was secondary in origin, likely resulting from the photochemical transformation of volatile organic compounds. Additionally, WSOC/OC ratios suggested contributions from both primary emissions and secondary processing.

Elemental analysis identified Ca, S, Cl, and K as the most abundant species, with enrichment factor analysis revealing extremely high anthropogenic contributions for Br, S, Cl, Ni, Zn, Pb, Cu, V, and Cr. Correlation analysis indicated major contributions from mineral dust resuspension, vehicular emissions, fuel combustion, and industrial activities. Specific elements such as V and Mn were strongly linked to fossil fuel combustion, while Pb and Ni were likely influenced by long-range transport or background sources, as their concentrations remained stable across different school environments.

The results revealed variations in the OP of PM_{10} both between

schools and throughout the sampling period, with a wide range of values observed within each school. These variations suggest that OP was influenced by fluctuations in local environmental conditions, pollution sources, and indoor activities. Correlation analysis showed that OP^{DTT} was strongly associated with organic carbon, WSOC, and several transition metals (e.g., V, Sr, Ni, Cr, Ti, and Zn), supporting their role in driving oxidative stress, whereas OP^{AA} exhibited significant correlations only with Ni, Sr, and Zn. Complementary PLSR analyses, which account for collinearity among variables, identified overlapping but also distinct subsets of influential predictors, highlighting that different statistical approaches capture complementary aspects of the OP signal. These findings reinforce the importance of using multiple assays and analytical approaches to comprehensively characterise the oxidative activity of PM.

The findings reinforce the need for improved air quality management in schools, particularly through structural improvements, dust mitigation strategies, and policies to minimise exposure to harmful pollutants. Further research is recommended to explore the health impacts of chronic exposure to PM_{10} and its constituents in school environments, to develop targeted interventions to reduce indoor air pollution in educational settings, and to investigate the influence of socioeconomic conditions, such as income level, traffic density, and industrial distribution, on indoor air quality. Additionally, future campaigns should include simultaneous outdoor PM measurements to better distinguish indoor and outdoor contributions.

CRediT authorship contribution statement

Célia Alves: Visualization, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Estela D. Vicente:** Writing – review & editing, Methodology, Formal analysis. **Teresa Nunes:** Writing – review & editing, Methodology, Formal analysis. **Yago Cipoli:** Writing – review & editing, Methodology, Formal analysis. **Isabella Charres:** Writing – review & editing, Methodology. **Eduardo Yubero:** Writing – review & editing, Methodology. **Nuria Galindo:** Writing – review & editing, Methodology. **Jiří Ryšavý:** Writing – review & editing, Methodology. **Anabela Leitão:** Writing – review & editing, Resources.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Celia Alves reports financial support was provided by Foundation for Science and Technology. Yago Cipoli reports financial support was provided by Foundation for Science and Technology. Isabella Charres reports financial support was provided by Foundation for Science and Technology. Estela Vicente reports financial support was provided by Foundation for Science and Technology Jiří Ryšavý reports financial support was provided by the European Union. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.atmosenv.2025.121640.

Data availability

Data will be made available on request.

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