



# Silane-grafted Nano-TiO<sub>2</sub> Air Monitoring Filters for Enhanced PM<sub>2.5</sub> Filtration and Detection in Urban Atmospheres

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## ABSTRACT

The global health risks posed by fine particulate matter (PM<sub>2.5</sub>) demand advanced materials that integrate high-efficiency filtration with real-time sensing capabilities. Herein, the fabrication and validation of a dual-function air filtration and sensing substrate based on aminosilane-grafted titanium dioxide (TiO<sub>2</sub>) nanoparticles are reported. TiO<sub>2</sub> nanoparticles were modified with (3-aminopropyl)triethoxysilane (APTES) to achieve robust surface immobilization and introduce terminal amine (–NH<sub>2</sub>)-based chemical affinity. Scanning electron microscopy (SEM) revealed a transformation from smooth to rough granular morphology; energy-dispersive X-ray spectroscopy (EDX) detected a silicon (Si) peak and a nitrogen (N) peak consistent with amine groups; Fourier transform infrared spectroscopy (FTIR) verified Ti–O–Si bond formation and N–H bending vibrations; and X-ray diffraction (XRD) showed retention of anatase TiO<sub>2</sub> crystallinity along with a concurrent amorphous siloxane surface network. A 15-day ambient PM<sub>2.5</sub> sampling demonstrated markedly enhanced collection performance of APTES–TiO<sub>2</sub> compared with pristine TiO<sub>2</sub> and unmodified filters. Inductively coupled plasma optical emission spectroscopy (ICP-OES) quantification provided definitive evidence that amine functionalities induce chemisorptive capture, yielding significantly higher retained masses for metallic species (including Zn, Cu, Pb) and carbonaceous aerosols. Laser-induced breakdown spectroscopy (LIBS) measurements exhibited nanostructure-enhanced LIBS (NELIBS) signal amplification, and the LIBS intensities correlated strongly and positively with ICP-OES concentrations, validating LIBS as a rapid proxy for mass loading. Together, these results establish the APTES–TiO<sub>2</sub> composite as an effective dual-function substrate that combines superior chemical capture with optical signal enhancement, offering a practical pathway toward next-generation active monitoring systems for sensitive, near-real-time analysis of airborne contaminants.

**Keywords:** PM<sub>2.5</sub> capture; Titanium dioxide; APTES functionalization; Aminosilane; LIBS; NELIBS; ICP-OES; Optical sensing; Chemisorption; Dual-function substrate.

## 1. INTRODUCTION

The intensifying global environmental crisis of air pollution, driven by accelerated industrial expansion, combustion-based energy and transport systems, and unchecked urbanization, presents a formidable challenge to modern society. Despite the implementation of stricter emission controls and advancements in green technologies, ambient air quality in major urban centers frequently violates international safety standards, creating severe risks for public health, ecosystem integrity, and global climate patterns (Jena *et al.* 2023; Singh *et al.* 2020; Karri *et al.* 2024). International health organizations attribute millions of premature deaths annually to atmospheric contamination, with particulate matter consistently identified as a primary driver of respiratory and cardiovascular mortality (Mukherjee and Agrawal, 2017; Brook *et al.* 2010; Moradi *et al.* 2023). The persistent nature of these airborne pollutants, their capacity for long-range atmospheric transport, and their

complex chemical behavior demand the urgent development of sustainable, efficient, and scalable mitigation technologies (Li *et al.* 2021; Hageman *et al.* 2015).

Among the diverse array of atmospheric contaminants, fine particulate matter with an aerodynamic diameter of 2.5 µm or less (PM<sub>2.5</sub>) is a subject of profound scientific concern. These submicron particles can bypass the body's upper respiratory defenses, infiltrate the alveolar region, and potentially translocate into the systemic circulation, leading to widespread physiological damage (Hu *et al.* 2024; Zaib *et al.* 2025). Chronic exposure to PM<sub>2.5</sub> is epidemiologically linked to the onset or aggravation of chronic obstructive pulmonary disease (COPD), asthma, lung cancer, ischemic heart disease, and neurodegenerative disorders (Rückerl *et al.* 2011; Chowdhury *et al.* 2025; Amadi, 2025). Furthermore, PM<sub>2.5</sub> actively contributes to environmental degradation

by impairing atmospheric visibility, promoting the chemical weathering of materials, and altering cloud formation processes, thus exerting a significant influence on regional and global climate (Omokpariola, 2025; Öncü *et al.* 2025).

Existing air purification infrastructure, which predominantly includes mechanical filters (High-Efficiency Particulate Air filters, HEPA), electrostatic precipitators, activated carbon sorbents, and wet scrubbers, is widely deployed in industrial, commercial, and residential applications. While these conventional systems offer reliable performance for larger particles, they are often burdened by significant limitations, including high pressure drop, susceptibility to fouling and clogging, substantial energy penalties, and a general inability to remediate nanoscale contaminants or volatile organic compounds (VOCs) (Szcotko *et al.* 2022; Wang *et al.* 2015; Singh *et al.* 2024). Most critically, these technologies function as passive collectors, accumulating hazardous materials without providing any feedback on filter integrity, saturation state, or the potential for secondary pollutant release. Consequently, a strategic shift toward advanced functional materials that enable simultaneous high-efficiency filtration, active pollutant degradation, and intelligent operational monitoring is essential for next-generation air quality control.

The merging of nanotechnology with environmental science has provided a rich toolkit for engineering filtration media with superior performance, tailored surface functionalities, and novel remediation capabilities. Among the various classes of nanomaterials, semiconductor photocatalysts have attracted immense interest for their ability not only to capture but also to actively destroy pollutants. Titanium dioxide (TiO<sub>2</sub>), in particular, has emerged as a benchmark material for environmental purification due to its low cost, non-toxicity, exceptional chemical and thermal stability, and robust photocatalytic activity (Nagaraj *et al.* 2025; Gatou *et al.* 2024). Under appropriate light irradiation (typically UV), TiO<sub>2</sub> generates highly reactive oxygen species (ROS) capable of mineralizing a broad spectrum of organic pollutants and inactivating harmful microorganisms (Guo *et al.* 2011). This property positions TiO<sub>2</sub> as an ideal candidate for creating self-cleaning and disinfecting air filtration systems.

However, the practical application of pristine TiO<sub>2</sub> nanoparticles (TiO<sub>2</sub> NPs) in filter systems is hindered by several persistent challenges. As a fine powder, TiO<sub>2</sub> exhibits very poor adhesion to common filter substrates (polymers or quartz fibers), leading to material loss and potential secondary contamination (Nawaz *et al.* 2022; Khan *et al.* 2025). Furthermore, the nanoparticles tend to agglomerate, which significantly reduces the available active surface area and, consequently, the overall photocatalytic efficiency (Li *et al.* 2010). Surface functionalization via silanization

presents a highly effective strategy to resolve these issues. The grafting of silane coupling agents onto the TiO<sub>2</sub> surface acts as a bridge, forming strong covalent bonds with both the inorganic oxide surface and the filter substrate (Zhao *et al.* 2012; Riaz *et al.* 2021). This process not only ensures the robust immobilization of the nanoparticles but also helps to maintain a well-dispersed layer, maximizing the exposure of active sites and enhancing interfacial compatibility.

The integration of silane-grafted TiO<sub>2</sub> NPs onto porous filter substrates offers a synergistic solution for advanced PM<sub>2.5</sub> capture and remediation. In this composite architecture, the silane layer provides a stable and durable anchor for the nanomaterial, preventing delamination and ensuring long-term operational integrity. The immobilized TiO<sub>2</sub> NPs, in turn, provide a high-surface-area bed for PM<sub>2.5</sub> capture while simultaneously offering an active photocatalytic surface. This design moves beyond passive filtration, enabling the *in situ* degradation of trapped organic aerosols and the neutralization of viable bioaerosols, thereby creating a regenerative, self-cleaning filtration platform. This research makes use of this synergistic combination to develop a next-generation filter medium designed for enhanced, active, and sustainable PM<sub>2.5</sub> control.

## 2. EXPERIMENTAL METHODS

### 2.1 Materials and Reagents

Analytical-grade titanium(IV) butoxide (TBOT, ≥97%), hydrochloric acid (HCl, 37%), (3-aminopropyl)triethoxysilane (APTES, ≥99%), ethanol (≥99.8%), and ammonia solution (25 wt%) were procured from Sigma-Aldrich and used without further purification. High-purity quartz microfiber filters (QM-A, Whatman, USA), widely employed in regulatory air quality monitoring due to their thermal stability and minimal inorganic interference, served as the filtration substrate. Its technical specifications are listed in Table 1. All aqueous preparations utilized deionized water (18.2 MΩ·cm resistivity). Prior to synthesis and coating procedures, glassware was thoroughly cleaned using 10% nitric acid, rinsed repeatedly with deionized water, and oven-dried to avoid trace contamination during subsequent spectroscopic or gravimetric analysis. All experiments were conducted under ambient laboratory conditions unless otherwise specified.

### 2.2 Synthesis and Functionalization of TiO<sub>2</sub> NPs

TiO<sub>2</sub> NPs were synthesized using a modified hydrothermal method. In a typical procedure, 15 mL of titanium (IV) butoxide (TBOT) was added dropwise to 150 mL of an ice-cold 6 M HCl solution under vigorous stirring. The resulting transparent solution was transferred to a Teflon-lined stainless-steel autoclave and heated at 180 °C for 24 h. After cooling to room

temperature, the white precipitate (bulk layered titanate) was collected by centrifugation, washed thoroughly with deionized water and ethanol to remove residual ions, and dried at 80 °C. To achieve nanoparticle morphology, 2 g of the resulting powder was dispersed in 200 mL of deionized water and subjected to ultrasonication for 2 h. The dispersion was centrifuged at 4000 rpm for 30 min to remove unexfoliated aggregates, and the supernatant containing few-layer TiO<sub>2</sub> NPs was collected and dried at 60 °C overnight. Surface modification was performed to enhance interfacial interaction between the nanoparticles, quartz fiber matrix, and airborne particulate pollutants. Briefly, 500 mg of exfoliated TiO<sub>2</sub> was dispersed in 200 mL of ethanol and sonicated for 30 min. APTES (5 mL) mixed with aqueous ammonia (2 mL) in 50 mL ethanol was added dropwise, and the reaction mixture was refluxed at 80 °C for 6 h with continuous stirring. The resulting silane-grafted TiO<sub>2</sub> was recovered by centrifugation, washed three times with ethanol to remove unreacted silanes, and dried at 70 °C for 12 h. The functionalized powder was stored in airtight containers until use. This modification step introduces amine-terminated silane bridges, which enhance nanoparticle dispersion, affinity for quartz fibers, and surface interaction with fine airborne particulates.

**Table 1. Technical specifications of the filters used**

| Property                     | Specification                    |
|------------------------------|----------------------------------|
| Grade                        | QM-A                             |
| Material                     | Quartz microfiber                |
| Particle Retention in Liquid | 2.1 µm                           |
| Air Flow                     | 6.5 s / 100 mL / in <sup>2</sup> |
| Typical Thickness            | 455 µm                           |
| Basis Weight                 | 86 g/m <sup>2</sup>              |

### 2.3 Fabrication of Nanomodified Filtration Media and Ambient PM<sub>2.5</sub> Sampling

Before modification, all quartz filters were conditioned at 20 °C and 50% relative humidity for a period of 24 h, and their initial mass was determined using a microbalance with a precision of ±0.01 mg. Three distinct filter types were prepared for comparative analysis: unmodified filters, filters coated with pristine TiO<sub>2</sub> NPs, and filters coated with silane-functionalized TiO<sub>2</sub> NPs. The unmodified filters served as a baseline control and were set aside after the initial conditioning and weighing. To fabricate the nanomaterial-coated filters (second and third types), a 200-ppm dispersion was prepared by suspending 20 mg of pristine and silane-grafted TiO<sub>2</sub> in 100 mL of ethanol, followed by 15 min of sonication to achieve a uniform suspension.

For each filter to be coated, 1 mL of the respective suspension was pipetted and distributed uniformly across the surface, facilitating capillary-driven infiltration into the fibrous network. The coated filters

were subsequently dried under fume-hood ventilation for 30 min, followed by a final drying step at 50 °C for 1 h. After cooling and reconditioning under identical humidity and temperature settings, all filters, including the unmodified controls, were weighed again to precisely quantify the mass of the deposited nanomaterial. Ambient particulate matter sampling was conducted using a portable MiniVol™ Tactical Air Sampler, calibrated to maintain a constant flow rate of 5 L min<sup>-1</sup>. Each filter was exposed continuously to ambient air for 15 days at an urban roadside location to accumulate sufficient aerosol mass for a long-term performance evaluation of the nanocoatings. The sampler's inlet was positioned at breathing-zone height to accurately represent human exposure levels. Throughout the sampling process, key meteorological parameters such as temperature, relative humidity, and wind conditions were systematically recorded. Upon completion of the exposure period, all filters were carefully sealed in sterile containers, transported to the laboratory, and subjected to a final conditioning cycle at controlled humidity and temperature before a final gravimetric measurement. The collected PM<sub>2.5</sub> mass was then determined using the standard mass-difference method. This extended sampling protocol ensured consistent particle accumulation and enhanced the detectability of trace metal species, all while adhering to established particulate monitoring methodologies.

### 2.4 Chemical Digestion, Optical Sensing and Characterization

To evaluate particulate composition and determine whether the nanocoating enhanced trapping efficiency for trace metals, each filter was sectioned and digested in freshly prepared aqua regia (3:1 HCl:HNO<sub>3</sub>) at 80 °C for 3 h. The digested solution was diluted to 50 mL with deionized water, filtered, and analyzed using inductively coupled plasma optical emission spectroscopy (ICP-OES). This enabled the quantitative determination of pollution-associated metals such as Na, K, Ca, Fe, Mg, Zn, and Pb accumulated during the 15-day sampling period.

For sensing evaluation, laser-induced breakdown spectroscopy was used. A Q-switched Nd:YAG laser (1064 nm; 50 mJ pulse energy; 5 ns pulse width) was focused on the filter surface to generate plasma, and optical emission between 200–700 nm was collected using an echelle spectrometer coupled to an intensified CCD detector. A delay time of 1500 ns and a gate width of 2000 ns were employed to maximise spectral resolution and suppress continuum background. Multiple spectra were recorded from each filter to account for deposition heterogeneity. Emission intensities for characteristic atmospheric marker elements were evaluated to determine the enhancement

in spectral response arising from silane-TiO<sub>2</sub> modification.

Morphological and structural features of the nanoparticles and coated filters were investigated before and after sampling. SEM combined with EDS mapping was used to visualise nanoparticle distribution and particulate adherence. XRD was employed to confirm crystalline structure integrity, while FTIR spectroscopy verified silane functionalization through characteristic Si-O-Ti and amine (N-H) stretching signatures.

### 3. EXPERIMENTAL RESULTS

#### 3.1 Morphological and Compositional Analysis of TiO<sub>2</sub> Nanomaterials

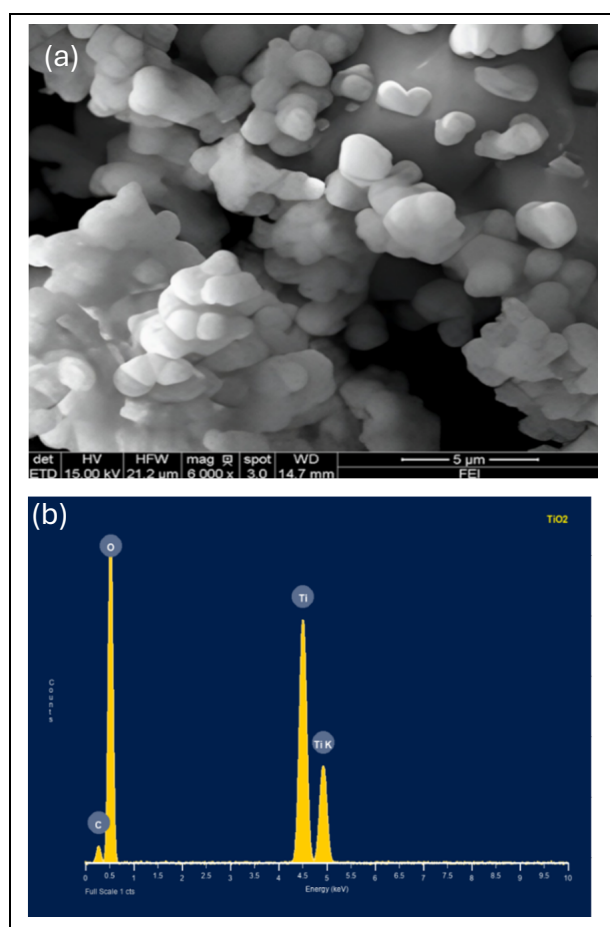


**Fig. 1: (a) SEM micrograph and (b) EDX spectrum of pristine TiO<sub>2</sub> particles**

The surface morphology and elemental composition of the pristine TiO<sub>2</sub> particles and the silane-functionalized (APTES-TiO<sub>2</sub>) material were investigated by SEM and EDX analyses. Fig. 1(a) presents the morphology of the as-synthesized, pristine TiO<sub>2</sub> material. The micrograph reveals that the material is composed of quasi-spherical or globular primary particles, which are

heavily agglomerated into larger, porous secondary structures. These agglomerates appear to be loosely packed, creating a significant amount of inter-particle void space. The surfaces of the individual primary particles appear relatively smooth and well-defined. This highly porous, agglomerated structure is typical for materials produced via hydrothermal methods and is advantageous as it inherently possesses a high specific surface area, which is beneficial for any adsorption-based application (Darr *et al.* 2017).

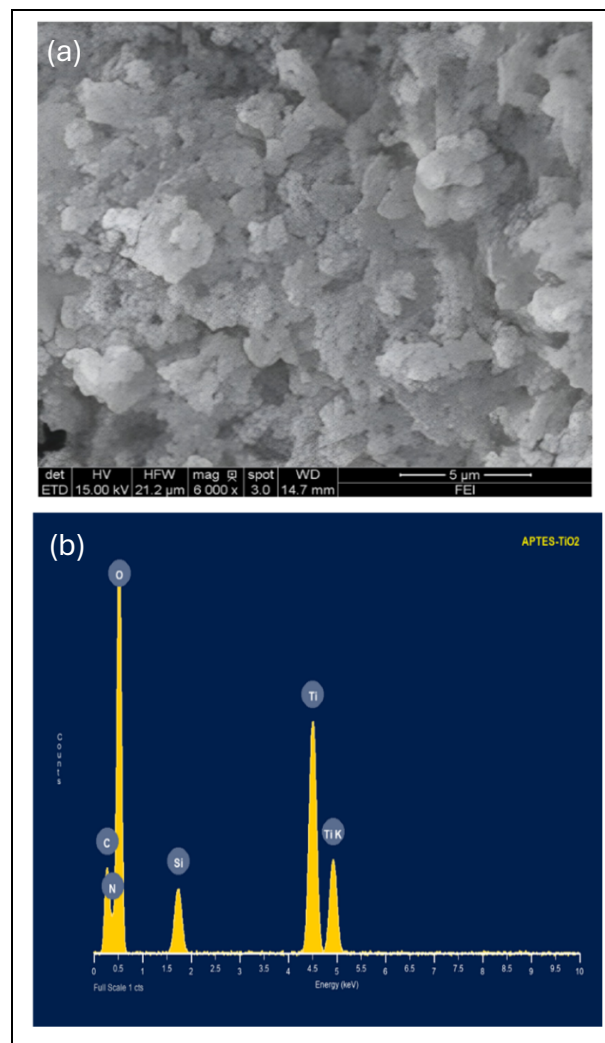


**Fig. 2: (a) SEM micrograph and (b) EDX spectrum of silane-functionalized APTES-TiO<sub>2</sub>**

The corresponding EDX spectrum, shown in Fig. 1(b), confirms the high chemical purity of the synthesized control material. The spectrum is dominated by prominent characteristic peaks for Ti at approximately 4.51 keV (Kα) and 4.93 keV (Kβ), and O at 0.53 keV. The minor C peak is a common and expected artifact, attributed to the carbon-based conductive tape used for sample mounting during SEM preparation (Islam *et al.* 2019). Crucially, the spectrum shows a clean baseline

with the complete absence of signals for Si or N, establishing a definitive baseline for comparison.

Following the silanization process, the morphology of the material is visibly and significantly altered, as seen in Fig. 2(a). The distinct, smooth surfaces of the original TiO<sub>2</sub> particles are no longer visible. Instead, they are obscured by a finer, more granular and amorphous-looking overlayer. This new nanotextured coating appears to act as a binder, binding the primary particles together and creating a rougher, more cohesively bonded, and texturally complex surface. This morphological change is a strong indicator that the APTES did not simply physisorb, but rather hydrolyzed and condensed on the TiO<sub>2</sub> surfaces, forming a distinct siloxane network (Aslanidou *et al.* 2016). This binder effect is also theorized to improve the mechanical adhesion of the particles to the quartz filter fibers, reducing the risk of the nanocoating being dislodged during high-volume air sampling.

This conclusion is clearly confirmed by the compositional analysis in Fig. 2(b). The EDX spectrum of the APTES-TiO<sub>2</sub> sample shows the definitive appearance of two new, significant elemental peaks that were absent in the control: Si at 1.74 keV and N at 0.39 keV. The Si peak is a direct indicator of the silane component of APTES, confirming its successful grafting onto the particle surfaces, likely through the formation of stable Ti–O–Si covalent bonds. The N peak is perhaps the most critical piece of evidence, as it confirms the presence of the terminal amine (–NH<sub>2</sub>) group; this is the active functional group intended to enhance the filter's chemical affinity for airborne particulates. Furthermore, the C peak is visibly more intense compared to the control spectrum in Fig. 1(b). This increase is consistent with the addition of the organic propyl (C<sub>3</sub>H<sub>7</sub>) chains from the APTES molecule, further corroborating the successful functionalization (Bhowmick *et al.* 2012).

The SEM and EDX results provide clear and complementary evidence for the successful surface modification. The pristine TiO<sub>2</sub> particles were effectively coated with (3-aminopropyl)triethoxysilane. This process not only changed the physical surface texture, creating a rougher, more complex morphology, but also, and more importantly, successfully introduced the nitrogen-containing amine functional groups. These groups are expected to act as active chemical sites, enhancing the capture of fine particulate matter (PM<sub>2.5</sub>) through chemisorption and acid-base interactions, in addition to the baseline physical filtration mechanisms.

### 3.2 XRD Analysis

To evaluate the crystalline phase and structural integrity of the nanomaterials before and after functionalization, X-ray diffraction analysis was conducted. As shown in the XRD patterns (Fig. 3), the

pristine TiO<sub>2</sub> sample (blue line) displays a series of high-intensity, sharp diffraction peaks. The prominent peaks are located at 2 $\theta$  angles of 25.3°, 37.8°, 48.0°, 53.9°, 55.1°, and 62.7°. These peaks are unambiguously assigned to the (101), (004), (200), (105), (211), and (204) lattice planes, respectively. This pattern is in excellent agreement with the standard diffraction data for the pure tetragonal anatase phase of TiO<sub>2</sub> (JCPDS No. 21-1272). The pronounced sharpness and high intensity of these reflections, coupled with a low baseline, indicate a high degree of crystallinity. This well-ordered structure is highly advantageous, providing a stable and well-defined substrate for the subsequent surface modification reaction. Following functionalization, the APTES–TiO<sub>2</sub> pattern (red line) shows a complete retention of all characteristic anatase peaks, demonstrating the robustness of the core nanomaterial.

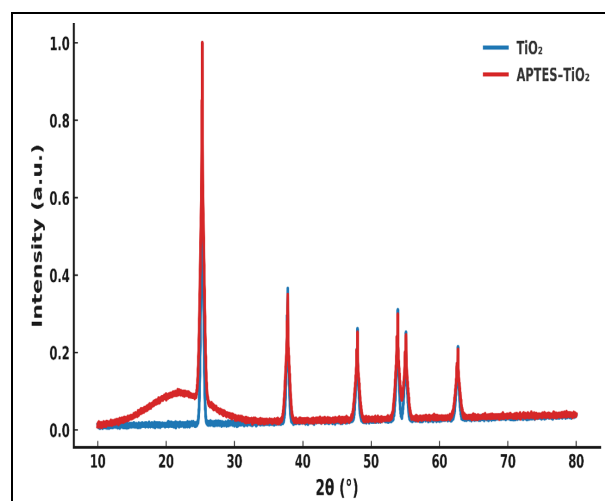


**Fig. 3: XRD patterns of pristine TiO<sub>2</sub> (blue) and APTES–TiO<sub>2</sub> (red)**

Crucially, there are no observable shifts in 2 $\theta$  positions or any significant degradation in peak intensity or broadening. This is a key finding, as it confirms that the wet-chemical silanization process was a comparatively gentle, surface-level modification. It did not induce lattice strain, introduce interstitial impurities, or otherwise disrupt the underlying crystalline core of the TiO<sub>2</sub>. However, a notable difference is the emergence of a very broad, low-intensity amorphous zone, which is most prominent in the low-angle region between 15 and 23° 2 $\theta$ . This diffuse scattering feature is absent in the pristine sample and is characteristic of a non-crystalline, amorphous material. It is unambiguously attributed to the amorphous polymeric siloxane (Si–O–Si) network formed by the successful hydrolysis and condensation of the APTES molecules as they polymerize across the particle surfaces (Woźnica *et al.* 2023). Thus, the XRD analysis provides evidence that the anatase TiO<sub>2</sub> core remains structurally intact and highly crystalline, while a new, amorphous silane layer has been successfully deposited on its surface.

### 3.3 FTIR Analysis

FTIR was employed to chemically confirm the grafting of the silane molecule and to verify the presence of the desired functional groups. Fig. 4 shows the spectrum of pristine  $\text{TiO}_2$  (blue line), which is dominated by features typical of a hydrated metal oxide. A very broad and strong absorption band is centered around  $3400\text{ cm}^{-1}$ , which is attributed to the O-H stretching vibrations from both physisorbed water molecules and the surface hydroxyl (Ti-OH) groups. These hydroxyls are the primary active sites that initiate the silanization reaction (Villa *et al.* 2016). The associated O-H bending (scissoring) vibration of this adsorbed water is noted as a distinct peak at  $1630\text{ cm}^{-1}$ . The strong, broad absorption below  $900\text{ cm}^{-1}$  is the fingerprint of the Ti-O-Ti lattice vibrations within the  $\text{TiO}_2$  crystal.

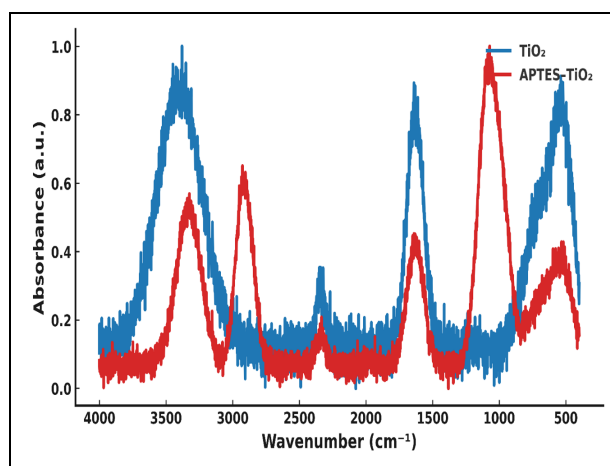


**Fig. 4:** FTIR spectra of pristine  $\text{TiO}_2$  and APTES- $\text{TiO}_2$  sample (red)

On the other hand, the APTES- $\text{TiO}_2$  spectrum (red line) reveals several new, distinct absorption bands that serve as definitive proof of a successful functionalization. New sharp (though low-intensity) peaks are found in the  $2900\text{--}2950\text{ cm}^{-1}$  region. These are clearly assigned to the symmetric and asymmetric C-H stretching vibrations of the propyl ( $\text{C}_3\text{H}_7$ ) chain from the APTES, confirming the incorporation of the molecule's organic property (Özel *et al.* 2021). The appearance of a new shoulder peak around  $1560\text{ cm}^{-1}$  is important. This band is assigned to the N-H bending vibration of the terminal primary amine ( $-\text{NH}_2$ ) group. Its presence is the key evidence that the amino part of the (3-aminopropyl) triethoxysilane is intact and present on the surface, providing the desired chemical functionality for interacting with airborne particulates. The most prominent new feature is the strong, broad absorption band that emerges between  $1050\text{ cm}^{-1}$  and  $1100\text{ cm}^{-1}$ . This complex band is a significant feature of composites representing both Si-O-Si (from the polymeric siloxane network) and Ti-O-Si (from the silane-to-titania anchor

point) stretching vibrations. The identification of this Ti-O-Si linkage is particularly significant, as it provides direct evidence of a covalent bond between the silane and the  $\text{TiO}_2$  substrate. This covalent linkage ensures the coating is robust and chemically anchored, rather than merely physically adsorbed, which is essential for the long-term durability of the filter medium.

### 3.4 Post-exposure Analysis of Filter Surfaces

To directly correlate the surface modifications with real-world performance, the filters were subjected to a 15-day ambient air sampling. Following this exposure, the filter surfaces were re-examined using SEM to visualize the particulate loading morphology and EDX to provide a semi-quantitative elemental analysis of the captured matter.

Fig. 5(a) illustrates the surface of the unmodified control filter. The underlying network of quartz microfibrers remains clearly discernible, indicating a comparatively sparse particulate load. The captured particles are observed as individual or small agglomerates adhering to the fiber surfaces.

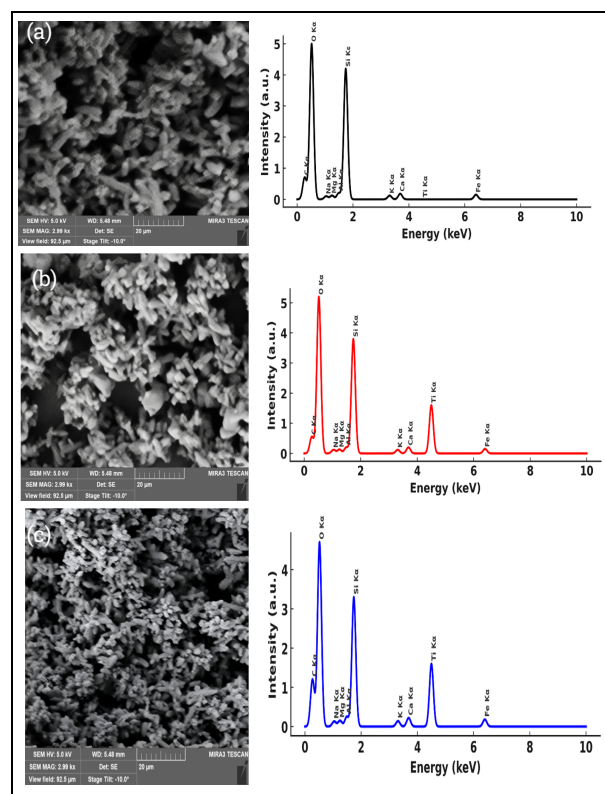


**Fig. 5:** SEM micrographs and EDX spectra of: (a) Unmodified control filter, (b) Pristine  $\text{TiO}_2$ -modified filter and (c) APTES- $\text{TiO}_2$ -modified filter

This morphology suggests that the primary capture mechanisms are limited to physical interception and impaction, with the particles likely retained by relatively weak physisorption mechanisms, such as van

der Waals forces (Yildirim and Kara, 2013). The corresponding EDX spectrum is, as expected, dominated by the Si and O signals originating from the quartz (SiO<sub>2</sub>) filter substrate. Smaller, yet distinct, characteristic peaks for C, Na, K, Ca, and Fe are also evident. These are well-established elemental markers for a heterogeneous mix of anthropogenic and natural aerosols, including crustal material, road dust, and combustion byproducts (Shandilya and Khare, 2012; West *et al.* 2012). An examination of the pristine TiO<sub>2</sub>-modified filter, shown in Fig. 5(b), reveals a visibly higher particle load. The underlying fibers are more effectively obscured by a combination of the TiO<sub>2</sub> NPs and the trapped PM. The TiO<sub>2</sub> appears to have formed a porous, high-surface-area scaffold on the fibers, which, in turn, has provided a more effective trapping bed for the incoming aerosols. The captured particles appear embedded within the TiO<sub>2</sub> agglomerates, resulting in a more substantial and complex loading morphology. This visual observation of enhanced capture is supported by the EDX spectrum. In addition to the substrate and PM peaks, prominent Ti peaks are present, confirming the stability and retention of the nanocoating. Significantly, the relative intensities of the PM-related peaks (e.g., Ca, Fe) are more pronounced when compared to the substrate's Si signal. This provides strong semi-quantitative evidence that increasing the specific surface area and textural complexity has enhanced particle capture efficiency relative to the control. The most substantial change is observed in Fig. 5(c), which presents the silane-functionalized APTES-TiO<sub>2</sub> filter. This sample exhibits a profoundly different post-exposure morphology.

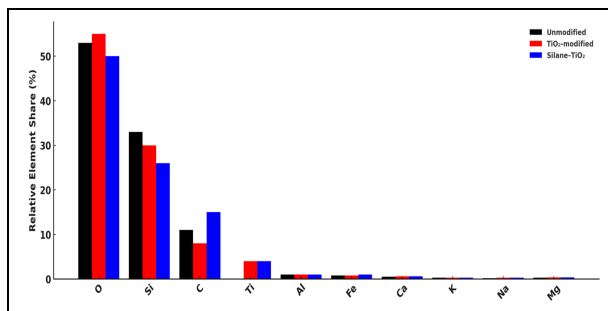


**Fig. 6: Comparison of elemental shares of unmodified (black), TiO<sub>2</sub>-modified (red), and silane-TiO<sub>2</sub>-modified (blue) filters after a 15-day ambient PM<sub>2.5</sub> exposure**

The underlying quartz fiber network is almost completely occluded by a dense, thick, and relatively uniform deposition layer of particulate matter. This visual evidence indicates a superior particle capture efficiency, far exceeding the other two samples. This interpretation is corroborated by the EDX analysis. While the Si (substrate) and Ti (coating) peaks are still detectable, their relative intensities are significantly diminished, being overshadowed by the intense signals from the captured PM. The peaks for C, Na, K, Ca, and Fe are all substantially larger than in the other samples. The

pronounced increase in the C signal is particularly noteworthy, strongly suggesting a much higher capture efficiency for carbonaceous aerosols (soot), a critical and toxic component of urban PM<sub>2.5</sub> (Li *et al.* 2016). This demonstrates the synergistic effect of the modification (high surface area of the TiO<sub>2</sub> and the introduction of the -NH<sub>2</sub> functional group). These active sites introduce a chemical affinity for the aerosol surfaces via stronger, more targeted interactions (such as acid-base or hydrogen bonding), which are absent in the other filter types (Xu *et al.* 2025). Fig. 6 presents the overall relative elemental share (wt.%) of the filters after the 15-day ambient exposure, as determined by a wide-area EDX scan. As expected, all samples are dominated by O and Si, which are the main components of the base quartz SiO<sub>2</sub> filter. The Ti signal, present only in the modified samples, confirms the presence of nanocoating. The most critical finding is in the carbon share, a primary marker for soot and organic aerosols. The silane-TiO<sub>2</sub>-modified filter (blue bar, 15%) captured a significantly higher share of carbon than both the unmodified (11%) and pristine TiO<sub>2</sub>-modified (8%) filters. This result strongly indicates that the silane functionalization provides a superior chemical affinity for capturing carbonaceous pollutants.

### 3.5 Quantitative Analysis of Captured Elemental Species via ICP-OES

**Table 2. ICP results for 15 operating days for the unmodified and nano-modified filters**

| Parameter                       | Filter-1             | Filter-2                  | Filter-3                |
|---------------------------------|----------------------|---------------------------|-------------------------|
| Injected Material               | Unmodified (Control) | Pristine TiO <sub>2</sub> | Silane-TiO <sub>2</sub> |
| Injected Material Concentration | Nil                  | 150 mg/L                  | 150 mg/L                |
| Na (mg/L)                       | 80.00                | 96.00                     | 108.00                  |
| Mg (mg/L)                       | 6.00                 | 7.20                      | 8.10                    |
| Al (mg/L)                       | 10.00                | 12.00                     | 13.50                   |
| K (mg/L)                        | 18.00                | 21.60                     | 24.30                   |
| Ca (mg/L)                       | 75.00                | 90.00                     | 101.25                  |
| Fe (mg/L)                       | 14.00                | 16.80                     | 18.90                   |
| Zn (mg/L)                       | 7.00                 | 8.40                      | 9.45                    |
| Cu (mg/L)                       | 1.50                 | 1.80                      | 2.03                    |
| Pb (mg/L)                       | 0.60                 | 0.72                      | 0.81                    |
| Mn (mg/L)                       | 5.00                 | 6.00                      | 6.75                    |

To move beyond the morphological and semi-quantitative elemental data from SEM/EDX, the filters were subjected to acid digestion and the resulting solutions were analyzed using ICP-OES. This procedure provides a precise quantitative determination of the mass of specific elemental species captured during the 15-day sampling period. The results, presented as concentrations in Fig. 7, offer a direct and robust comparison of the capture efficiencies of the three filter types. The data in Table 2 reveal a clear and consistent trend across all ten

metallic elements analyzed. The unmodified control filter (yellow bars) established a baseline capture level for the ambient aerosol. As expected, this PM was dominated by crustal elements such as Na, Ca, and K, which are characteristic of suspended road dust and soil-derived particles in an urban environment (Zeb *et al.* 2018). The pristine TiO<sub>2</sub> filter (orange bars) demonstrated a systematically enhanced capture for every single element. For example, the captured mass of Ca increased from approximately 75 mg/L on the control filter to 90 mg/L on the TiO<sub>2</sub> filter.

This uniform improvement confirms the theory that by coating the fibers with the high-surface-area TiO<sub>2</sub> nano-scaffold, the physical trapping efficiency of the filter is significantly enhanced. The most significant finding of this analysis is the performance of the APTES–TiO<sub>2</sub> filter (red bars), which consistently and substantially outperformed both the control and the pristine TiO<sub>2</sub> filter across all measured species. This two-step improvement is a critical finding. The initial jump in performance from unmodified to TiO<sub>2</sub> can be primarily attributed to the enhanced surface area and more complex topography. However, the subsequent and significant performance jump from TiO<sub>2</sub> to APTES–TiO<sub>2</sub> (Ca increasing from 90 mg/L to over 100 mg/L) provides direct quantitative evidence of an enhanced chemical affinity imparted by the surface functionalization. This enhancement is attributed to the amine functional groups (–NH<sub>2</sub>) introduced by the APTES. These groups are known to act as effective Lewis bases, forming strong coordination complexes with metal ions, which are often present as oxides or salts in particulate matter (Donga *et al.* 2022). This allows the filter to chemisorb particles, providing a much stronger capture mechanism than mere physisorption. This effect is not only evident in the macro-elements but is also, and more importantly, confirmed in the capture of toxic heavy metals.

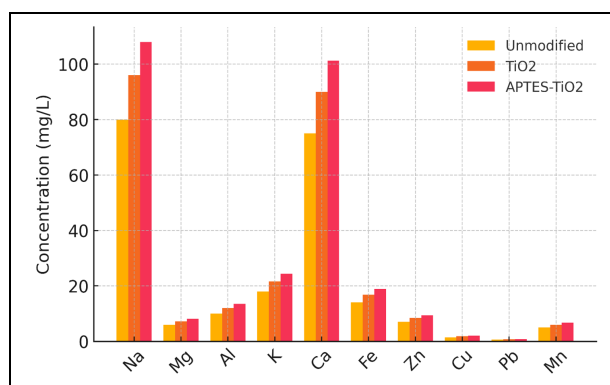


**Fig. 7: Quantitative elemental analysis of captured PM<sub>2.5</sub> via ICP-OES**

The APTES–TiO<sub>2</sub> filter shows a markedly superior capture of Zn, Cu, and Pb. The enhanced removal of these hazardous pollutants, which are of

significant environmental and human health concern (Baltrėnaitė *et al.* 2014), highlights the practical efficacy of the chemical functionalization approach. These quantitative data fully corroborate the qualitative and semi-quantitative findings from the SEM/EDX analysis (Fig. 5), confirming that aminosilane functionalization provides a robust and highly effective pathway for improving PM capture.

### 3.6 Optical Sensing Evaluation via LIBS

In addition to evaluating the total particle capture capacity of the filters via bulk digestion (ICP-OES), their potential for use as active substrates for *in situ*, rapid optical sensing was investigated. Laser-induced breakdown spectroscopy (LIBS) was selected for this purpose due to its ability to perform real-time, micro-scale elemental analysis directly on solid samples. As shown in Fig. 8, this technique involves focusing a high-energy, pulsed laser beam onto the filter surface. This ablates a small volume of the captured particulate matter and the underlying substrate, generating a high-temperature plasma. As this plasma cools, the excited atoms and ions relax to their ground states, emitting photons at characteristic wavelengths. By collecting this light with a spectrometer, the elemental composition of the captured PM (Zn at 330.2 nm, Na at 589.5 nm, Ti at 506.4 nm) was identified. The primary quantitative results of this analysis are presented in Fig. 9, which plots the normalized emission intensities for the ten target elements across the three filter types. The data in Table 3 reveal an unambiguous and highly consistent trend. For every element analyzed, the unmodified filter (yellow) produced the lowest signal intensity, the pristine TiO<sub>2</sub> filter (orange) produced an intermediate signal, and the APTES–TiO<sub>2</sub> filter (red) generated the strongest signal by a significant margin.

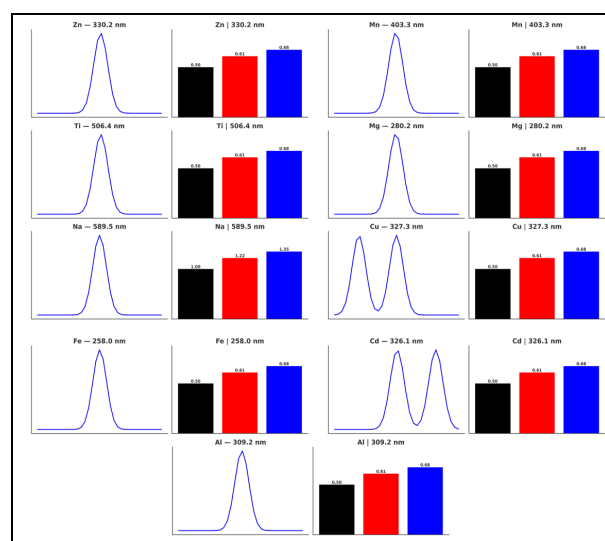


**Fig. 8: Surface analysis of filters after exposure using LIBS**

This graduated enhancement is not only statistically significant for high-concentration crustal elements such as Na and Ca but is also, and more critically, observed for hazardous trace metals such as Zn, Cu, and Pb, which are often present at much lower concentrations. This systematic signal enhancement can be attributed to a powerful synergistic combination of two distinct mechanisms. The first is a straightforward mass-loading effect. The LIBS signal intensity is fundamentally proportional to the number of target atoms ablated by the laser pulse. As comprehensively demonstrated by both the visual SEM evidence (Fig. 5) and the quantitative ICP-OES data (Fig. 7), the APTES–TiO<sub>2</sub> filter captured a substantially higher mass of all elemental species.

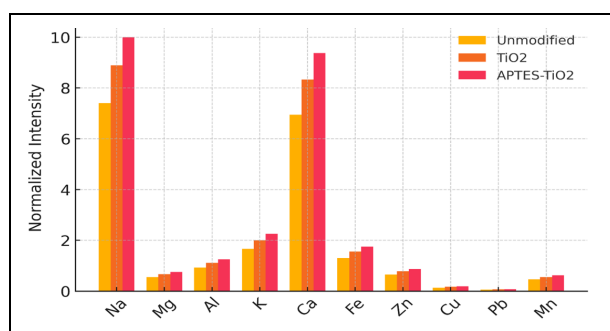


**Fig. 9: Bar chart summarizing the normalized LIBS intensities (a.u.) for all detected elements**

Therefore, any random laser shot on its surface would ablate a larger quantity of analyte, naturally leading to a stronger emission signal (Laserna *et al.* 2018). This finding positions LIBS as a valid, rapid-analysis technique that effectively corroborates the results from the more laborious, time-consuming digestion methods. However, the second mechanism, substrate signal enhancement, is arguably more significant from a material-science perspective. The increase in signal is not merely a linear reflection of the increased mass. The jump in intensity from the unmodified to the pristine TiO<sub>2</sub> filter suggests the TiO<sub>2</sub> nanostructure itself is acting as an active-enhancement substrate. This phenomenon is known as Nanostructure-Enhanced LIBS (NELIBS). The nanostructured coating, as opposed to the smooth bulk quartz fiber, provides superior plasma confinement. The nanostructure traps the plasma, reduces rapid heat dissipation into the filter substrate, and allows for more efficient energy coupling from the laser to the target particles.

This results in a hotter, denser, and more sustained plasma, which in turn leads to more complete atomization and excitation of the captured analytes, yielding a stronger emission signal per unit of mass (Palop *et al.* 2023). The APTES–TiO<sub>2</sub> filter appears to optimize this effect, as the chemical functionalization provides intimate chemical bonding and superior thermal contact between the captured particles and the enhancing

substrate, maximizing the energy transfer and subsequent signal output.

**Table 3. Distribution determined by LIBS**

| Element | Unmodified | TiO <sub>2</sub> | APTES–TiO <sub>2</sub> |
|---------|------------|------------------|------------------------|
| Na      | 7.4        | 8.8              | 10                     |
| Mg      | 0.55       | 0.66             | 0.75                   |
| Al      | 0.92       | 1.11             | 1.25                   |
| K       | 1.66       | 2                | 2.25                   |
| Ca      | 6.94       | 8.33             | 9.375                  |
| Fe      | 1.29       | 1.55             | 1.75                   |
| Zn      | 0.64       | 0.77             | 0.875                  |
| Cu      | 0.14       | 0.16             | 0.1875                 |
| Pb      | 0.055      | 0.066            | 0.075                  |
| Mn      | 0.462      | 0.55             | 0.625                  |

The LIBS analysis confirms that the APTES–TiO<sub>2</sub> material is a dual-function substrate. It demonstrates superior chemical affinity for capturing a higher mass of pollutants, and simultaneously acts as an active sensing platform that significantly amplifies the optical detection signal for those same pollutants. This property is critical as it drastically lowers the effective limit of detection (LOD), opening the possibility of integrating these filters into in-field monitoring systems for real-time, sensitive analysis of airborne heavy metals.

#### 4. COMPARATIVE VALIDATION OF LIBS AGAINST ICP-OES

A critical objective of this research, beyond developing the capture substrate, was to evaluate the feasibility of using LIBS as a rapid, *in situ*, and minimally destructive analytical method. This requires a rigorous validation against an established, trusted technique. For quantitative elemental analysis of environmental samples, ICP-OES is the definitive benchmark, offering exceptional accuracy and low detection limits. However, it is an inherently destructive, laboratory-bound, and time-consuming method that requires complete sample digestion (Mehdizadeh *et al.* 2025). By contrast, LIBS offers a compelling alternative as it is exceptionally fast (requiring seconds per measurement), can be field-deployed, and is only micro-destructive, allowing for a large number of spatial measurements to be taken across a single filter (Elazem, 2023). To validate the LIBS-based approach, the relative signal intensities (in arbitrary units) obtained from LIBS (Fig. 9) were directly compared against the absolute concentration data (in mg/L) obtained from the destructive ICP-OES analysis (Fig. 7). Fig. 10 provides a direct visual comparison of these two datasets for four representative elements: two high-concentration macro-elements (Na and Mn) and two high-priority trace heavy metals (Zn and Cu). This

comparative analysis reveals a remarkably strong and consistent positive correlation between the two techniques. For all four elements, and indeed for all elements measured in this study, the qualitative trend in capture efficiency is identical. Both ICP-OES and LIBS independently and unequivocally confirm the same graduated performance. The unmodified filter shows the lowest concentration/intensity, the pristine  $\text{TiO}_2$  filter shows an intermediate value, and the APTES- $\text{TiO}_2$  filter consistently yields the highest quantitative result.

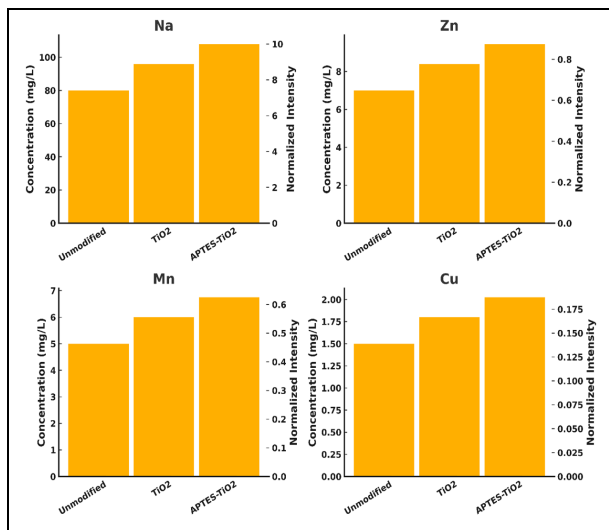


**Fig. 10: Comparative validation of LIBS with ICP-OES**

This one-to-one correspondence in the performance ranking is a critical finding. It demonstrates that while LIBS provides a relative intensity and ICP-OES provides an absolute concentration, the LIBS signal is a highly reliable and faithful proxy for the true elemental mass loading. This strong positive correlation bridges the gap between slow, precise laboratory work and fast field analysis. The data in Fig. 10 effectively demonstrate that LIBS can be used to determine the relative performance of different filter media or to map the relative severity of a pollution event. This validation is a key outcome of the study, as it proves that the developed APTES- $\text{TiO}_2$  filter is not just a passive capture medium but can be successfully integrated with an optical sensing system (like LIBS) for on-site, near real-time monitoring. This capability is of immense practical value, enabling applications such as identifying high-pollution events, mapping environmental hotspots, or providing rapid feedback on occupational exposure, all without the significant cost and delay associated with traditional laboratory-based chemical analysis.

## 5. CONCLUSION

This study successfully demonstrated the fabrication and superior performance of a dual-function

air filtration and sensing substrate based on aminosilane-grafted titanium dioxide ( $\text{TiO}_2$ ) nanoparticles. The comprehensive characterization provided unequivocal evidence of the material's successful synthesis. The morphological changes and elemental addition of nitrogen and silicon were confirmed by SEM and EDX studies, while FTIR and XRD verified the covalent grafting of the APTES molecule, via Ti-O-Si bonds, while preserving the underlying crystalline anatase  $\text{TiO}_2$  structure.

The true efficacy of this modification was revealed in the performance testing. A 15-day ambient air exposure demonstrated the profound synergistic effect of the nanocoating. The pristine  $\text{TiO}_2$  NPs offered a moderate performance boost over the unmodified control by enhancing physical capture mechanisms through increased surface area and complex topography. However, the APTES- $\text{TiO}_2$  filter substantially outperformed both. Furthermore, the LIBS analysis not only corroborated the superior mass capture of the functionalized filter but also revealed its second, equally important function. The nanostructured, chemically active surface acted as a hot substrate, dramatically amplifying the optical signal of the captured PM.

In conclusion, the APTES- $\text{TiO}_2$  material proved to be an advanced, dual-function substrate that both captures a higher mass of toxic pollutants through a synergistic physical and chemical mechanism and enhances their optical detectability for *in situ* sensing. This work provides a clear pathway for developing next-generation active monitoring systems capable of real-time, sensitive analysis of airborne contaminants.

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## CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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## REFERENCES

- Amadi, C. W., The Impact of Air Borne Toxins from Gas Flaring on Cardiopulmonary and Other Systemic Functions, *Sch. Int. J. Anat. Physiol.*, 8(1), 12-28(2025).  
<https://doi.org/10.36348/sijap.2025.v08i01.003>
- Aslanidou, D., Karapanagiotis, I. and Panayiotou, C., Tuning the wetting properties of siloxane-nanoparticle coatings to induce superhydrophobicity and superoleophobicity for stone protection, *Mater. Des.*, 108, 736-744(2016).  
<https://doi.org/10.1016/j.matdes.2016.07.014>
- Baltrėnaitė, E., Baltrėnas, P., Lietuvninkas, A., Šerevičienė, V. and Zuokaitė, E., Integrated evaluation of aerogenic pollution by air-transported heavy metals (Pb, Cd, Ni, Zn, Mn and Cu) in the analysis of the main deposit media, *Environ. Sci. Pollut. Res.*, 21(1), 299-313(2014).  
<https://doi.org/10.1007/s11356-013-2046-6>
- Bhowmick, D. K., Linden, S., Devaux, A., De Cola, L. D. and Zacharias, H., Functionalization of Amorphous SiO<sub>2</sub> and 6H-SiC (0001) Surfaces with Benzo [ghi] perylene-1, 2-dicarboxylic Anhydride via an APTES Linker, *Small.*, 8(4), 592-601(2012).  
<https://doi.org/10.1002/smll.201101941>
- Brook, R. D., Rajagopalan, S., Pope III, C. A., Brook, J. R., Bhatnagar, A., Diez-Roux, A.V., Holguin, F., Hong, Y., Luepker, R.V., Mittleman, M. A., Peters, A., Siscovick, D., Smith, S. C., Whitsel, L. And Kaufman, J. D., Particulate matter air pollution and cardiovascular disease: an update to the scientific statement from the American Heart Association, *Circulation*, 121(21), 2331-2378(2010).  
<https://doi.org/10.1161/CIR.0b013e3181dbecel>
- Chowdhury, M., Ghosh, B., Rabha, R. and Padhy, P. K., Assessment of Haematological and Respiratory Health Risk from Air Pollution, *Airborne Part. Matter. Springer, Chem.*, 109-125(2025).  
[https://doi.org/10.1007/978-3-031-84408-9\\_7](https://doi.org/10.1007/978-3-031-84408-9_7)
- Darr, J. A., Zhang, J., Makwana, N. M. and Weng, X., Continuous hydrothermal synthesis of inorganic nanoparticles: applications and future directions, *Chem. Rev.*, 117(17), 11125-11238(2017).  
<https://doi.org/10.1021/acs.chemrev.6b00417>
- Donga, C., Mishra, S. B., Aziz, A. S. A. E., Ndlovu, L. N., Mishra, A. K. and Kuvarega, A. T., (3-Aminopropyl) Triethoxysilane (APTES) functionalized magnetic nanosilica graphene oxide (MGO) nanocomposite for the comparative adsorption of the heavy metal [Pb (II), Cd (II) and Ni (II)] ions from aqueous solution, *J. Inorg. Organomet. Polym. Mater.*, 32, 2235-2248((2022).  
<https://doi.org/10.1007/s10904-022-02287-z>
- Elazem, M. A. E. A., LIBS Principles, Advantages, Applications, Outline of Nanostructure Enhanced LIBS (NELIBS), *J. Basic Environ. Sci.*, 10(1), 26-38(2023).  
<https://doi.org/10.21608/jbes.2023.372068>
- Gatou, M. A., Syrrakou, A., Lagopati, N. and Pavlatou, E. A., Photocatalytic TiO<sub>2</sub>-based nanostructures as a promising material for diverse environmental applications: a review, *React.*, 5(1), 135-194(2024).  
<https://doi.org/10.3390/reactions5010007>
- Guo, Y., Cheng, C., Wang, J., Wang, Z., Jin, X., Li, K., Kang, P. and Gao, J., Detection of reactive oxygen species (ROS) generated by TiO<sub>2</sub> (R), TiO<sub>2</sub> (R/A) and TiO<sub>2</sub> (A) under ultrasonic and solar light irradiation and application in degradation of organic dyes, *J. Hazard. Mater.*, 192(2), 786-793(2011).  
<https://doi.org/10.1016/j.jhazmat.2011.05.084>
- Hageman, K. J., Bogdal, C. and Scheringer, M., Long-range and regional atmospheric transport of POPs and implications for global cycling, *Compr. Anal. Chem.*, 67, 363-387(2015).  
<https://doi.org/10.1016/B978-0-444-63299-9.00011-9>
- Hu, A., Li, R., Chen, G. and Chen, S., Impact of respiratory dust on health: a comparison based on the toxicity of PM<sub>2.5</sub>, silica, and nanosilica, *Int. J. Mol. Sci.*, 25(14), 7654(2024).  
<https://doi.org/10.3390/ijms25147654>
- Islam, R., Khair, N., Ahmed, D. M. and Shahariar, H., Fabrication of low cost and scalable carbon-based conductive ink for E-textile applications, *Mater. Today Commun.*, 19, 32-38(2019).  
<https://doi.org/10.1016/j.mtcomm.2018.12.009>
- Jena, M. C., Mishra, S. K. and Moharana, H. S., Challenges and way forward to maintain air quality standard in urban areas, *Global Environ. Eng.*, 10, 33-43(2023).  
<https://doi.org/10.15377/2410-3624.2023.10.4>
- Karri, R. R., Vera, T., Hassan, S. K. M., Khoder, M. I., Dehghani, M. H., Mubarak, N. M. and Ravindran, G., Classification, sources, and occurrence of outdoor air pollutants: a comprehensive overview, *Health Environ. Eff. Ambient Air Pollut.*, 1, 1-34(2024).  
<https://doi.org/10.1016/B978-0-443-16088-2.00002-8>
- Khan, N., Garg, S., Arora, I., Hegde, G., Sagadeven, S., Ledwani, L. and Chandra, A., Immobilization of TiO<sub>2</sub> on Various Substrates, *Nanostruct. TiO<sub>2</sub>.*, 5, 87-114(2025).  
<https://doi.org/10.1002/9783527848348.ch05>
- Laserna, J., Vadillo, J. M. and Purohit, P., Laser-induced breakdown spectroscopy (LIBS): Fast, effective, and agile leading edge analytical technology, *Appl. Spectrosc.*, 72(1), 35-50(2018).  
<https://doi.org/10.1177/0003702818791926>
- Li, C., Chen, P., Kang, S., Yan, F., Hu, Z., Qu, B. and Sillanpää, M., Concentrations and light absorption characteristics of carbonaceous aerosol in PM<sub>2.5</sub> and PM<sub>10</sub> of Lhasa city, the Tibetan Plateau, *Atmos. Environ.*, 127, 340-346(2016).  
<https://doi.org/10.1016/j.atmosenv.2015.12.059>

- Li, G., Lv, L., Fan, H., Ma, J., Li, Y., Wan, Y. and Zhao, X. S., Effect of the agglomeration of TiO<sub>2</sub> nanoparticles on their photocatalytic performance in the aqueous phase, *J. Colloid Interf. Sci.*, 348(2), 342-347(2010).  
<https://doi.org/10.1016/j.jcis.2010.04.045>
- Li, M., Gazang, C., Ge, H., Li, J., Huang, T., Gao, H., Zhao, Y., Mao, X., Du, J., Wu, M. and Ma, J., The atmospheric travel distance of persistent organic pollutants-revisit and application in climate change impact on long-rang transport potential, *Atmos. Res.*, 255, 105558(2021).  
<https://doi.org/10.1016/j.atmosres.2021.105558>
- Mehdizadeh, M., Omid, A., Ikegwu, T. M., Okolo, C. A., IfedibaluChukwu, E. I. and Kumasi, L. C. N., Laser-Induced Breakdown Spectroscopy (LIBS) for Rapid Food Safety Monitoring: Advancements, Applications, and Future Directions, *Food Saf. Health.*, xxxx, 70046(2025).  
<https://doi.org/10.1002/fsh3.70046>
- Moradi, M., Behnoush, A. H., Kangevari, M. A., Moghaddam, S. S., Soleimani, Z., Esfahani, Z., Naderian, M., Malekpour, M. R., Rezaei, N., Keykhaei, M., Khanmohammadi, S., Tavolinejad, H., Rezaei, N., Larijani, B. and Farzadfar, F., Particulate matter pollution remains a threat for cardiovascular health: findings from the global burden of disease 2019, *J. Am. Heart Assoc.*, 12(16), e029375(2023).  
<https://doi.org/10.1161/JAHA.123.029375>
- Mukherjee, A. and Agrawal, M., A global perspective of fine particulate matter pollution and its health effects, *Rev. Environ. Contam. Toxicol.*, 244, 5-51(2017).  
[https://doi.org/10.1007/398\\_2017\\_3](https://doi.org/10.1007/398_2017_3)
- Nagaraj, K., Radha, S., Deepa, C. G., Raja, K., Umapathy, V., Badgujar, N. P., Parekh, N. M., Manimegalai, T., Devi, L. A. and Uthra, C., Photocatalytic advancements and applications of titanium dioxide (TiO<sub>2</sub>): Progress in biomedical, environmental, and energy sustainability, *Next Res.*, 2(1), 100180(2025).  
<https://doi.org/10.1016/j.nexres.2025.100180>
- Nawaz, H., Umar, M., Maryam, R., Nawaz, I., Razzaq, H., Malik, T. and Liu, X., Polymer Nanocomposites based on TiO<sub>2</sub> as a reinforcing agent: An Overview, *Adv. Eng. Mater.*, 24(11), 2200844(2022).  
<https://doi.org/10.1002/adem.202200844>
- Omokpariola, D. O., Spatiotemporal Analysis of Atmospheric Aerosols in African Environments Using MERRA-2 Data (1980-2024): Impacts on Climate Extremes, *iSci.*, 28(8), 112995(2025).  
<https://doi.org/10.1016/j.isci.2025.112995>
- Öncü, T., Yazman, M. M., Ustaoglu, F., Hristova, E. and Yüksel, B., Source dynamics and environmental risk of street dust as a vector of human exposure to potentially toxic elements in Istanbul, Türkiye, *Sci. Rep.*, 15(1), 30550(2025).  
<https://doi.org/10.1038/s41598-025-11472-2>
- Özel, C., Akat, C., Alosmanov, R., Kahveci, M. U., Emir, C. and Yücel, S., Surface modification of zeolite and kaolin with 3-(aminopropyl) triethoxysilane and 3-(trimethoxysilyl) propyl methacrylate, *Bulg. Chem. Commun.*, 53(4), 464-470(2021).  
<https://doi.org/10.34049/bcc.53.4.T003>
- Palop, C. B., Purohit, P., Fortes, F. J. and Laserna, J., Ultrafast laser excitation improves LIBS performance for the analysis of optically trapped single nanoparticles owing to characteristic interaction mechanisms, *Anal. Chem.*, 95(39), 14541-14550(2023).  
<https://doi.org/10.1021/acs.analchem.3c01376>
- Riaz, S., Ashraf, M., Hussain, T., Hussain, M. T., Younus, A., Raza, M. and Nosheen, A., Selection and optimization of silane coupling agents to develop durable functional cotton fabrics using TiO<sub>2</sub> nanoparticles, *Fibers Polym.*, 22(1), 109-122(2021).  
<https://doi.org/10.1007/s12221-021-9245-4>
- Rückerl, R., Schneider, A., Breitner, S., Cyrus, J. and Peters, A., Health effects of particulate air pollution: a review of epidemiological evidence, *Inhal. Toxicol.*, 23(10), 555-592(2011).  
<https://doi.org/10.3109/08958378.2011.593587>
- Shandilya, K. K. and Khare, M., Particulate matter: sources, emission rates and health effects, *Adv. Environ. Res.*, 23, 265-322(2012).
- Singh, N., Singh, S. and Mall, R. K., Urban ecology and human health: implications of urban heat island, air pollution and climate change nexus, *Urban Ecol.*, 317-334(2020).  
<https://doi.org/10.1016/B978-0-12-820730-7.00017-3>
- Singh, S., Vishwakarma, P. and Gupta, T., Review of current and future indoor air purifying technologies, *ACS EST Eng.*, 4(11), 2607-2630(2024).  
<https://doi.org/10.1021/acsestengg.4c00460>
- Szczotko, M., Orych, I., Mąka, Ł. and Solecka, J., A review of selected types of indoor air purifiers in terms of microbial air contamination reduction, *Atmos.*, 13(5), 800(2022).  
<https://doi.org/10.3390/atmos13050800>
- Villa, S., Riani, P., Locardi, F. and Canepa, F., Functionalization of Fe<sub>3</sub>O<sub>4</sub> NPs by silanization: use of amine (APTES) and thiol (MPTMS) silanes and their physical characterization, *Mater.*, 9(10), 826(2016).  
<https://doi.org/10.3390/ma9100826>
- Wang, Y. H., Wang, H., Zhao, C. Z. and Zhang, Y., Research progress of air purifier principles and material technologies, *Adv. Mat. Res.*, 1092-1093, 1025-1028(2015).  
<https://doi.org/10.4028/www.scientific.net/AMR.1092-1093.1025>

- West, M., Ellis, A. T., Potts, P. J., Strel, C., Vanhoof, C., Wegrzynek, D. and Wobrauschek, P., Atomic spectrometry update—X-ray fluorescence spectrometry, *J. Anal. At. Spectrom.*, 27(10), 1603-1644(2012).  
<https://doi.org/10.1039/C2JA90045A>
- Woźnica, M., Sobiech, M. and Luliński, P., A fusion of molecular imprinting technology and siloxane chemistry: A way to advanced hybrid nanomaterials, *Nanomater.*, 13(2), 248(2023).  
<https://doi.org/10.3390/nano13020248>
- Xu, Y., Xiao, H. W. and Xiao, H., Amino acid and amine compounds in fine aerosol particles: A review of determination methods, abundances, origins, and atmospheric processes, *Aerosol Sci. Eng.*, 45(3), 1-16(2025).  
<https://doi.org/10.1007/s41810-025-00299-z>
- Yildirim, H. and Kara, A., Effect of van der Waals interactions on the adsorption of olympicene radical on Cu (111): Characteristics of weak physisorption versus strong chemisorption, *J. Phys. Chem. C.*, 117(6), 2893-2902(2013).  
<https://doi.org/10.1021/jp311361e>
- Zaib, S., Lu, J., Yan, G., Yin, X., Lei, X., Shahid, M. Z., Siddique, A. and Al-Nesf, M. A.Y., Characterization of ambient air quality and its relationship with respiratory morbidity in typical cities of Northwest China (NWC), *Air Qual. Atmos. Health*, 2025, 1-15 (2025).  
<https://doi.org/10.1007/s11869-025-01842-0>
- Zeb, B., Alam, K., Sorooshian, A., Blaschke, T., Ahmad, I. and Shahid, I., On the morphology and composition of particulate matter in an urban environment, *Aerosol Air Qual. Res.*, 18(6), 1431-1447(2018).  
<https://doi.org/10.4209/aaqr.2017.09.0340>
- Zhao, J., Milanova, M., Warmoeskerken, M. M. C. G. and Dutschk, V., Surface modification of TiO<sub>2</sub> nanoparticles with silane coupling agents, *Colloids Surf., A.*, 413, 273-279(2012).  
<https://doi.org/10.1016/j.colsurfa.2011.11.033>