

From natural systems to urban environments: a geochemistry-driven approach to enhance air quality monitoring

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As societies tackle escalating challenges due to air pollution, geochemistry-driven solutions are providing essential tools to enhance traditional air quality monitoring methods. This study introduces a novel, integrated, low-cost approach for monitoring key air pollutants with significant climate and/or health impacts. By employing geochemical expertise and skills, this approach addresses limitations in conventional air monitoring, which often struggles to meet the growing global demand for mitigation strategies and does not fit with local issues.

The study was developed in two phases:

- Design, development, and testing of innovative multiparametric monitoring stations, equipped with low-cost sensors for CO₂, CH₄, and PM concentrations.
- Field deployment of low-cost stations at fixed monitoring sites, coupled with a mobile unit equipped with high-tech instruments for CO₂, CH₄, H₂S, and SO₂ concentrations, and $\delta^{13}\text{C-CO}_2$ and $-\text{CH}_4$ values, to assess air pollution in specific regions impacted by both natural and anthropogenic emissions.

To enhance sensor reliability, a machine learning-based calibration algorithm was applied to the low-cost CO₂ and CH₄ sensors, using high-tech analyzers as reference instruments across multiple environments and seasons. This minimized site transferability issues, achieving high accuracy with mean absolute errors below 4 ppm for CO₂ and 40 ppb for CH₄. Meanwhile, the inter-unit repeatability of PM sensors was evaluated with an Intraclass Correlation Coefficient analysis.

The second phase validated this strategy in selected case studies: (i) Vulcano Island and Pozzuoli (southern Italy), where residents live with volcanic-hydrothermal emissions; (ii) Padule di Fucecchio (central Italy), a wetland ecosystem subject to intense urban pressure, accelerating CH₄ production and release into the atmosphere; (iii) a plant for CO₂ exploitation and refining in central Italy, where natural and anthropogenic CO₂- and H₂S-rich emissions occur. Fixed-site monitoring revealed pollutant temporal trends, identifying critical zones for extended monitoring. The mobile unit provided high-resolution spatial mapping, pinpointing key sources and processes based on isotope

chemical data.

This research establishes an integrated fixed-mobile monitoring strategy, combining low-cost and high-tech instruments as a scalable, adaptable solution for air quality assessment. The findings highlight its potential to support public health, inform policy, and foster community engagement, paving the way for next-generation air monitoring networks.