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Mid-term Performance and Calibration of Multi-sensor Low-Cost Systems for Air Quality Monitoring in Urban Environments

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RESEARCH

Mid-term Performance and Calibration of Multi-sensor Low-Cost Systems for Air Quality Monitoring in Urban Environments

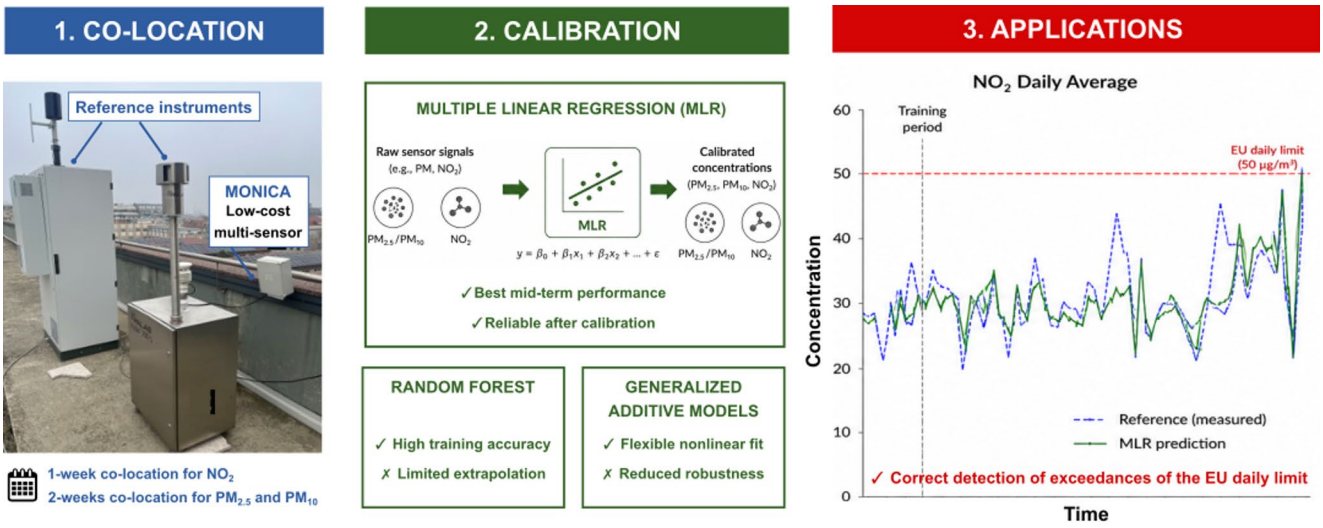
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Abstract

This study evaluates mid-term calibration strategies for MONICA, a compact low-cost multi-sensor device for urban air quality monitoring, in the context of the upcoming EU Air Quality Directive 2024/2881. A key objective is to optimize the trade-off between calibration duration and long-term monitoring performance, balancing statistical robustness with practical deployment constraints. This question is particularly relevant in mid-latitude regions, where seasonal variability may introduce biases if calibration and observation periods are misaligned. Over a three-and-a-half-month winter co-location with reference-grade instruments, we assessed three models—Multiple Linear Regression (MLR), Random Forest (RF), and Generalized Additive Models (GAM)—across three pollutants: $PM_{2.5}$, PM_{10}, and NO_2. MLR emerged as the most stable model for temporal extrapolation, while RF and GAM, although accurate short-term, showed performance degradation outside the training range. A two-week calibration period was sufficient for PM, whereas NO_2 required only one week. Although sensor accuracy declines over time-especially for NO_2—the MONICA system remains effective in tracking temporal trends and identifying regulatory exceedances. These results support the development of efficient and scalable low-cost sensor networks, offering practical insights for planning reliable air quality monitoring campaigns.

Graphical abstract



Keywords Low-cost sensors · Air quality monitoring · Sensors calibration · Machine learning regression · Sensor co-location

Sofia Fellini and Davide Gallione have contributed equally to this work.

1 Introduction

Air pollution is a leading environmental health risk, contributing to millions of premature deaths annually through respiratory and cardiovascular diseases e.g., (Di et al. 2017; Hystad et al. 2020; Lin et al. 2021; De Bont et al. 2024). Urban areas are particularly vulnerable due to high emission densities and complex morphologies that limit pollutant dispersion (Salizzoni et al. 2009; Fellini et al. 2021).

Among urban air pollutants, particulate matter (PM) and nitrogen dioxide (NO_2) remain the most critical due to their documented health effects and widespread exceedance of regulatory thresholds (Kim et al. 2015; Chen and Hoek 2024; Kang and Choi 2024). $PM_{2.5}$ is of particular concern due to its ability to penetrate deep into the respiratory system (Pope and Dockery 2006; WHO 2021), while NO_2 is strongly associated with respiratory inflammation (Khreis et al. 2017; Anenberg et al. 2022; Soulhac et al. 2023). These pollutants are regulated under the updated European Directive 2024/2881 (European Parliament and Council 2024), which tightens air quality standards in line with WHO recommendations and the European Green Deal's zero-pollution ambition.

Accurately estimating ground-level concentrations in urban areas is essential for assessing individual exposure. However, pollutants exhibit high spatiotemporal variability (Steinle et al. 2015; Fellini et al. 2024) that traditional, sparse monitoring networks, managed by environmental agencies, cannot fully capture. Consequently, understanding local air quality often relies on modeling approaches, including deterministic (McHugh et al. 1997; Soulhac et al. 2011; Kim et al. 2018; Suter et al. 2021) and statistical models (Hoek et al. 2008; Beelen et al. 2013; Ma et al. 2024), whose application is often constrained by the available input data and the required spatial resolution.

In recent years, however, the emergence of low-cost sensors (LCS) has enabled high-resolution air quality monitoring, particularly in complex and heterogeneous urban environments (Liu et al. 2024). Characterized by their compactness, low energy requirements, and affordability (Schmitz et al. 2024), LCS are increasingly used to create large-scale real-time monitoring networks that integrate both indoor and outdoor air quality measurements (Tang et al. 2024). LCS systems have been successfully used to monitor air quality in areas lacking official stations, demonstrating their potential to enhance exposure assessments across diverse environments (Cross et al. 2017; Thomas et al. 2018; Johnson et al. 2018; Hagan et al. 2018).

Despite their advantages, low-cost sensors still face significant challenges related to accuracy, precision, and durability (Badura et al. 2018; Cavaliere et al. 2018; Wang et al. 2015; Bulot et al. 2019; Giordano et al. 2021). To address these, LCS are commonly co-located with reference instruments for a calibration period, during which intra-sensor consistency (repeatability over time) and inter-sensor consistency (agreement between sensors and references) are assessed (Tang et al. 2024). Importantly, the selection of a suitable calibration model is a critical step, and its appropriateness depends on the specific pollutant being measured.

PM sensor calibration commonly employs multiple linear regression and machine learning techniques (Venkatraman Jagatha et al. 2021; Zimmerman 2022; Tang et al. 2024). These models often incorporate environmental variables like temperature and humidity, which are known to significantly influence sensor output (Crilley et al. 2018; Di Antonio et al. 2018; Macías-Hernández et al. 2023). Research includes long-term co-location campaigns using large sensor datasets (Datta et al. 2020; Giordano et al. 2021) and assessment of the impact of specific conditions such as particle sources or relative humidity on measurement performance (Badura et al. 2018; Bulot et al. 2019). Reviews by Venkatraman Jagatha et al. (2021) and Giordano et al. (2021) have highlighted both the promise and variability in sensor behavior and calibration strategies.

For NO_2, the literature is more limited and the calibration performances are generally less robust. Previous studies have employed multiple linear regression (Jiao et al. 2016; Mijling et al. 2018; Ratingen et al. 2021), while others have tested machine learning approaches, including random forests (Nowack et al. 2021; Kim et al. 2022) and neural networks (Malings et al. 2019). These works underline the importance of both long-term calibration and the inclusion of environmental covariates to mitigate sensor drift and improve prediction accuracy.

Although previous studies have provided important insights, several key limitations remain. In particular, few works have systematically evaluated calibration strategies for integrated multi-sensor systems measuring both PM and gaseous pollutants simultaneously (Jiao et al. 2016; Cross et al. 2017; Gäbel et al. 2022; Cavaliere et al. 2023). This is a significant gap, given the increasing use of such platforms in urban air quality networks. Moreover, calibration duration is seldom systematically assessed, despite its crucial role in ensuring model reliability under the temporal constraints typical of open-field monitoring deployments. There is currently no standardized co-location duration, and the reported co-location durations in recent works have varied from several days to several months (Levy Zamora et al. 2023). This issue is especially relevant for non-linear and data-driven models which may suffer from reduced generalizability when applied beyond the temporal range of their training data (Nowack et al. 2021). The long-term stability of calibrated sensors and the performance decay also remain poorly understood. These uncertainties hinder the effective

deployment of LCS, especially in long-term monitoring where recalibration is costly or logistically challenging.

To address these limitations, this study evaluates the MONICA device (De Vito et al. 2020, 2021; Fattoruso et al. 2022; De Vito et al. 2023; Ramel-Delobel et al. 2024). This integrated platform allows for multi-pollutant monitoring, relevant for urban-scale networks. We assess three calibration models (Multiple Linear Regression, MLR; Random Forest, RF; and Generalized Additive Models, GAM) across NO_2, $PM_{2.5}$, and PM_{10}. The analysis addresses three core questions: (1) which calibration models provide the highest accuracy for each pollutant; (2) what is the minimum co-location period required to achieve stable and reliable calibration, depending on the model; and (3) for how long calibrated sensors maintain acceptable performance over time. A key focus of the study is to determine the maximum practical ratio between the calibration phase (2) and the total observation period (3). This is especially relevant for two reasons. First, in mid-latitude regions, extending the calibration period over several weeks or months may introduce seasonal biases if environmental conditions differ between the training and deployment phases. Second, given the limited lifespan of LCS (typically 1–2 years), an excessively long co-location phase limits the device's actual monitoring utility.

The campaign was conducted in the city of Turin (Po Valley), one of Europe's major air pollution hotspots, where persistent pollution levels are driven by intense local emissions and unfavorable meteorological conditions (Bo et al. 2020).

This work offers operational guidance for LCS-based campaigns, optimizing calibration strategies for robust and scalable monitoring networks for urban air pollution assessment.

2 Material and Methods

The experimental campaign was conducted in Turin, Italy, over a period of approximately four months, from November 6, 2023, to February 25, 2024. During this time, the MONICA multi-sensor systems were co-located with certified reference instruments at the DIATI (Department of Environment, Land and Infrastructure Engineering, Politecnico di Torino) monitoring station. This period allowed the systems to be exposed to a wide range of typical urban winter concentrations: hourly averaged concentrations of NO_2 ranged from 3 to 85 μg/m^3, while PM_{10} and $PM_{2.5}$ varied between 2–132 μg/m^3 and 1–132 μg/m^3, respectively. These data provided the basis for both the development (training) of the regression models and the subsequent validation of their temporal stability, as the sensors remained in the same location throughout the entire campaign.

2.1 MONICA Low Cost Sensors

The ENEA MONICA device is a compact, cost-effective microsensor designed for air quality monitoring in both fixed and mobile applications. It is housed in a robust, waterproof enclosure (see box in Fig. 1) with mesh-protected inlets to allow air exchange while preventing contamination from insects or debris. Inside the box, the monitoring setup includes both the MONICA sensor and a Raspberry Pi unit. The Raspberry Pi communicates with the MONICA device via Bluetooth to receive raw data, and–when connected to the local Wi-Fi network–it transfers the collected data to a cloud-based storage and visualization platform. The Raspberry Pi also allows for local access to raw files and remote control via RealVNC, enabling troubleshooting and system monitoring when necessary.

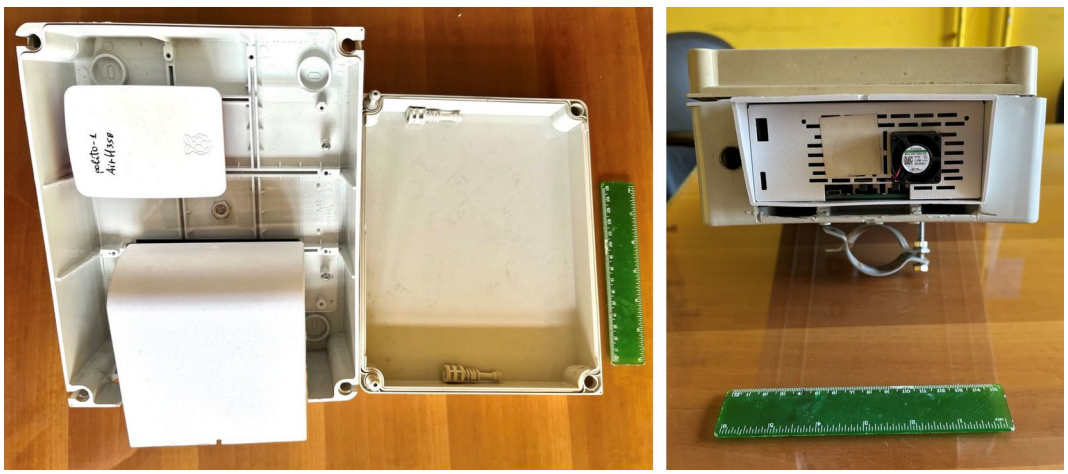


Fig. 1 ENEA MONICA device. Left: Internal view of the device. Right: Close-up of the chamber housing the PM and NO_2 microsensors. The overall dimensions of the device are 19 × 24 × 10 cm^3, and the microsensor chamber measures 12.5 × 13.5 × 6 cm^3. A 15 cm ruler is placed next to the device for scale reference

The MONICA system incorporates a Plantower PMS7003 optical particle counter (Beijing Plantower Co., Ltd 2024) and several electrochemical sensors for gas monitoring: the Alphasense CO-A4 (Alphasense - AMETEK Inc. 2024) for carbon monoxide, the NO2-A43F (Alphasense - AMETEK Inc. 2024) for nitrogen dioxide, and the OX-A431 (Alphasense - AMETEK Inc. 2026) for ozone detection. The MONICA device also records meteorological parameters such as temperature (T) and relative humidity (rH) via a DHT22 sensor (Guangzhou Aosong Electronics Co., Ltd. 2026). Details regarding the measurement ranges for the sensors deployed in this study are summarized in Table 1.

The MONICA system estimates NO_2 concentrations using the voltage signals from two electrochemical sensors: the NO_2-selective sensor (NO2-A43F) and the OX-A431 sensor, which is primarily sensitive to ozone but also exhibits cross-sensitivity to NO_2. Both sensors (Alphasense A4 series) provide outputs from a working electrode (WE) and an auxiliary electrode (AE); the latter is specifically designed to physically compensate for temperature-dependent baseline shifts (Spinelle et al. 2015; Castell et al. 2017). The corresponding signals (NO_2WE, NO_2AE, NO_2O_3WE, NO_2O_3AE) are used to correct the NO_2 response by accounting for both thermal drift and ozone interference (Spinelle et al. 2015; Castell et al. 2017).

Particulate matter concentrations are derived from the optical particle counter. It provides mass concentrations under standard conditions ($PM_{2.5}$SP, PM_{10}SP in Table 1), assuming a reference particle size distribution and dry aerosol state. Since field conditions rarely conform to these assumptions, the system also provides adjusted values ($PM_{2.5}$AE, PM_{10}AE in Table 1) that account for ambient temperature and relative humidity. These corrections are applied using a factory-defined regression model, which internally adjusts the raw signals based on typical atmospheric responses. However, this model is not site-specific: the regression parameters are predefined by the manufacturer and remain fixed across locations and conditions.

Additionally, the MONICA device reports particle number concentrations for particles larger than 2.5 µm ($NP_{2.5}$) and 10 µm (NP_{10}), which provide complementary information on aerosol number and size distribution.

Data collected by MONICA are transmitted in real-time to a dedicated web platform, where users can visualize measurements through time-series graphs and location-based air quality maps.

2.2 Certified Instruments for Sensor Calibration and Validation

Two air quality monitoring stations were used to provide reference measurements for the calibration and validation of the MONICA sensors: the fixed station CC-Green Roof Lab (Fig. 2, left) and the mobile laboratory CC-TrAIRer Lab (Boanini et al. 2021) (Fig. 2, right). Both stations are equipped with certified instruments for air quality and meteorological monitoring.

Specifically, the following reference instruments were used in this study: a Palas Fidas 200 S (2 in Fig. 2) for particulate matter ($PM_{2.5}$ and PM_{10}), an Envea AC32e analyzer (3 in Fig. 2) and a Serinus 40 analyzer (4 in Fig. 2) for NO_2 , and a Davis Vantage Pro 2 weather station (5 in Fig. 2) for temperature, relative humidity, precipitation, wind speed, and direction.

The Palas Fidas 200 S is an optical spectrometer designed for atmospheric pollution monitoring, certified according to the EN 16450 standard. It enables continuous and simultaneous measurement of various particulate fractions: PM_1, $PM_{2.5}$, PM_4, PM_{10}, and total suspended particles (TSP), along with particle number concentration and size

Table 1 Sensor output parameters from the ENEA MONICA low-cost system relevant to the measurement of NO $_2$, $PM_{2.5}$, PM_{10}, temperature and humidity

Nitrogen dioxide – NO_2		
NO_2WE	Terminal voltage (mV)—Working Electrode, sensitive primarily to NO_2	Alphasense NO2-A43F Range: 0–20 ppm
NO_2AE	Terminal voltage (mV)—Auxiliary Electrode, for interference compensation	
NO_2O_3WE	Terminal voltage (mV)—Working Electrode, sensitive to O_3 and NO_2	Alphasense OX-A431 Range: 0–20 ppm
NO_2O_3AE	Terminal voltage (mV)—Auxiliary Electrode, for interference compensation	
Particulate Matter—PM		
$PM_{2.5}$SP	$PM_{2.5}$ concentration (µg/m^3)—under standard particle conditions	Plantower PMS7003 Range: 0–500 µg/m^3
PM_{10}SP	PM_{10} concentration (µg/m^3)—under standard particle conditions	
$PM_{2.5}$AE	$PM_{2.5}$ concentration (µg/m^3) under atmospheric conditions	
PM_{10}AE	PM_{10} concentration (µg/m^3) under atmospheric conditions	
$NP_{2.5}$	Number of particles with diameter > 2.5 µm	
NP_{10}	Number of particles with diameter > 10 µm	
Meteorological Parameters		
rH	Relative Humidity (%)	DHT22. Range: 0–100% RH; [−40, +80] °C
T	Air Temperature (°C)	

Sensor models and their manufacturer-specified measurement ranges are provided in the final column



Fig. 2 Positioning of ENEA MONICA microsensors and reference instruments for calibration at DIATI—Politecnico di Torino. Left: CC-Green Roof. Right: CC-TrAIRer Lab. 1—ENEA MONICA™ microsensors, 2—Palas Fidas 200 S optical sensor for PM measurement, 3—Sampling head for ENVEA AC32e analyzer for NO_2 measurements, 4—Sampling head for Serinus 40 analyzer for NO_2 measurements, 5—Davis Vantage Pro 2 weather station

distribution. The measurement range is 0.18 µm to 18 µm. For this study, only $PM_{2.5}$ and PM_{10} data were used.

The Serinus 40 NOx Analyzer is a high-precision instrument designed to measure nitrogen oxides using the gas-phase chemiluminescence method. Ambient air, pre-filtered through 47 mm Teflon filters to remove large particles, enters the reaction cell through two alternating pathways dedicated to nitric oxide (NO) and nitrogen oxides (NO_x) measurements. In the first pathway, atmospheric NO reacts with O_3, producing a chemiluminescent signal proportional to its concentration. In the second pathway, the airflow passes through a delay loop and an NO_2-to-NO converter. The delay loop, a coiled flow circuit, ensures proper separation of the two measurement sequences, enabling the sequential detection of NO and total NO_x.

The ENVEA AC32e is an eco-designed reference air quality monitor that utilizes the chemiluminescence principle, which is the standard method for measuring NO_2 and NO concentrations in ambient air (certified according to EN 14211). To measure NO_x, the instrument passes the sample through a heated catalyst, which converts all nitrogen oxides into NO. By alternately introducing and bypassing the catalyst in the sample path, the analyzer compares the resulting signals, allowing for the indirect quantification of NO_2.

The Davis Vantage Pro 2 weather station is designed to monitor and record data related to the weather and climate conditions of a location, with variable frequency. The measured parameters include temperature, atmospheric pressure, humidity, wind speed and direction, solar radiation, rainfall rate, and ultraviolet radiation.

2.3 Regression Models for Calibration of the LCS

Accurate calibration of the MONICA low-cost sensor system is essential to correct for environmental interferences and sensor-specific variability (Spinelle et al. 2015; Castell et al. 2017). In this study, the MONICA device was colocated with the DIATI reference stations described in Sect. 2.2. During the co-location period, MONICA sensor outputs were paired with hourly reference measurements of NO_2, $PM_{2.5}$, and PM_{10}. These data were used to train regression models capable of translating raw sensor signals (e.g., electrode voltages and particle counts) into calibrated pollutant concentrations. This in-field calibration addresses limitations of factory-set models, which do not adapt to local environmental conditions (Lewis et al. 2018; Levy Zamora et al. 2023).

We applied three different regression models commonly used in the literature to calibrate the MONICA devices.

The first model is a Multiple Linear Regression (MLR) (Neter et al. 1996) of the following form:

$$Y = \alpha_0 + \alpha_1 X_1 + \alpha_2 X_2 + \cdots + \alpha_n X_n, \quad (1)$$

where Y is the predicted target variable, α_0 is the intercept, $\alpha_1, \alpha_2, \ldots, \alpha_n$ are the coefficients for each predictor, and $X_1, X_2, \ldots, X_n$ are the input features.

The second model is a Generalized Additive Model (GAM) with smoothing splines applied to each predictor (Wood 2017). GAMs extend linear models by allowing non-linear relationships, providing a more flexible framework to capture subtle trends in the data. The equation for a GAM can be represented as:

$$Y = f_1(X_1) + f_2(X_2) + \cdots + f_n(X_n), \quad (2)$$

where Y is the predicted target variable, $f_1(X_1), f_2(X_2), \ldots, f_n(X_n)$ are smoothing functions of each predictor.

The third model is a Random Forest (RF) regressor. Random forests are ensemble methods that combine multiple decision trees to improve predictive accuracy and mitigate overfitting through averaging (Breiman 2001a). The general equation is:

$$Y = \frac{1}{n}\sum_{i=1}^{n} T_i(X), \tag{3}$$

where Y is the predicted target variable, n is the number of trees, $T_i(X)$ is the output of the i^{th} decision tree, and X is the input feature vector. This approach is particularly effective for capturing non-linear dependencies and complex interactions between variables. The RF model was implemented using the *scikit-learn* library in Python. The number of trees (200) was selected based on a sensitivity analysis where the Root Mean Square Error (RMSE) was evaluated as a function of the number of trees. We observed that the model performance stabilized well before reaching 200 trees; therefore, this value was chosen as an optimal trade-off between predictive accuracy and computational efficiency. While increasing the number of trees typically does not, by itself, induce overfitting (as predictions are obtained through ensemble averaging (Breiman 2001b)) it is recognized that beyond a certain complexity, adding further trees generally yields diminishing returns in performance while increasing the computational burden. Consequently, the chosen threshold was deemed sufficient to ensure both model stability and generalizability without unnecessary complexity. To ensure reproducibility, a fixed random seed (*random_state* = 42) was applied, while other hyperparameters were kept at their default settings to maintain a robust configuration for capturing non-linear relationships.

The calibration was performed using continuous time windows rather than shuffled data to prevent temporal data leakage and to evaluate the sensors' performance under realistic deployment conditions (Nowack et al. 2021). For the same reason, the "time of day" was not included as a predictor; avoiding site-specific temporal features reduces the risk of overfitting to local emission cycles and ensures better model transferability across different locations and periods.

For each pollutant, the regression models initially incorporated all meteorological parameters (temperature and relative humidity) along with pollutant-related parameters from the MONICA system (Table 1).

To optimize the model and ensure its robustness, a systematic feature selection was performed using an all-subset regression approach (implemented via the `bestlm` R function). This procedure evaluated all possible combinations of predictors to identify the most effective subset for each pollutant. The selection process was based on maximizing the model's predictive accuracy while maintaining parsimony; specifically, parameters that did not provide a statistically significant improvement to the regression performance were subsequently excluded.

For illustrative purposes, the following multiple linear regression (MLR) equations correspond to the model calibrated using a two-week training period, which–as will be discussed in the following sections–represents a good trade-off between calibration effort and predictive performance:

$$\mathrm{PM}_{2.5} = \alpha_0 + \alpha_1 \cdot \mathrm{PM}_{2.5}\mathrm{AE} + \alpha_2 \cdot \mathrm{NP}_{2.5} + \alpha_3 \cdot \mathrm{rH} \tag{4a}$$

$$\mathrm{PM}_{10} = \beta_0 + \beta_1 \cdot \mathrm{PM}_{10}\mathrm{AE} + \beta_2 \cdot \mathrm{PM}_{10}\mathrm{SP} + \beta_3 \cdot \mathrm{rH} \tag{4b}$$

$$\mathrm{NO}_2 = \gamma_0 + \gamma_1 \cdot \mathrm{NO}_2\mathrm{WE} + \gamma_2 \cdot \mathrm{NO}_2\mathrm{O}_3\mathrm{WE} + \gamma_3 \cdot \mathrm{rH}. \tag{4c}$$

The regression coefficients from the two-week training period are reported in Table 2. These are dimensional coefficients, as the regression models were trained using the predictors in their original units without normalization.

The same predictor variables shown in Eqs. 4a-c were also used in the generalized additive model (GAM) and the random forest (RF) model.

As shown in Eqs. 4a-c, and in line with previous studies (Ramel-Delobel et al. 2024), relative humidity emerges as a key factor influencing sensor response. In contrast, no explicit dependence is observed between pollutant concentrations and temperature. This outcome, resulting from the feature selection process, can be explained by the specific conditions of the winter campaign, where the observed temperature range was relatively narrow (0.6 to 20.9 °C), and a moderate Pearson correlation coefficient of 0.53 was found between T and rH. Under these specific conditions, the variance associated with temperature may be sufficiently captured by the humidity parameter, rendering T a redundant predictor for the algorithms. Furthermore, as

Table 2 Coefficients for MLR model (Eqs. 4) obtained from the two-week training period

Pollutant	Regression coefficients			
$PM_{2.5}$	$\alpha_0 = 8.420$	$\alpha_1 = 0.516$	$\alpha_2 = -0.036$	$\alpha_3 = -0.090$
PM_{10}	$\beta_0 = 16.207$	$\beta_1 = 0.541$	$\beta_2 = -0.039$	$\beta_3 = -0.152$
NO_2	$\gamma_0 = -1328.265$	$\gamma_1 = 4.468$	$\gamma_2 = -0.137$	–

The coefficients are dimensional and their magnitude reflects the specific scales of the raw sensor outputs (e.g., mV or particle counts)

detailed in Sect. 2.1, the MONICA sensors already incorporate hardware and firmware-level thermal compensations. Among the pollutant-related parameters, some were found to be more influential than others. For instance, the $NP_{2.5}$ parameter, which represents the number of $PM_{2.5}$ particles, was included in the regression model for $PM_{2.5}$ concentration. In contrast, the corresponding NP_{10} parameter for PM_{10} was excluded, as it did not contribute to improving the model's accuracy.

As shown in Eq. 4c and Table 2, the NO_2 model explicitly incorporates the NO_2O_3WE signal from the OX-A431 sensor to compensate for ozone interference. While O_3 levels were typically low during this winter campaign, including these terms ensures that the model is chemically consistent and remains robust against localized or transient fluctuations in ozone concentrations. Nevertheless, further testing during summer months would be necessary to fully assess the sensors' performance under higher O_3 concentrations and broader temperature fluctuations, which could alter the weight of the ozone-correction term. In such scenarios, the inclusion of T might also become essential to maintain model stability.

2.4 Data Processing and Performance Metrics

Although the monitoring campaign spanned the entire period from November 2023 to February 2024 (as described at the beginning of this section), several interruptions affected the operation of the reference instruments, reducing the time windows available for direct comparisons. Specifically, for $PM_{2.5}$ and PM_{10}, comparisons were possible from 6 November 2023 to 5 January 2024, and again from 25 January to 25 February 2024. For NO_2, valid comparison data were available from 6 November 2023 to 5 January 2024, and from 25 January to 4 February 2024.

For the training and evaluation periods, the analysis was organized by full weeks (Monday to Sunday), as field measurement campaigns are typically structured in this manner. As shown in Table 5 in the A, there were 12 full weeks available for particulate matter ($PM_{2.5}$ and PM_{10}) and 9 full weeks for NO_2. Only the weeks with complete data coverage are numbered.

Table 3 Mathematical definitions of the performance metrics used for sensor validation

Metric	Definition
R^2	$1 - \frac{\sum_{i=1}^{N}(C_i - C_{\mathrm{ref},i})^2}{\sum_{i=1}^{N}(C_i - \overline{C})^2}$
RMSE	$\left[\frac{1}{N}\sum_{i=1}^{N}(C_i - C_{\mathrm{ref},i})^2\right]^{0.5}$
FB	$\frac{\sum_{i=1}^{N}\left(\overline{C_i} - \overline{C}_{\mathrm{ref},i}\right)}{\sum_{i=1}^{N}\overline{C}_{\mathrm{ref},i}}$
NFB	$\frac{2\sum_{i=1}^{N}(C_i - C_{\mathrm{ref},i})}{\sum_{i=1}^{N}(C_i + C_{\mathrm{ref},i})}$
MGB	$\exp\left(\frac{1}{N}\sum_{i=1}^{N}\ln\left(\frac{C_i}{C_{\mathrm{ref},i}}\right)\right)$

To assess the agreement between measurements from the MONICA sensors and the reference instruments, we employed standard statistical indicators commonly recommended in the literature for evaluating correlation, error, and bias (Kang and Choi 2024). These include the coefficient of determination (R^2), the Fractional Bias (FB), the Root Mean Square Error (RMSE), the Normalized Fractional Bias (NFB), and the Mean Geometric Bias (MGB). The selection of these metrics allows for a comprehensive evaluation of the sensor's accuracy, precision, and systematic errors, which are essential for low-cost sensor validation.

The definitions and mathematical expressions for these metrics are presented in Table 3, where the following symbols are used in the definitions: C_i denotes the concentration measured by the low-cost sensor for the i-th observation, $C_{\mathrm{ref},i}$ denotes the concentration measured by the reference instrument for the i-th observation, $\overline{C}$ is the mean concentration provided by the low-cost sensor, $\overline{C_{\mathrm{ref}}}$ is the mean concentration provided by the reference instrument, and N represents the number of paired measurements.

R^2 quantifies the extent to which sensor measurements explain the variance in reference data and is widely used to evaluate correlation strength. Values above 0.7 indicate strong agreement, while values below 0.5 reflect weak predictive performance (Moore and Kirkland 2007). The Root Mean Square Error (RMSE) measures the average magnitude of error between sensor and reference measurements. As a key indicator of overall accuracy, lower RMSE values denote better agreement (Holstius et al. 2014; Mei et al. 2020). In addition, the FB and NFB are commonly used indicators in sensor validation studies e.g., (Lopez-Restrepo et al. 2021; Bisignano et al. 2022) to assess systematic errors between sensor and reference measurements. FB indicates relative bias, helping to detect consistent over- or underestimation, while NFB normalizes this measure, allowing for comparisons across sensors and varying concentration levels. Finally, we consider the geometric mean of the ratio between sensor and reference measurements (MGB). Unlike additive bias metrics, MGB is particularly valuable for capturing multiplicative errors, common in environmental measurements, where inaccuracies often scale with concentration levels. This is especially relevant when pollutant concentrations span multiple orders of magnitude, as traditional error metrics may disproportionately emphasize high-concentration deviations. By providing a scale-invariant measure of the bias, MGB ensures a more

balanced evaluation across different concentration ranges (Chang and Hanna 2004).

3 Results

This section begins by describing the meteorological and air quality conditions observed during the measurement campaign (Sect. 3.1). It then evaluates the performance of different regression models applied to the MONICA system data (Sect. 3.2), followed by an analysis of the temporal stability of the calibration and the minimum duration required to achieve effective calibration (Sect. 3.3). Finally, it examines the capability of the low-cost sensors to detect exceedances of air quality thresholds defined by the new European Directive 2024/2881 (Sect. 3.4).

3.1 Temporal Analysis of Meteorological Data and Pollutant Concentration

Figure 3 illustrates the meteorological and air quality trends measured by the reference instruments (Sect. 2.2) during the monitoring period. For better visual clarity and to ensure a continuous time series, the figure focuses on the measurements collected from early November to late December 2023.

As is typical for the winter season in northern Italy, temperatures ranged from 0 to 15 °C during the day, with occasional peaks nearing 20 °C and an average temperature of approximately 8 °C. The lowest temperatures were observed in the first week of December. Relative humidity ranged between 14% and 95%, maintaining above 60% in the first half of November and during the central part of December. Rainfall was almost absent.

Pollutant concentrations reveal significant temporal variability over the monitoring period, with particularly elevated levels of PM and NO_2 during the colder months. In early November, $PM_{2.5}$ reached daily maximum values around 30 μg/m^3, and PM_{10} peaked at approximately 50 μg/m^3. In the second half of November, more pronounced fluctuations were observed, with daily concentrations reaching 50 μg/m^3 for $PM_{2.5}$ and 75 μg/m^3 for PM_{10}. A further rise occurred in late December, where $PM_{2.5}$ remained consistently above 40 μg/m^3 and peaked at 80 μg/m^3, while PM_{10} exceeded 50 μg/m^3 on most days and reached values up to 100 μg/m^3. However, considering the entire three-and-a-half-month campaign, pollution events were even more acute, with hourly peaks reaching 132 μg/m^3 for $PM_{2.5}$ and 132 μg/m^3 for PM_{10}.

NO_2 concentrations followed a similar trend, gradually increasing through November and reaching hourly peaks of 50 μg/m^3. In late December, NO_2 levels rose further, with hourly maximum values approaching 80 μg/m^3. The absolute hourly maximum for the full campaign was recorded at 85 μg/m^3.

The green dashed lines in the figure represent the daily mean limit values established by the new European Directive (EU) 2024/2881. During the monitoring period, the

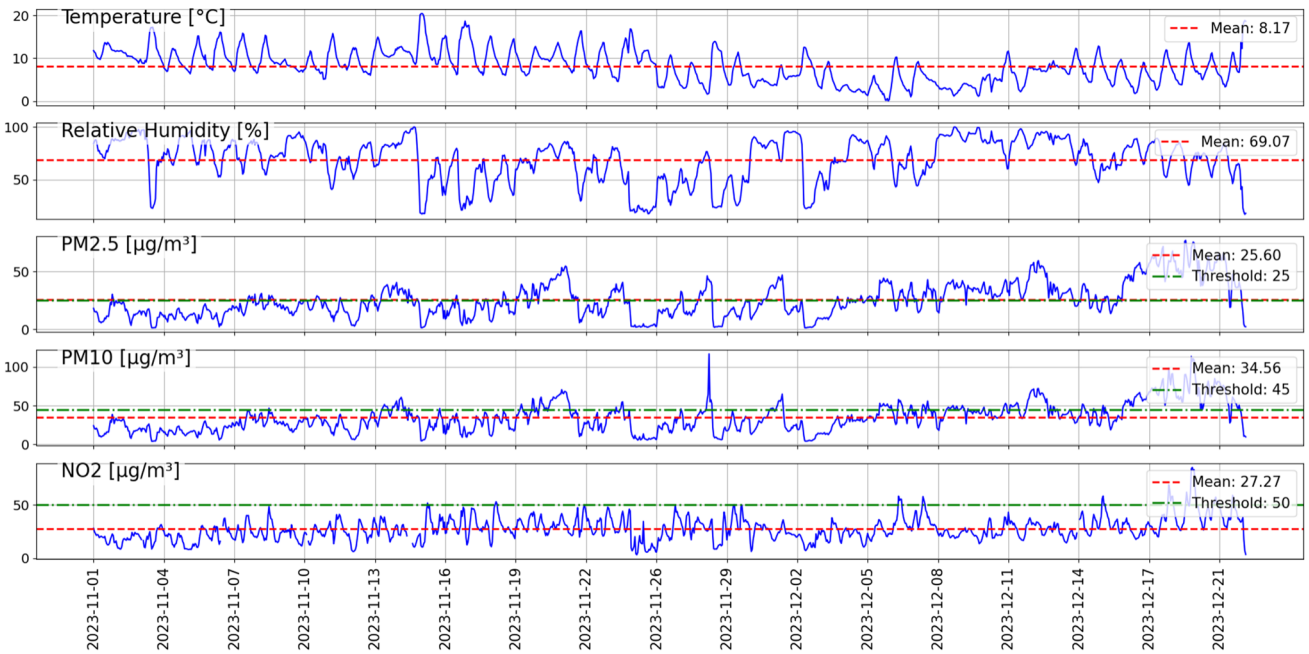


Fig. 3 Hourly trend of meteorological parameters and pollutant concentrations measured by the fixed reference station of the Politecnico di Torino. From top to bottom: Temperature, Relative Humidity, $PM_{2.5}$, PM_{10}, and NO_2. The green dashed lines in the figure represent the daily mean limit values established by the new European Directive (EU) 2024/2881

reference instruments frequently recorded concentrations above these thresholds, particularly for $PM_{2.5}$ and PM_{10} in December. While these observations highlight the critical air quality conditions of the site, a systematic analysis of the exceedances and the ability of the low-cost MONICA sensors to correctly identify them is provided in Sect. 3.4.

3.2 Performance of the Three Regression Models

The three regression models presented in Sect. 2.3 were trained using concentration data from the reference instruments and the predictor variables from the MONICA system listed in Table 1. While various training durations were tested (as discussed in the following sections), this subsection focuses on evaluating the performance of the three regression models during a standard two-week training phase, which serves as our baseline for comparison.

Figure 4 presents scatter plots comparing the hourly averaged concentrations derived from sensor measurements and those predicted by the regression models during the training phase. The RF model (third row) achieves the best overall performance, with R^2 consistently above 0.95 across all pollutants. The GAM model performs slightly worse, particularly for NO_2, with R^2 dropping to 0.66 and higher RMSE values due to underestimation of peak concentrations. MLR shows a similar behavior but with slightly lower performance compared to the other models.

During the two-week training period, the concentration ranges measured were approximately 1-40 $\mu g/m^3$ for $PM_{2.5}$, 4-60 $\mu g/m^3$ for PM_{10}, 6-53 $\mu g/m^3$ for NO_2. The regression models are thus trained on these concentration ranges.

The regression models calibrated on these two weeks, were then applied to the predictor values measured by the MONICA sensors in the following weeks. In Fig. 5, the regression model results are compared to the reference instrument measurements during Week 7 (i.e., five weeks after the training period). The scatter plots in the first row show that the MLR regression model is able to accurately reconstruct pollutant concentrations, especially for particulate matter. For both $PM_{2.5}$ and PM_{10}, data points align well with the bisector, and statistical indicators confirm a good agreement. However, NO_2 concentrations tend to be underestimated, as indicated by the negative values of the fractional bias.

In the second row, the scatter plots for the GAM model highlight a limitation in predicting high concentration values, especially for PM. At low and moderate concentrations, model performance is comparable to that of MLR, but at higher levels - beyond approximately 40 $\mu g/m^3$ for $PM_{2.5}$ and 50 $\mu g/m^3$ for PM_{10} - the predicted values increasingly deviate from the bisector. This progressive divergence reduces the R^2 and increases RMSE, indicating a deterioration in model performance. For NO_2, on the other hand, GAM predictions remain closer to the bisector across the concentration range and yield performance metrics similar to those of MLR.

The RF model (third row) exhibits a performance pattern comparable to the GAM but with a more pronounced *saturation* effect. While it accurately reproduces concentrations up to the training thresholds, it displays a characteristic flattening in the upper portion of the scatter plots. This behavior aligns with the inherent structural limitations of non-parametric models: unlike parametric approaches (e.g., MLR) that assume a global functional form, models like RF are strictly data-driven and cannot extrapolate beyond the training range e.g., (Nowack et al. 2021). Specifically, predictions are constrained to the maximum values encountered during training because the ensemble cannot predict values outside the range of its leaf nodes.

The impact of this limitation varies depending on how far test values exceed the training range. For $PM_{2.5}$ and PM_{10}, concentration levels during Week 7 reached levels nearly double the training maxima (up to 80 and 110 $\mu g/m^3$, respectively). In this regime, the superior extrapolation capability of MLR clearly highlights the saturation effect of the RF model. Conversely, for NO_2, the performance gap is less pronounced. Although the RF model remains constrained by its training ceiling, the MLR benchmark itself exhibits significant underestimation at higher concentrations. Consequently, the inherent limitations of the non-parametric model are less evident for NO_2, as the linear reference also struggles to accurately capture the extreme values in that specific range.

These results emphasize the importance of including sufficient variability, particularly higher concentration episodes, in the training dataset when calibrating low-cost sensors with non-linear data-driven approaches. At the same time, field campaigns must account for practical constraints: calibration must be conducted close to the measurement period, under similar environmental conditions, and without compromising the time allocated for actual data collection. Striking a balance between statistical robustness and operational feasibility is thus essential in designing effective calibration strategies.

While Fig. 5 focused on model performance during a specific week (Week 7), Fig. 6 illustrates how the performance of the different regression models evolves over time.

For particulate matter, the R^2 values for the GAM model drop sharply after Week 5, indicating limited robustness and a significant reduction in predictive capability over time. In contrast, MLR and RF maintain consistently high performance until around Week 8, after which a visible decrease in R^2 is observed–particularly between Weeks 8 and 9. This drop suggests that, although more stable than GAM, these

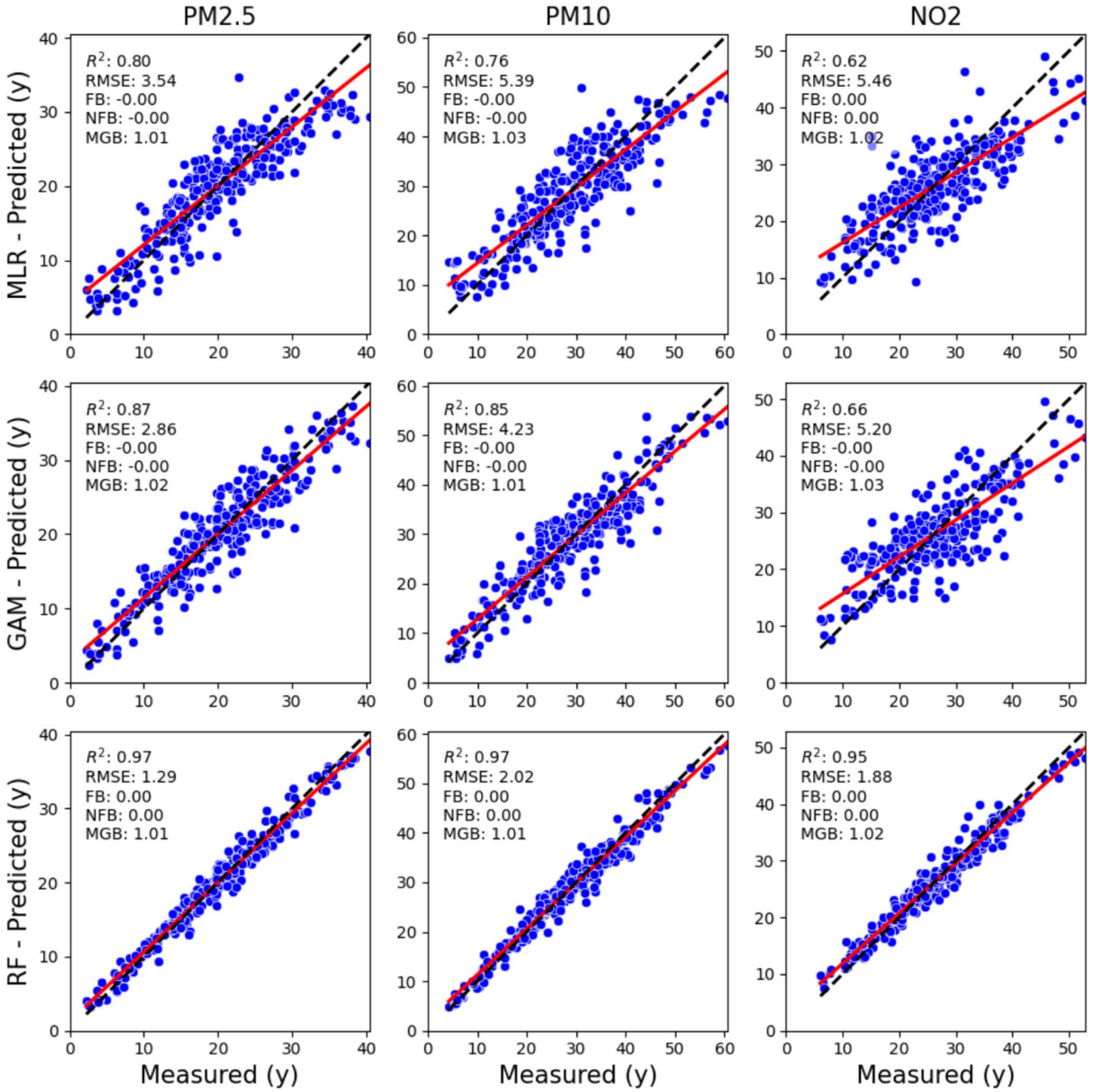


Fig. 4 Scatter plots comparing the regression results of models trained over 2 weeks with the data measured during the same 2-week period. Each column corresponds to a pollutant ($PM_{2.5}$, PM_{10}, NO_2), each row corresponds to a statistical indicator (R^2, FB, RMSE). Each point represents an hourly averaged concentration value, obtained by aggregating sensor measurements at hourly resolution

models also experience a decline in accuracy when applied beyond a certain temporal window from the calibration period. For NO_2, all three models follow a similar pattern, with R^2 values around 0.5 during the early weeks and a more pronounced decline after Week 8. This performance loss coincides with a one-month gap in reference data between Weeks 8 and 9 (see A) and likely reflects a temporal drift in sensor response. These findings suggest that, for all pollutants, model accuracy tends to degrade over time when applied to periods increasingly distant from the calibration, with NO_2 being particularly sensitive to this effect.

The RMSE trends highlight a gradual increase of error occurring immediately after the training period. For PM_{10} and $PM_{2.5}$, the error increases dramatically for the GAM model, while the MLR and the RF models maintain good performance, with MLR showing a slight advantage. Regarding NO_2, the error rises after the training period, stabilizing at a plateau before a sudden increase in Week 7.

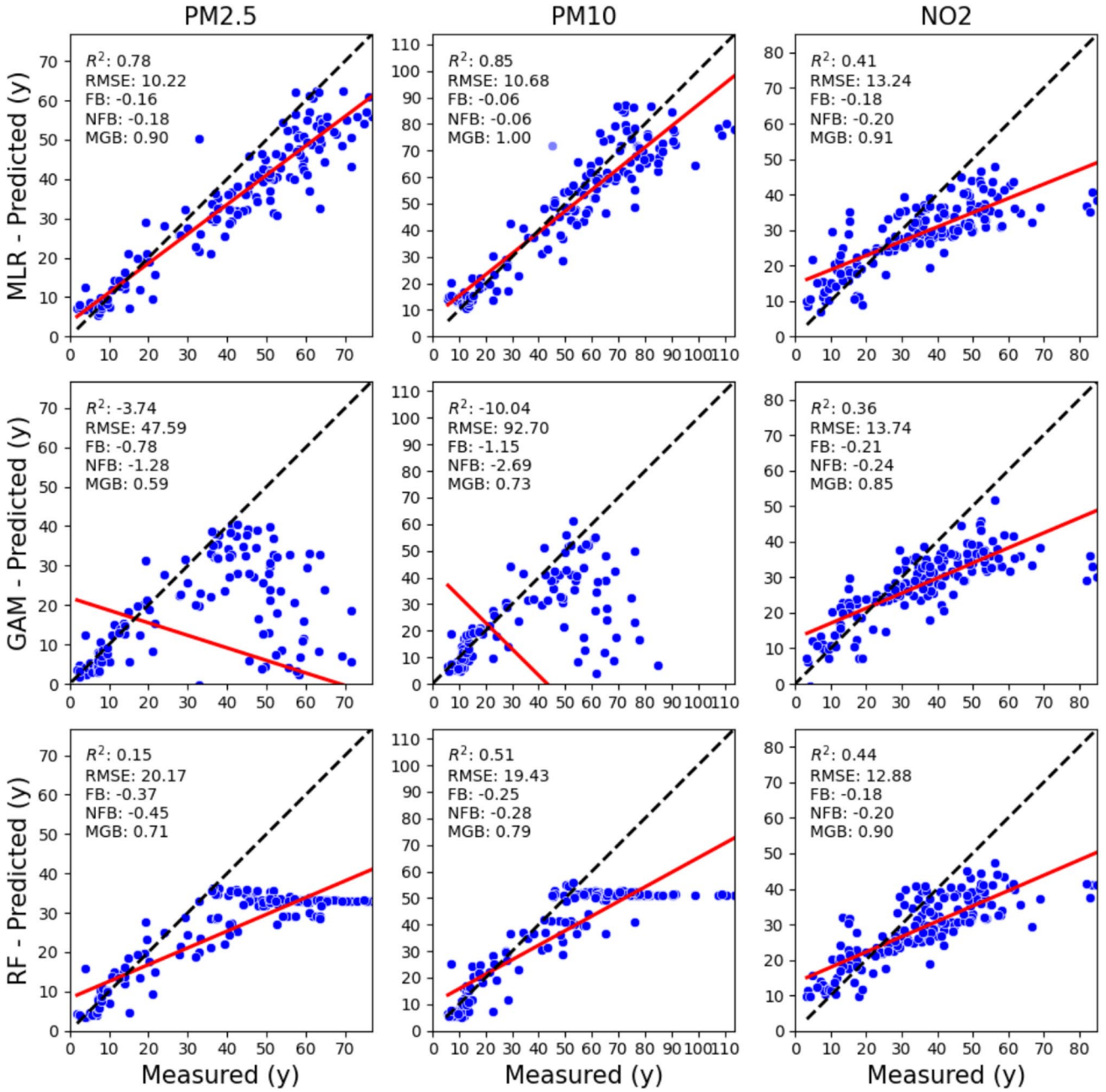


Fig. 5 Scatter plots comparing the regression results of models trained over 2 weeks with the data measured during Week 7. Each column corresponds to a pollutant ($PM_{2.5}$, PM_{10}, NO_2), each row corresponds to a statistical indicator (R^2, FB, RMSE). Each point represents an hourly median concentration value, obtained by aggregating sensor measurements at hourly resolution

Finally, the FB provides insight into whether the low-cost sensors are underestimating (negative FB) or overestimating (positive FB) pollutant concentrations compared to reference measurements. For particulate matter, the MONICA sensors progressively underestimate concentrations over time, with the GAM model performing the worst. In the case of NO_2, there is a slight overestimate in Week 4, followed by a gradual underestimate until Week 7. As highlighted also by the RMSE trends, model performance appears to improve in Week 8 (when R^2 also shows good values) but then deteriorates again in Week 9 (after the one-month interruption).

Overall, Fig. 6 confirms that the MLR model consistently provides the most reliable results across pollutants and time, though even this model shows performance degradation when applied far from the calibration window.

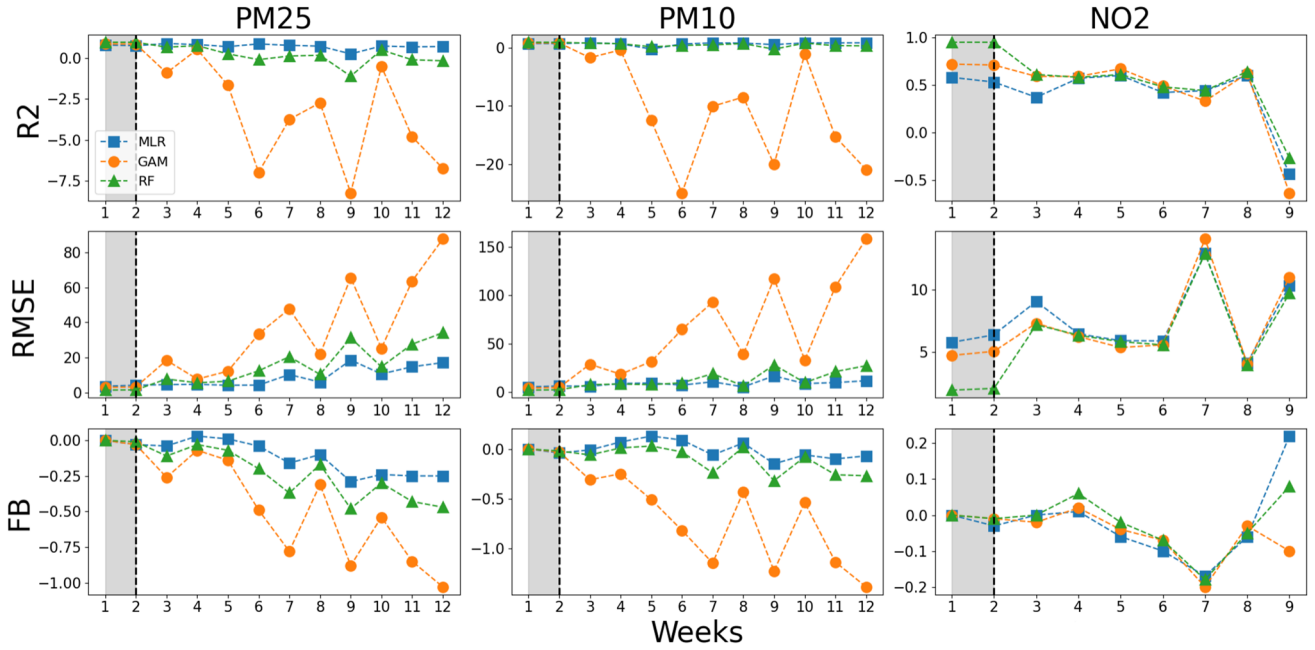


Fig. 6 Evolution of performance metrics for the different models (MLR, GAM, and RF) considering 2 weeks of training (shaded area): calibration performance over the weeks. Each column corresponds to a pollutant ($PM_{2.5}$, PM_{10}, NO_2). The three regression models–MLR, GAM, and RF–are represented by blue squares, orange circles, and green triangles, respectively. The rows display the trends for R^2, RMSE, and FB over time, illustrating how model performance evolves

The same analysis using a 3-week calibration period is provided in Appendix B, while the choice of training duration is further discussed in the following section.

3.3 Choice of the Calibration Duration

In the previous section, the performance of the regression models was analyzed using a two-week training period. This duration was selected based on a specific analysis examining how the length of the calibration phase affects the predictive accuracy of the low-cost sensors.

Figure 7 presents this analysis for the MLR model, identified as the most reliable model overall. Different markers represent the temporal evolution of model performance for varying training durations, ranging from 1 to 4 weeks. Notably, the curve corresponding to a two-week training period (orange circles) aligns with the MLR results shown in Fig. 6. The training weeks were selected as the initial N weeks of the campaign to simulate a realistic deployment scenario, where a sensor is typically calibrated immediately after installation.

For all three performance metrics (R^2, RMSE, and FB), increasing the training period from one to two weeks significantly enhances the accuracy of low-cost sensor measurements for $PM_{2.5}$ and PM_{10}. However, for NO_2, the analysis suggests that even a one-week training period is sufficient, as extending the training duration beyond that does not lead to substantial performance improvements.

This difference in optimal training duration may be explained by the representativeness of the concentration ranges encountered during the initial weeks. For NO_2, the first week alone was characterized by a high dynamic range (6–48 μg/m^3), which already covered 57% of the maximum concentration observed over the entire three-month campaign (85 μg/m^3). In contrast, for $PM_{2.5}$ and PM_{10}, the first week captured a more limited portion of the seasonal peaks (23% and 35%, respectively). By extending the training to two weeks, these coverage percentages increased to 31% (40 μg/m^3) for $PM_{2.5}$ and 46% (60 μg/m^3) for PM_{10}.

Compared to Figs. 6 and 7 provides a clearer depiction of the long-term calibration stability for the MLR model, refining the findings from the previous section.

For particulate matter, both RMSE and FB show a progressive decline in performance starting from Week 6, with a more marked degradation from Week 9 onward–following the one-month interruption in the measurements. However, R^2 remains relatively high even after this point (see values from Week 10 to 12). This indicates that while the model continues to capture the temporal variability and overall trends in PM concentrations (i.e., good correlation), it progressively diverges in terms of absolute values–resulting in increased bias and error. In other words, the model maintains its ability to follow the shape of the time series, but its accuracy in estimating the actual concentration levels decreases over time.

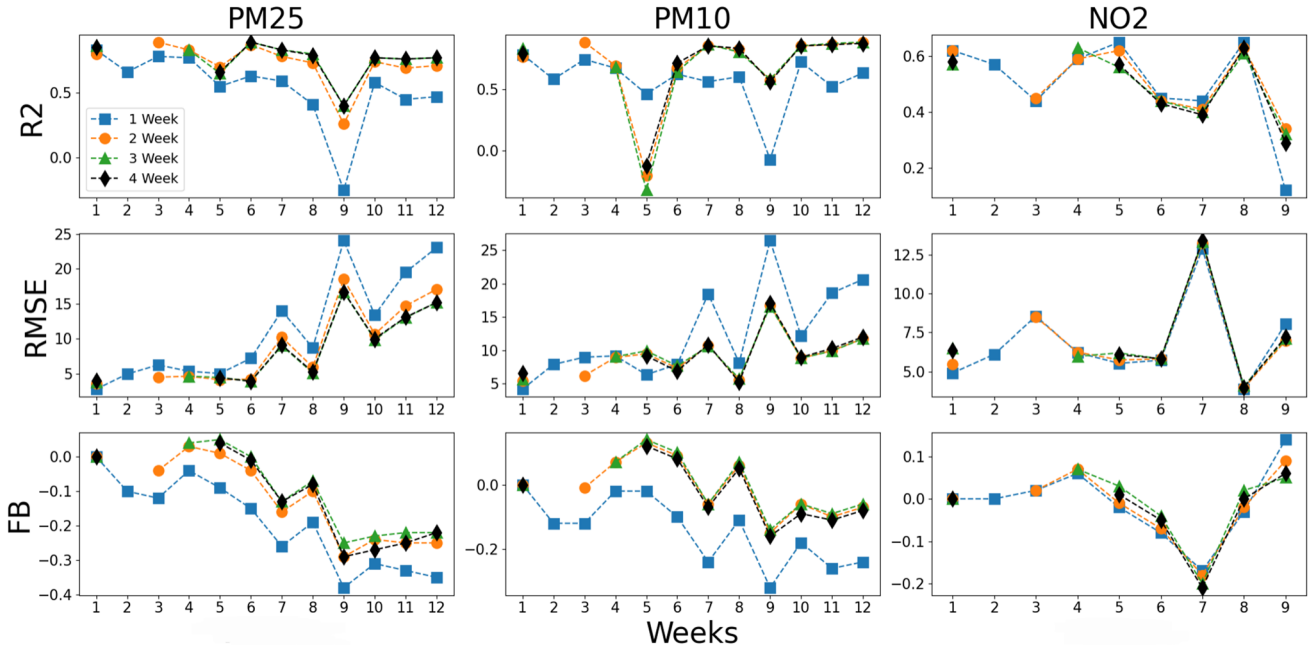


Fig. 7 Evolution of performance metrics for MLR model considering different weeks as training: effect of calibration duration on performance. Each column corresponds to a pollutant ($PM_{2.5}$, PM_{10}, NO_2), each row corresponds to a statistical indicator (R2, FB, RMSE). Each panel represents the trend of the statistical indicator over the weeks for each model used

In contrast, the performance for NO_2 does not exhibit a consistent trend but shows a localized increase in error and bias in Week 7, and a sharp drop in all the three statistics in Week 9–after the one-month interruption. This may indicate a shift in the underlying pollutant dynamics that is not accounted for by the initial calibration, highlighting the need for more frequent recalibration in the case of NO_2, a reactive gas with greater temporal variability.

Overall, this analysis suggests that the long-term stability of calibration models can vary significantly across pollutants and performance metrics. While the MLR model maintains good correlation with reference data over time–particularly for particulate matter–its accuracy in predicting absolute concentrations tends to deteriorate. For NO_2, calibration stability is more sensitive to time and environmental variability, indicating the need for more frequent recalibration to ensure reliable performance.

This sensitivity is closely linked to the seasonal variability of pollutants and meteorological drivers. The performance degradation observed after the one-month interruption suggests that short-term training may not fully capture the shifts in chemical and physical dynamics that emerge as seasonal patterns evolve.

3.4 Daily Concentration Trends and Regulatory Threshold Analysis

After identifying the most suitable regression model (i.e., MLR), determining the optimal calibration duration (i.e., two weeks), and evaluating its long-term performance, we examined the temporal evolution of daily-averaged concentrations for $PM_{2.5}$ (Fig. 8), PM_{10} (Fig. 9), and NO_2 (Fig. 10). This analysis is particularly relevant in light of the new Directive (EU) 2024/2881, which introduces stricter daily (24-hour) limit values compared to previous legislation. Specifically, a new daily threshold of 50 μg/m^3 is established for NO_2 (not to be exceeded more than 18 times per calendar year), whereas the previous directive focused primarily on hourly peaks. Regarding particulate matter, the daily limit for PM_{10} has been reduced from 50 μg/m^3 to 45 μg/m^3, and the allowed number of annual exceedances has been halved from 35 to 18. Additionally, for $PM_{2.5}$, a daily limit of 25 μg/m^3 has been introduced (not to be exceeded more than 18 times per year)–a parameter that was not strictly regulated in the 2008/50/EC Directive. These changes reflect a more rigorous approach to urban air quality management.

Figures 8, 9, and 10 illustrate the daily-averaged concentrations for $PM_{2.5}$, PM_{10}, and NO_2 throughout the campaign, with the interruption period of the measurements indicated by two wavy vertical lines. For each pollutant, the plots indicate the relevant daily concentration limits set by the new EU Directive. In addition to pollutant concentrations, the figures also display the trend of relative humidity, the only meteorological variable found to significantly contribute to the site-specific calibration models (see Sect. 2.3).

Figure 8 illustrates the progressive increase in $PM_{2.5}$ concentrations throughout the winter period. Measurements

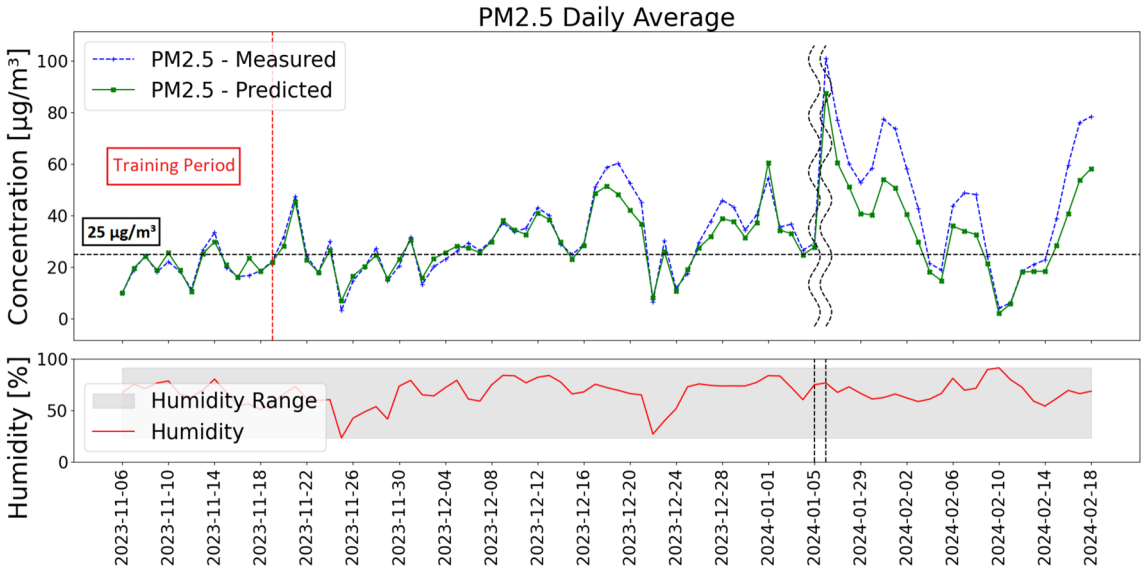


Fig. 8 Comparison of daily average $PM_{2.5}$ concentrations measured by the reference instrument (dashed blue line) and those estimated by MONICA (green line) using the MLR regression model trained over a two-week period. The regulatory limit established by Directive (EU) 2024/2881 is shown as a dashed horizontal line. The trend of relative humidity is also reported (red line). The measurement interruption period is indicated by vertical dashed lines

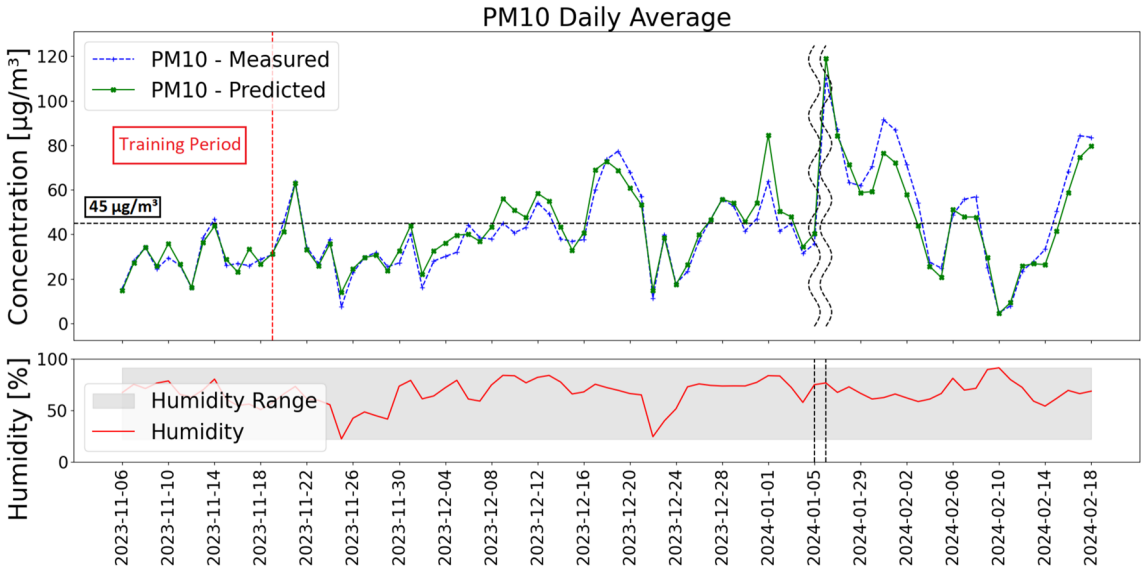


Fig. 9 Comparison of daily average PM_{10} concentrations measured by the reference instrument (dashed blue line) and those estimated by MONICA (green line) using the MLR regression model trained over a two-week period. The regulatory limit established by Directive (EU) 2024/2881 is shown as a dashed horizontal line. The trend of relative humidity is also reported (red line). The measurement interruption period is indicated by vertical dashed lines

from the MONICA sensors show good agreement with those from the reference instruments. As previously discussed, a gradual divergence between the two datasets is observed, likely due to the progressive degradation of calibration performance. Multiple exceedances of the 25 µg/m^3 daily concentration limit, as established by Directive (EU) 2024/2881, are recorded.

The agreement between MONICA and reference instruments is even more consistent for PM_{10} (Fig. 9), reflecting the slightly lower RMSE and FB values obtained for PM_{10} compared to $PM_{2.5}$ (see Fig. 7). The temporal trends of PM_{10} and $PM_{2.5}$ are closely aligned. Notably, exceedances of the 45 µg/m^3 daily limit are frequent starting from the second week of December. In Fig. 10, MONICA sensors demonstrate a strong ability to replicate both the temporal dynamics and concentration levels of NO_2. However, a systematic underestimation of extreme values–both peaks and troughs–is evident. Notably, a significant underestimation

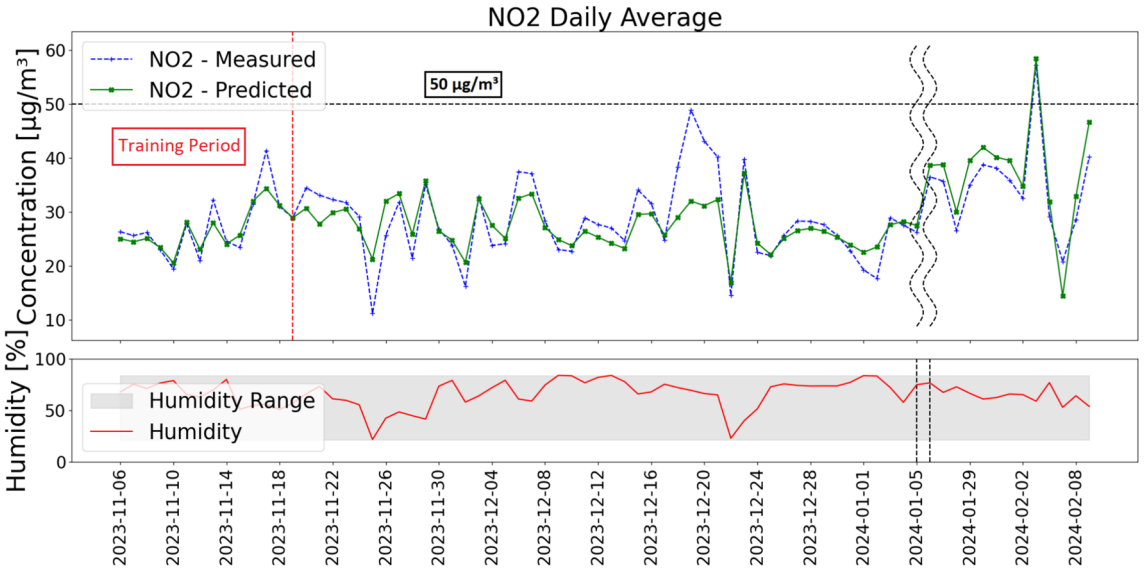


Fig. 10 Comparison of daily average NO_2 concentrations measured by the reference instrument (dashed blue line) and those estimated by MONICA (green line) using the MLR regression model trained over a two-week period. The regulatory limit established by Directive (EU) 2024/2881 is shown as a dashed horizontal line. The trend of relative humidity is also reported (red line). The measurement interruption period is indicated by vertical dashed lines

Table 4 Number of exceedances based on the daily limits established by European Directive (EU) 2024/2881, as estimated over a 12-week measurement period for particulate matter (PM_{10} and $PM_{2.5}$) and a 9-week measurement period for NO_2, along with average concentrations over the entire period for each pollutant

Instrument	Exceedances [#]			Average concentration		
	$PM_{2.5}$ 25 µg/m^3	PM_{10} 45 µg/m^3	NO_2 50 µg/m^3	$PM_{2.5}$ [µg/m^3]	PM_{10} [µg/m^3]	NO_2 [µg/m^3]
Ref. Instr	51	31	1	33.90	42.43	29.26
MONICA	50	33	1	27.90	36.81	29.02

occurs between 16 and 20 December (Week 7). This period is marked by a peak in RMSE and a negative FB, as shown in Fig. 6. After the interruption period, while R^2 in Fig. 6 shows a significant decline for Week 9, a clear decrease in correlation is not evident in the time series data. Similar to particulate matter, NO_2 levels increase over the study period, peaking in early February, a trend that is well captured by the low-cost sensor. However, unlike PM, NO_2 concentrations exceed the regulatory threshold of 50 µg/m^3 only once throughout the entire period.

As a complementary analysis, Appendix B reports the same temporal trends of Figs. 8, 9, and 10 using a three-week calibration period. However, no substantial differences were observed compared to the two-week calibration, confirming its adequacy for this application.

Table 4 summarizes the number of exceedances for each pollutant, based on the daily thresholds set by Directive (EU) 2024/2881. The number of exceedances estimated by MONICA (two-weeks training) is almost identical to that recorded by reference instrumentation, underscoring the potential of low-cost sensors for regulatory monitoring purposes. Notably, the daily limit for $PM_{2.5}$ is exceeded on more than 60% of the days in the observation period, approximately 40% for PM_{10}, and around 2% for NO_2. Directive (EU) 2024/2881 allows a maximum of 18 exceedances per year for each pollutant; this threshold is significantly surpassed in our dataset, despite the dataset spanning slightly more than three months.

Table 4 also includes the average concentrations for each pollutant over the measurement period. As expected, given the predominantly negative fractional bias values reported earlier, the MONICA sensors tend to underestimate concentrations by approximately 18% for $PM_{2.5}$, 13% for PM_{10}, and 1% for NO_2. It is worth noting that the average $PM_{2.5}$ concentration measured during the campaign exceeds the current annual limit of 10 µg/m^3 set by Directive (EU) 2024/2881. A similar pattern is observed for PM_{10}, whose reference average of 42.43 µg/m^3 exceeds both the current (European Directive 2008/50/CE (Parliament and Council 2008)) annual limit of 40 µg/m^3 and the upcoming 20 µg/m^3 limit. For NO_2, only the newly introduced annual limit of 20 µg/m^3 is exceeded. In performing these comparison, it is worth remembering that the measurements reported here refer only to the winter season, during which meteorological

conditions (and increased pollutant emissions, notably due to domestic heating) typically lead to the highest pollutant levels observed over the whole year.

4 Conclusions

This study evaluated the performance and calibration strategies of the MONICA low-cost sensor system for measuring particulate matter ($PM_{2.5}$ and PM_{10}) and nitrogen dioxide (NO_2) in an urban setting. Our primary objective was to identify the most reliable calibration model, assess the optimal co-location duration, and analyze the long-term stability of sensor performance.

Among the models tested, Multiple Linear Regression (MLR) proved to be significantly more robust than both the Generalized Additive Model (GAM) and Random Forest (RF) models. The latter models exhibited high sensitivity to the dataset used for calibration and struggled to predict the highest concentration values accurately.

In terms of calibration duration, our analysis revealed that a two-week calibration period was sufficient for particulate matter, providing reliable sensor performance for up to seven weeks post-calibration. For NO_2, however, a shorter, one-week calibration period proved to be adequate, as extending the duration beyond that did not result in significant performance improvements. This suggests that the calibration duration can vary depending on the pollutant and, more importantly, on the environmental representativeness of the training window. In our study, the high urban variability allowed the sensors to encounter a significant portion of the seasonal dynamic range (covering up to 57% of the campaign maximum for NO_2 in the first week, and 46% for PM_{10} by the second) within these short timeframes. This ensured that the models were well-constrained from the outset for the specific conditions of the monitored period.

The long-term evaluation revealed important differences in sensor behavior. While PM sensors maintained a good correlation with reference data over time, their accuracy in predicting absolute concentrations declined gradually, as reflected in increasing RMSE and fractional bias. For NO_2, a more abrupt degradation was observed, especially after two months, suggesting a higher susceptibility to sensor drift and environmental variability. This degradation also reflects the inherent seasonal limitations of the study; while the models included parameters to compensate for ozone interference, the narrow range of conditions typical of a winter campaign may limit their applicability to summer months, when higher ozone levels and broader temperature fluctuations occur. A general tendency toward underestimation was found for all pollutants, reinforcing the need for regular validation against reference-grade instruments.

Despite these limitations, MONICA sensors successfully captured temporal trends and regulatory exceedances, confirming their suitability for urban air quality surveillance and public health applications. Their affordability, compact design, and acceptable long-term performance make them attractive tools for enhancing spatial and temporal resolution in monitoring networks.

In summary, this study demonstrates that low-cost multi-pollutant systems like MONICA can deliver reliable results over extended periods, provided that calibration strategies are carefully designed and periodically updated. The findings provide operational guidance for optimizing sensor deployments under real-world constraints, contributing to the development of scalable and cost-effective air quality networks.

Future work should explore multi-seasonal deployments, longer observation periods, and parallel sensor configurations to evaluate spatial variability and further refine calibration methods. Integrating these insights into policy and urban planning could enhance the responsiveness and equity of air quality management strategies.

Time Windows with Valid Data for Calibration and Evaluation

The monitoring campaign took place from November 6, 2023, to February 25, 2024, with MONICA sensors co-located alongside reference instruments. Due to interruptions in the reference instruments, the time windows with valid data for direct comparison were limited: 12 full weeks for PM2.5 and PM10, and 9 full weeks for NO_2. Table A.1

Table 5 Availability of valid data for $PM_{2.5}$, PM_{10}, and NO_2, broken down by full weeks (Monday to Sunday)

Week	Date range	Available pollutants
Week 1	06–12 Nov 2023	$PM_{2.5}$, PM_{10}, NO_2
Week 2	13–19 Nov 2023	$PM_{2.5}$, PM_{10}, NO_2
Week 3	20–26 Nov 2023	$PM_{2.5}$, PM_{10}, NO_2
Week 4	27 Nov – 03 Dec 2023	$PM_{2.5}$, PM_{10}, NO_2
Week 5	04–10 Dec 2023	$PM_{2.5}$, PM_{10}, NO_2
Week 6	11–17 Dec 2023	$PM_{2.5}$, PM_{10}, NO_2
Week 7	18–24 Dec 2023	$PM_{2.5}$, PM_{10}, NO_2
Week 8	25–31 Dec 2023	$PM_{2.5}$, PM_{10}, NO_2
–	01–07 Jan 2024	$PM_{2.5}$, PM_{10}, NO_2 (only until 05 Jan)
–	08–14 Jan 2024	No data
–	15–21 Jan 2024	No data
–	22–28 Jan 2024	$PM_{2.5}$, PM_{10}, NO_2 (starting 25 Jan)
Week 9	29 Jan – 04 Feb 2024	$PM_{2.5}$, PM_{10}, NO_2
Week 10	05–11 Feb 2024	$PM_{2.5}$, PM_{10}
Week 11	12–18 Feb 2024	$PM_{2.5}$, PM_{10}
Week 12	19–25 Feb 2024	$PM_{2.5}$, PM_{10}

Only weeks with complete data coverage are numbered

indicates the weeks with complete data coverage as well as those with partial or no data.

Results for 3-Weeks Training

The comparison of three regression models and the analysis of their performance relative to the training period indicated that a 2-week training period for the MLR model offers the optimal balance for real-world campaigns conducted within a single season. In this appendix, we present the comparison between MONICA measurements and those from the reference instruments using a 3-week training period for the MLR model.

Figures 11, 12, and 13 show that a 3-week training period yields results that are practically identical to those observed in Figs. 9 and 10, confirming that a 2-week period is sufficient and optimal for calibration.

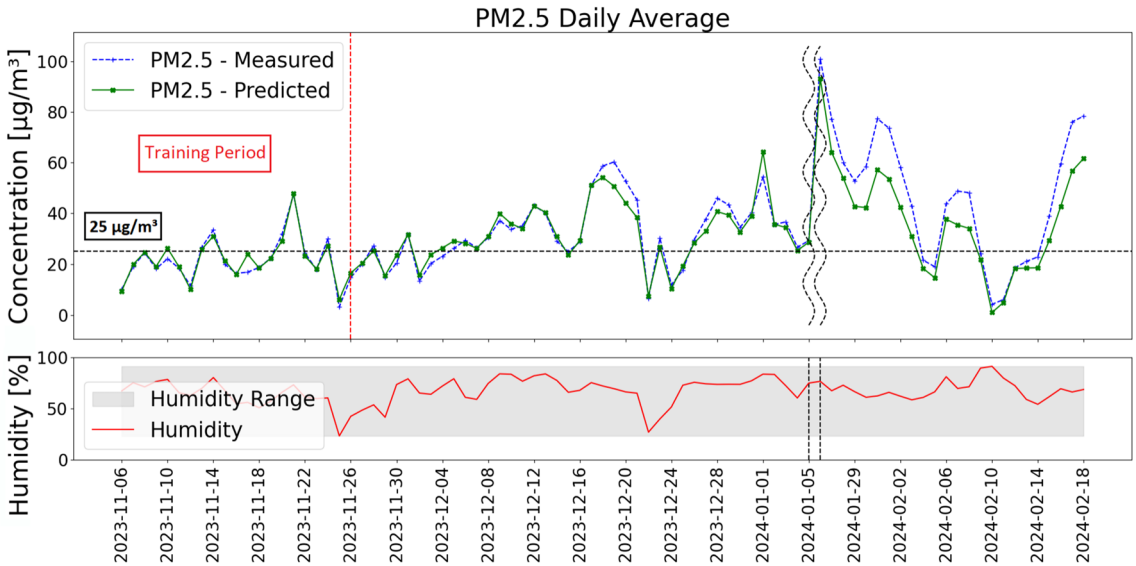


Fig. 11 Comparison of daily average $PM_{2.5}$ concentrations measured by the reference instrument (dashed blue line) and those estimated by MONICA (green line) using the MLR regression model trained over a three-week period. The regulatory limit established by Directive (EU) 2024/2881 is shown as a dashed horizontal line. The trend of relative humidity is also reported (red line). The measurement interruption period is indicated by vertical dashed lines

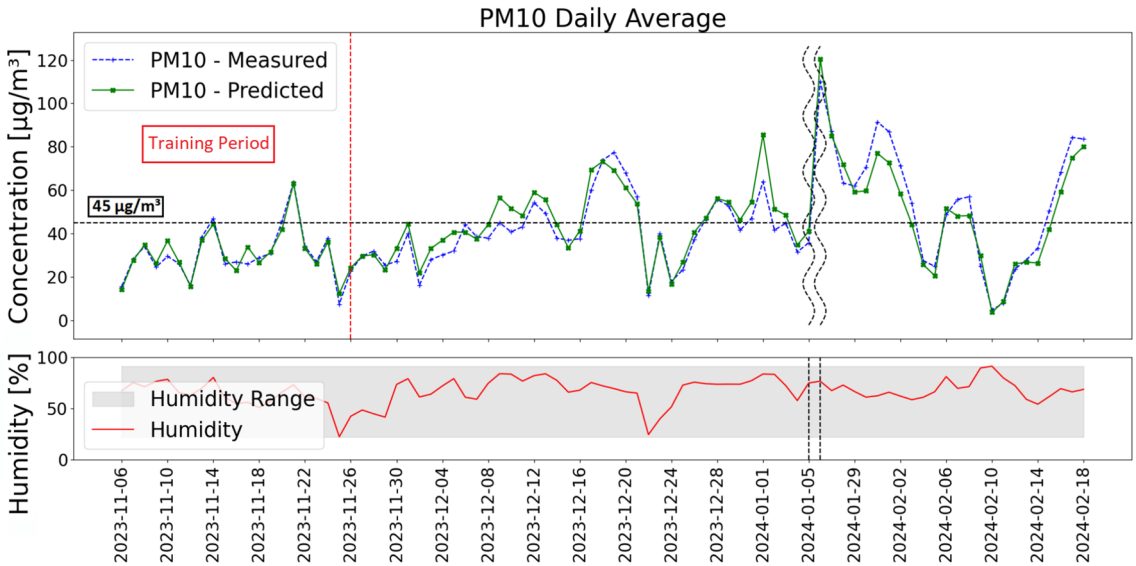


Fig. 12 Comparison of daily average PM_{10} concentrations measured by the reference instrument (dashed blue line) and those estimated by MONICA (green line) using the MLR regression model trained over a three-week period. The regulatory limit established by Directive (EU) 2024/2881 is shown as a dashed horizontal line. The trend of relative humidity is also reported (red line). The measurement interruption period is indicated by vertical dashed lines

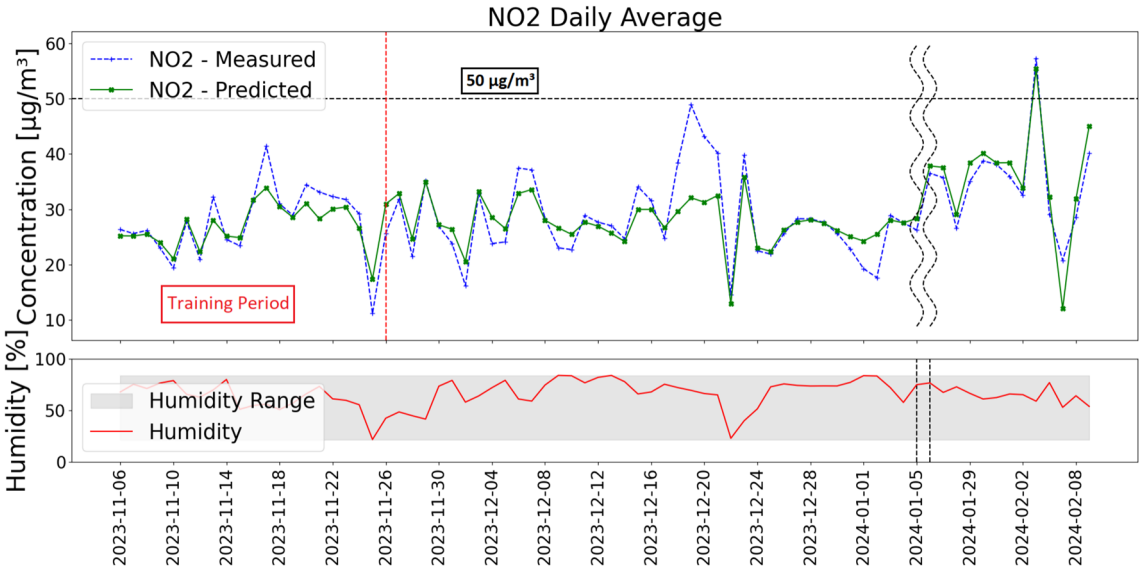


Fig. 13 Comparison of daily average NO_2 concentrations measured by the reference instrument (dashed blue line) and those estimated by MONICA (green line) using the MLR regression model trained over a three-week period. The regulatory limit established by Directive (EU) 2024/2881 is shown as a dashed horizontal line. The trend of relative humidity is also reported (red line). The measurement interruption period is indicated by vertical dashed lines

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Author contributions S.F. conceptualized the study, developed the methodology, and wrote the original draft. D.G. curated data, created visualizations, and contributed to writing the original draft. V.V. performed formal analysis, created visualizations, and contributed to writing the original draft. N.M. curated data and helped review the manuscript. G.F. provided resources. M.C. conceptualized the study, supervised and managed the project, reviewed the manuscript. P.S. conceptualized the study, supervised the work, reviewed the manuscript, and managed the project.

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Declarations

Competing interests The authors declare no conflict of interest.

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