Comparative Evaluation of Low-Cost and Reference-Grade PM2.5 Sensors to Support Air Quality Monitoring in Northern Ireland

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In this research, AI tools (ChatGPT) were used to improve grammar and structure. All content, analysis, and conclusions are original and student generated.

Contents

Abstract

Fine particulate matter (PM2.5) is a significant Environmental Health (EH) concern due to its well-established links with respiratory and cardiovascular disease and premature mortality. In Northern Ireland (NI), PM2.5 concentrations remain above World Health Organization (WHO) guideline levels, despite generally complying with current regulatory standards. This has increased interest in monitoring approaches that can provide more spatially representative air quality data. Low-cost sensors may expand monitoring coverage, but their performance under NI's conditions remains insufficiently understood.

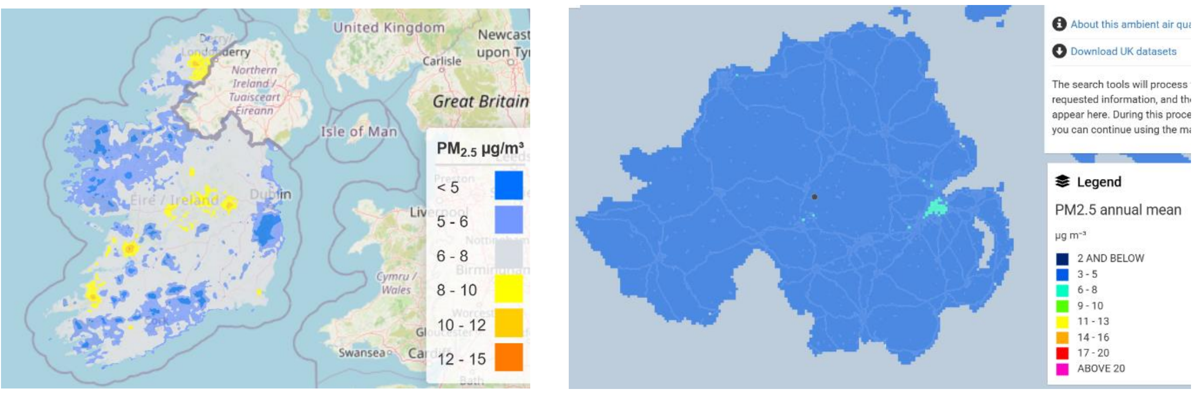
This study aimed to compare the performance of a low-cost Kunak AIR Pro PM2.5 sensor with a reference-grade BAM 1020 monitor at Armagh Air Quality Monitoring Station (AQMS) over a 14-day period. A quantitative comparative observational design was adopted. BAM 1020 data were converted from mg/m^3 to $\mu g/m^3$, Kunak timestamps were adjusted for temporal alignment, and one day of data was excluded due to BAM 1020 maintenance issues. The final analysis was based on 311 valid paired hourly observations. Pearson correlation, Root Mean Square Error (RMSE) and Bland–Altman analysis were used to assess relationship, error and agreement between the two devices.

The results showed a moderate positive correlation between the sensors ($r = 0.369$, $p < 0.001$), an RMSE of 4.02 $\mu g/m^3$, and a mean bias of −1.80 $\mu g/m^3$, indicating that the low-cost sensor generally underestimated PM2.5 concentrations compared with the reference monitor. While the Kunak AIR Pro could identify broad PM2.5 trends, variability in individual measurements and reduced reliability at higher concentrations were observed. The study concludes that low-cost sensors may be useful as supplementary tools to expand monitoring coverage, but they should complement rather than replace reference-grade systems. These findings are relevant to future air quality monitoring strategies in NI, including cross-border initiatives such as PEACEPLUS and PEACE-AIR.

Introduction

Air pollution remains one of the most significant environmental risks to human health, with fine particulate matter (PM2.5) recognised as one of the most harmful pollutants because of its ability to penetrate deep into the respiratory system and enter the bloodstream (WHO, 2021). Exposure to PM2.5 has been associated with respiratory disease, cardiovascular disease and premature mortality (WHO, 2021; McVicar et al., 2023). As understanding of these impacts has increased, the importance of accurate and representative air quality monitoring has become increasingly evident.

In NI, PM2.5 remains an important EH concern. Although concentrations generally comply with current regulatory limits, they remain above the WHO annual guideline value of 5 µg/m^3 (Department of Agriculture, Environment and Rural Affairs (DAERA), 2026; WHO, 2021). PM2.5 exposure is also unevenly distributed. Irish research has shown considerable spatial and temporal variation in particulate concentrations, with residential solid fuel burning identified as a particularly important source in urban and rural residential areas (Wenger et al., 2020; Byrne et al., 2023). This suggests that monitoring based on a limited number of fixed stations may not fully capture localised exposure hotspots.



(a) (b)

Figure 1: PM2.5 annual mean maps 2024; (a) Republic of Ireland (Environmental Protection Agency, n.d.), (b) (Department for Environment, Food and Rural Affairs, n.d.) Northern Ireland.

Traditionally, PM2.5 is measured at fixed air quality monitoring stations using high-cost, reference-grade instrumentation operated by Local Authority EH within statutory air quality management frameworks (Liu et al., 2019; DAERA, 2026). These systems provide accurate and reliable data, but their capital and operational costs limit the number of stations that can be deployed (Liu et al., 2019). As a result, low-cost sensors have attracted interest as a way of increasing spatial monitoring coverage and improving understanding of local air pollution patterns (Clements et al., 2022; Mukherjee et al., 2017).

However, the value of low-cost PM2.5 sensors depends on their accuracy, reliability and agreement with reference-grade instruments under real-world conditions. International studies have reported mixed findings, with performance influenced by calibration, humidity, temperature and local environmental conditions (Mukherjee et al., 2017; Polidori et al., 2017; Zou et al., 2021). Findings from other regions therefore cannot automatically be generalised to NI (Liu et al., 2019).

The aim of this study was to evaluate the performance of a low-cost PM2.5 sensor against a reference-grade monitor in order to assess its potential to support air quality monitoring in NI.

The research question was:

To what extent do PM2.5 measurements produced by the low-cost Kunak AIR Pro sensor agree with those produced by the reference-grade BAM 1020 monitor at Armagh Air Quality Monitoring Station?

The objectives of the study were:

1. To collect paired hourly PM2.5 concentration data from the Kunak AIR Pro and BAM 1020 over a 14-day monitoring period.
2. To compare the relationship between the two datasets using Pearson correlation analysis.
3. To assess measurement error and agreement using RMSE and Bland–Altman analysis.
4. To evaluate the suitability of the low-cost sensor for supporting supplementary air quality monitoring in Northern Ireland.

Literature Review

1.1 PM2.5 as an Environmental Health Risk

Fine particulate matter (PM2.5), defined as particles with an aerodynamic diameter of 2.5 micrometres or less, is widely recognised as one of the most harmful ambient air pollutants to human health. WHO identifies PM2.5 as the pollutant most strongly associated with premature mortality and cardiovascular and respiratory morbidity (WHO, 2021). The 2021 WHO Air Quality Guidelines (AQG) reduced the recommended annual mean limit for PM2.5 to 5 $\mu g/m^3$, reflecting growing evidence that adverse health effects occur even at low concentrations.

In contrast, the current NI regulatory annual mean limit for PM2.5 remains 25 $\mu g/m^3$ (DAERA, 2024), substantially higher than WHO recommendations. Although measured concentrations in NI are typically below the regulatory limit, they remain above WHO guidance. In 2024, the mean PM2.5 concentration across five urban background sites in NI was 7.0 $\mu g/m^3$, representing a slight increase from 6.8 $\mu g/m^3$ in 2023 (DAERA, 2026). While these concentrations appear relatively low compared with heavily polluted regions, they exceed the WHO AQG, indicating continued population exposure to potentially harmful levels.

The health burden associated with PM2.5 exposure in NI is significant. Public Health England estimated approximately 550 premature deaths in NI in 2010 attributable to anthropogenic fine particulate matter (Public Health England, 2014). McVicar et al. (2023) emphasise that it is "human-generated air pollution – anthropogenic air pollution – which is the biggest concern," due to its persistence and strong links to human activity. More recent work suggests that many individuals in NI continue to be exposed to PM2.5 concentrations above WHO guideline levels, with higher long-term exposure conditionally associated with increased reporting of poor general health and chronic illness (Rowland et al., 2024). The WHO further estimates that achieving Interim Target 4 (equivalent to the 2005 AQG) could result in a 47.8% reduction in deaths attributed to PM2.5 exposure (WHO, 2021).

1.2 Sources, Distribution and Meteorological Influences on PM2.5

Understanding the sources and distribution of PM2.5 is crucial for developing targeted mitigation strategies. Irish research indicates considerable spatial and temporal variability in particulate concentrations (Wenger *et al.*, 2020). More recent work by Byrne *et al.* (2023), using a city-wide sensor network in Cork, identified significant variation in PM2.5 across the urban area, with some locations experiencing daily average peaks approximately twice those recorded elsewhere in the city. This highlights the importance of localised monitoring for identifying micro-environmental differences in exposure that may not be captured by a limited number of fixed monitoring sites.

More recent evidence from the SAPPHIRE project identified residential solid fuel burning as a major contributor to PM2.5 in both urban and rural residential areas (Wenger *et al.*, 2020). Real-time monitoring of the chemical composition of PM2.5 showed that residential solid fuel burning was the dominant source category at all three monitoring locations, reinforcing its significance as the primary source of fine particulate pollution in these settings (Wenger *et al.*, 2020). Evening concentrations were often significantly higher than daytime levels, reflecting domestic heating patterns. Traffic and sea spray were identified as relatively minor sources in comparison (Wenger *et al.*, 2020), challenging the assumption that traffic is always the dominant urban pollutant source. These findings indicate that PM2.5 exposure in NI may be strongly influenced by localised domestic combustion activities.

Meteorological factors also influence PM2.5 concentrations. Liu et al. (2017) demonstrated that synoptic weather patterns significantly affect pollutant levels, with tropical weather types associated with higher concentrations and polar weather types linked to lower levels. In Ireland's maritime climate, frequent changes in weather systems may affect pollutant dispersion and accumulation. This reinforces the importance of interpreting air quality data within its environmental context.

1.3 Traditional PM2.5 Monitoring and Regulatory Context

Traditionally, PM2.5 is measured at fixed air quality monitoring stations using high-cost, reference-grade instrumentation by Local Authority EH traditionally, under the AQMA regulations. These systems are considered accurate and reliable and form the basis for regulatory compliance (Liu et al., 2019). However, their high capital and operational costs limit the number of stations that can be deployed. In Northern Ireland, this monitoring is underpinned by the Air Quality Standards Regulations (Northern Ireland) 2010 and related local authority duties to review, assess and manage local air quality.

In NI, monitoring is therefore concentrated at a relatively small number of sites, as seen in Figure 2. While these stations provide high-quality data, their limited spatial coverage may restrict understanding of micro-environmental variation, particularly in areas where solid fuel combustion is prevalent, potentially leading to the underestimation of localised exposure hotspots.

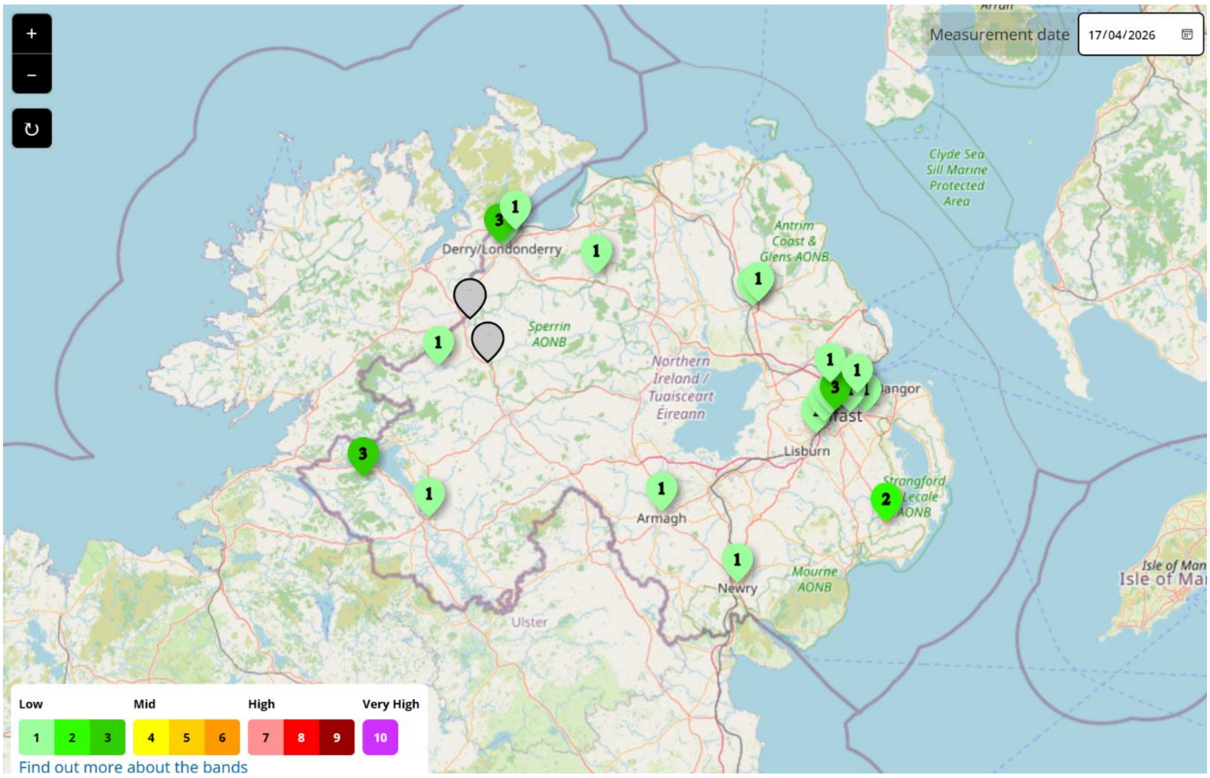


Figure 2: Monitoring Sites across NI (DAERA, 2026)

1.4 Low-Cost PM2.5 Sensors: Opportunities and Limitations

Low-cost PM2.5 sensors have emerged as a potential solution to spatial coverage limitations. Their relatively low price and ease of deployment make them attractive for expanding monitoring networks and supporting community-based air quality initiatives. However, concerns remain regarding their accuracy and reliability. Mukherjee et al. (2017) argue that sensors must be assessed comprehensively and under real-world conditions before large-scale deployment. Laboratory calibration alone may not reflect performance in outdoor environments.

Polidori et al. (2017) highlight that factors such as site location, season and meteorological conditions, including temperature and relative humidity, may influence sensor performance. In contrast, Zou et al. (2021) found no statistically significant relationship between temperature and sensor output within a 15°C–40°C range. This suggests that the influence of environmental variables may vary depending on sensor type or climatic context.

Liu et al. (2019) further demonstrate that field calibration under representative environmental conditions can significantly improve sensor accuracy. This finding is particularly relevant to NI, where relatively high humidity and variable weather conditions may affect optical particle sensors differently than in drier regions.

Overall, the literature suggests that while low-cost sensors show promise, their performance is context dependent. Results from studies conducted in California, Norway or other regions cannot automatically be generalised to Northern Ireland without local validation. (Mukherjee, A. et al, 2017, and Liu, H.-Y. et al , 2019)

Consequently, there is a need for locally conducted comparative evaluation of low-cost and reference-grade PM2.5 sensors under NI's specific meteorological and emission conditions. Establishing the accuracy and reliability of low-cost technologies in this context would provide an evidence base to determine whether wider deployment could complement existing monitoring infrastructure and support initiatives such as the PEACEPLUS Peace-Air programme.

1.5 Air Quality Governance and the PEACEPLUS Context

Northern Ireland's air quality governance operates within both domestic and European regulatory frameworks. While NI currently complies with EU limit values, DAERA (2026) has indicated that consideration is being given to adopting stricter annual limits in light of updated WHO guidelines.

The PEACEPLUS programme supports cross-border collaboration and data collection initiatives. Effective cross-border air quality management requires consistent and reliable monitoring methodologies across jurisdictions. Brennan, Purdy and Hjerp (2017) argue that environmental governance in NI can be fragmented, while Brennan et al. (2018) emphasise the importance of shared enforcement and cooperative mechanisms. In this context, expanding monitoring capacity through validated low-cost sensors could enhance evidence-based decision-making, particularly in a post-Brexit regulatory context where NI's environmental oversight structures remain under scrutiny.

Halkos and Tsilika (2019) suggest that policymakers are more likely to take effective action when supported by strong data. Therefore, improving spatial coverage of PM2.5 monitoring could strengthen both local and cross-border air quality policy under PEACEPLUS.

1.6 Research Gap

While numerous international studies have evaluated low-cost PM2.5 sensors, no published research has systematically compared low-cost and high-cost sensors under NI's specific meteorological and emission conditions. Given evidence that sensor performance may be influenced by environmental context, this represents a clear research gap.

A comparative field evaluation in NI would therefore provide locally relevant evidence on sensor performance, inform potential expansion of monitoring networks, and support the objectives of the PEACEPLUS Clean Air project. By generating robust data on accuracy, precision and reliability under real-world NI conditions, this study aims to contribute to improved EH protection and evidence-based policymaking.

Methodology

2.1 Research Design

This study adopted a quantitative comparative observational research design to assess the agreement between a low-cost particulate matter (PM2.5) sensor and a reference-grade air quality monitoring instrument. Quantitative methods were selected because the study involved the collection and analysis of numerical PM2.5 concentration data from two monitoring devices. This is consistent with the definition provided by Clements et al. (2022), who describe quantitative measurements as those expressed numerically, for example in micrograms per cubic metre ($\mu g/m^3$). The purpose of the study was to determine whether measurements produced by the low-cost sensor were comparable to those obtained from a reference-grade instrument used for regulatory air quality monitoring.

The research design was observational, as measurements were taken under real-world environmental conditions without manipulation of variables. Both sensors measured naturally occurring ambient PM2.5 concentrations simultaneously at the same location. A comparative approach was used in order to evaluate the level of agreement between the two monitoring methods.

The data collected in this study constitute primary data, as the measurements were collected directly from the monitoring instruments during the study period.

2.2 Study Location

Data collection took place at the Armagh AQMS on Londsdale Road in NI. This site forms part of the regional air quality monitoring network and contains a reference-grade PM2.5 monitoring instrument used for regulatory air quality monitoring.

The monitoring station was selected as the study site because it provides an established and calibrated monitoring environment where accurate PM2.5 measurements are routinely collected. Installing the low-cost sensor at this location enabled direct comparison with a trusted reference instrument under identical environmental conditions. This location was selected as a monitoring site because it represents both a roadside and residential environment, making it suitable for assessing sensor performance under locally relevant exposure conditions.

2.3 Instrumentation and Sensor Deployment

Two PM2.5 monitoring devices were used in this study, a reference-grade PM2.5 monitor located at the Armagh AQMS and a low-cost PM2.5 sensor deployed specifically for the purposes of this research.

The low-cost sensor was installed adjacent to the reference monitor to ensure that both devices were exposed to the same ambient air conditions. Co-locating sensors is a common approach used in sensor validation studies, as it allows direct comparison between monitoring instruments while minimising environmental variability.

Both sensors were operated in accordance with the manufacturer's operational guidelines and user instructions to ensure that measurements were collected under appropriate conditions.

The reference-grade monitor used was the BAM 1020 Particulate Monitor, while the low-cost sensor was the Kunak AIR Pro. Both monitors were operated in accordance with the manufacturers' operational guides (Met One Instruments, 2019; Kunak Technologies S.L., 2023).

2.4 Data Collection

The PM2.5 concentration data were collected over a 14-day monitoring period at the Armagh AQMS. During this period, both the reference-grade monitor and the low-cost sensor continuously measured ambient PM2.5 concentrations.

The sensors automatically recorded and transmitted measurements through their respective digital monitoring systems, with data uploaded to an online monitoring portal. This allowed continuous collection of PM2.5 data without the need for manual recording.

At the end of the monitoring period, the recorded datasets from both sensors were downloaded from the portal and prepared for analysis. Each dataset contained time-stamped PM2.5 concentration values recorded throughout the monitoring period. The monitoring period for this study was 3rd April 2026 – 17th April 2026.

Co-locating the sensors ensured that both devices recorded measurements under identical environmental conditions, allowing differences in recorded PM2.5 concentrations to be attributed primarily to sensor performance.

As fine particulate matter concentrations can be influenced by rainfall, atmospheric conditions were considered as part of the assessment of monitoring conditions. Total rainfall in Armagh during April 2026 was 38.4 mm (Armagh Observatory and Planetarium, 2026), compared with a long-term average April rainfall of 55.67 mm (Met Office, 2021).

2.5 Data Analysis

The collected data were analysed using Statistical Package for the Social Sciences (SPSS) software.

Initially, the datasets from both sensors were organised and aligned according to their time-stamped measurements to enable direct comparison of corresponding PM2.5 values. Descriptive statistical analysis was first conducted to summarise the recorded PM2.5 concentrations from each sensor. This included calculation of the mean, minimum, maximum and standard deviation values.

Prior to conducting Pearson's correlation analysis, the paired PM2.5 data were visually examined using scatter plots to assess the relationship between the two datasets and identify any obvious outliers. Pearson's correlation analysis was then performed to determine the strength and direction of the linear relationship between the measurements produced by the low-cost sensor and the reference monitor.

In addition, Root Mean Square Error (RMSE) was calculated to quantify the average magnitude of the differences between the PM2.5 concentrations recorded by the low-cost sensor and the reference-grade monitor. RMSE provides an indication of the overall measurement error between the two instruments.

To further evaluate agreement between the two measurement methods, Bland–Altman analysis was conducted. This method assesses agreement by examining the mean difference between paired measurements and calculating the limits of agreement. Bland–Altman analysis is widely used in method comparison studies as correlation alone does not determine whether two measurement techniques produce comparable values (Bland and Altman, 1986).

Together, these statistical analyses were used to evaluate the level of agreement between the low-cost sensor and the reference monitor and to determine the suitability of low-cost sensors for supporting expanded air quality monitoring networks.

2.6 Ethical Considerations

All ethical considerations were taken into account during the design and implementation of this study. The research did not involve human participants, vulnerable groups, or personal data. As the study focused solely on environmental monitoring data collected from air quality sensors, there was minimal risk of harm to individuals.

Permission was obtained from Armagh, Banbridge and Craigavon Borough Council, the body responsible for the monitoring site prior to installing the low-cost sensor. All collected data were handled responsibly and stored securely in accordance with institutional data management guidelines.

2.7 Study Limitations

This study was limited to a two-week monitoring period, which may not capture the full range of seasonal and meteorological variation that can influence PM2.5 concentrations and sensor performance. Additionally, the study was conducted at a single monitoring location, which may limit the generalisability of the findings to other environments with different pollution sources or environmental conditions.

Despite these limitations, the study provides a useful preliminary evaluation of the performance of a low-cost PM2.5 sensor under real-world monitoring conditions in NI.

Results

3.1 Preparation of the dataset

The collected PM2.5 concentration data were analysed using IBM SPSS Statistics Version 30 to assess the performance of the low-cost Kunak AIR Pro sensor against the reference-grade BAM 1020 monitor located at Armagh AQMS. A total of 311 valid paired hourly observations were included in the final analysis following timestamp adjustment and removal of unmatched values.

The BAM 1020 reference monitor recorded PM2.5 concentrations in milligrams per cubic metre (mg/m^3). As air quality standards and health-based guideline values are typically reported in micrograms per cubic metre (µg/m^3), all BAM 1020 results were converted from mg/m^3 to µg/m^3 by multiplying each value by 1000 prior to analysis. This allowed direct comparison with the Kunak AIR Pro data and improved interpretation against WHO and DAERA guideline values.

Prior to analysis, the Kunak AIR Pro timestamps were adjusted by one hour to ensure temporal alignment with the BAM 1020 data. Initial comparison indicated a time offset between the two datasets and, following adjustment, both sensors were matched on an hourly basis to allow direct comparison of PM2.5 concentrations.

Day 14 of the monitoring period was excluded from the final analysis as the BAM 1020 did not produce valid results due to a maintenance issue at the monitoring station. As no reference-grade data were available for this period, paired comparison was not possible, and these observations were removed to maintain consistency and reliability within the dataset.

Three statistical methods were used to assess sensor performance: Pearson correlation analysis, Root Mean Square Error (RMSE), and Bland–Altman analysis. Pearson correlation analysis was used to measure the strength and direction of a linear relationship between two continuous variables, namely low-cost and reference grade sensors. RMSE was used to quantify the average magnitude of error between the two instruments. Bland–Altman analysis was used to assess agreement between the two monitoring methods by calculating the mean difference and limits of agreement.

Together, these statistical analyses provided a comprehensive assessment of the suitability of the low-cost sensor for supplementary PM2.5 monitoring in NI.

Figure 3 shows the hourly PM2.5 concentrations recorded by the BAM 1020 and Kunak AIR Pro over the monitoring period. Both sensors followed similar broad temporal trends, although noticeable differences in magnitude were observed at several time points.

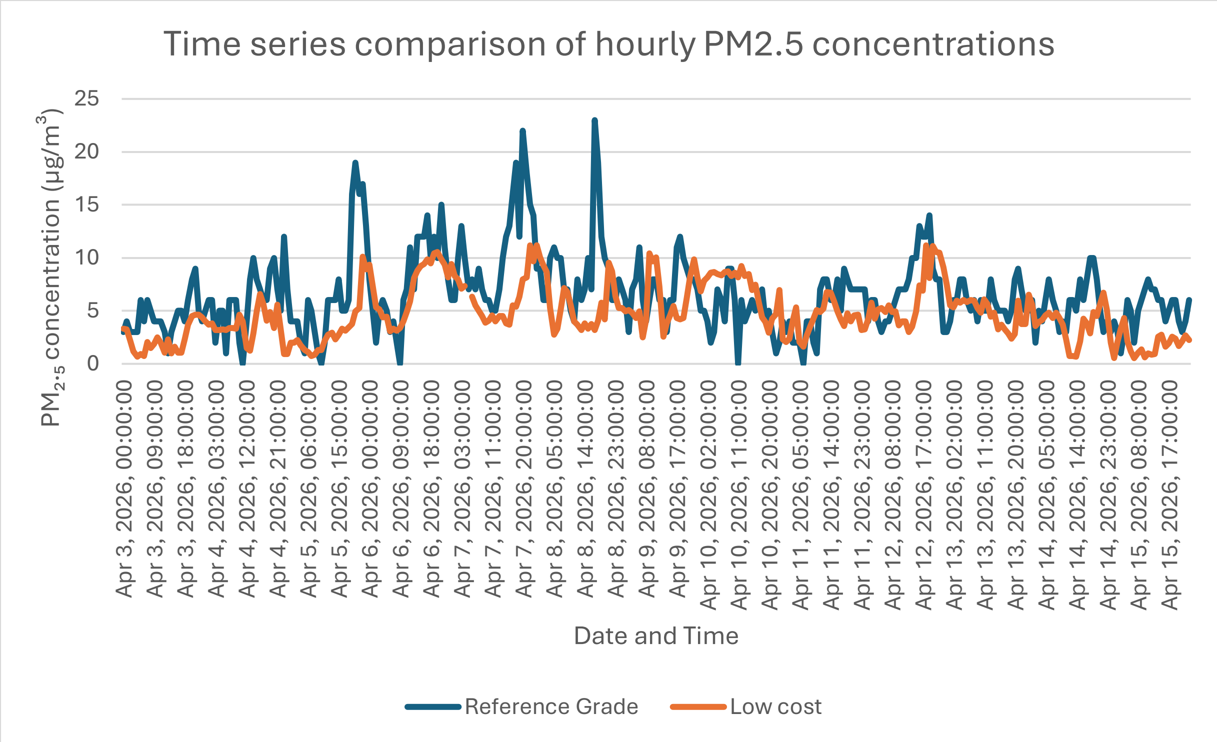


Figure 3 Time series comparison of hourly PM2.5 concentrations recorded by the BAM 1020 and Kunak AIR Pro

<u>3.2 Pearson Correlation Analysis</u>

Pearson's correlation analysis demonstrated a weak-to-moderate positive relationship between the low-cost Kunak AIR Pro sensor and the BAM 1020 reference-grade monitor ($r = 0.369$, $p < 0.001$, $n = 311$). This indicates that both sensors followed some similar trends in PM2.5 concentrations over the monitoring period. However, the relationship was modest rather than strong.

This suggests that while the low-cost sensor detected broad fluctuations in PM2.5 levels, there was considerable variability in measurement precision. The Kunak AIR Pro may therefore be useful for identifying general pollution trends, but its performance was not sufficiently strong to indicate close agreement with the BAM 1020 for regulatory monitoring purposes.

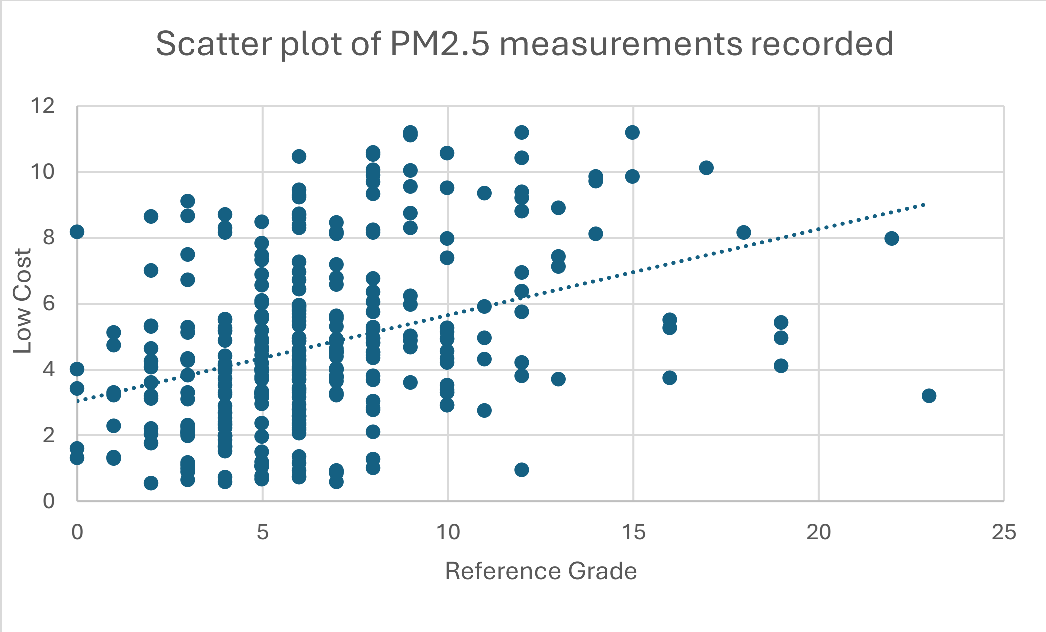


Figure 4. Scatter plot showing the relationship between BAM 1020 and Kunak AIR Pro PM2.5 measurements

3.3 Root Mean Square Error (RMSE)

The Root Mean Square Error (RMSE) between the two sensors was calculated as 4.02 μg/m^3. This represents the average magnitude of measurement error between the low-cost sensor and the BAM 1020.

An RMSE of 4.02 μg/m^3 indicates a moderate level of measurement difference between the two instruments. Considering that the WHO annual guideline value for PM2.5 is 5 μg/m^3, this level of variation is significant and suggests that low-cost sensor measurements should be interpreted with caution when used for public health decision-making or regulatory purposes.

The RMSE result supports the correlation findings by indicating that although both sensors follow similar trends, individual hourly measurements may differ considerably.

3.4 Bland–Altman Analysis

Bland–Altman analysis was used to assess the level of agreement between the low-cost and reference-grade PM2.5 monitors.

The mean difference (bias) between the two sensors was −1.80 μg/m^3, indicating that the Kunak AIR Pro generally underestimated PM2.5 concentrations when compared to the BAM 1020 reference monitor.

The standard deviation of the differences was 3.60 μg/m^3. Using the Bland–Altman method, the limits of agreement were calculated as:

- Upper Limit of Agreement: 5.25 μg/m^3
- Lower Limit of Agreement: −8.86 μg/m^3

Most data points fell within these limits, indicating moderate agreement between the two monitoring methods. However, the relatively wide range between the upper and lower limits demonstrates considerable variability in individual measurements.

The Bland–Altman plot (Figure 5) further showed that the spread of differences increased at higher PM2.5 concentrations. Several strong negative outliers were observed at elevated concentration levels, suggesting that the low-cost sensor became less reliable as pollutant concentrations increased. This indicates the presence of proportional bias, where sensor performance decreases at higher pollution levels.

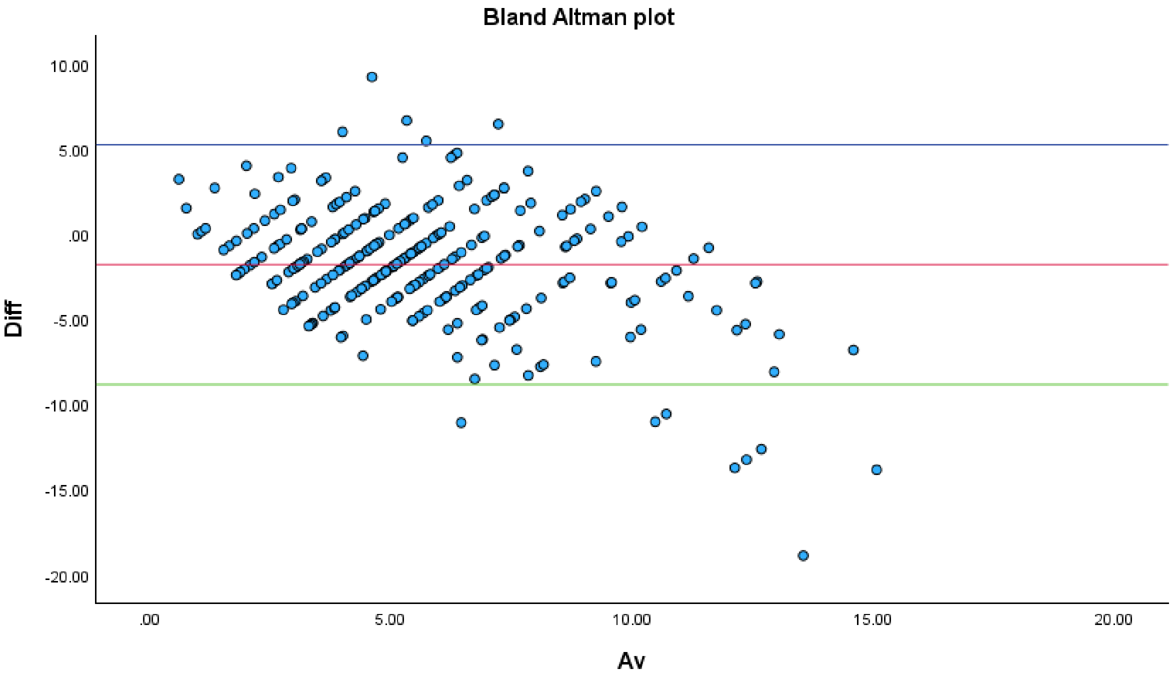


Figure 5 Bland Altman Plot showing agreement between the BAM 1020 and Kunak AIR Pro PM2.5 measurements

This finding is particularly important for EH monitoring, as underestimation during high pollution episodes may reduce the effectiveness of early intervention and public health protection measures.

3.5 Summary of Findings

Overall, the results suggest that the Kunak AIR Pro low-cost sensor demonstrated moderate performance when compared with the BAM 1020 reference-grade monitor. The Pearson correlation showed that both sensors generally followed similar temporal trends in PM2.5 concentrations, while the RMSE and Bland–Altman results identified consistent underestimation and variability in individual measurements.

These findings suggest that low-cost sensors may be valuable for expanding spatial monitoring coverage and supporting projects such as PEACEPLUS and PEACE-AIR, particularly where resource limitations restrict the use of multiple reference-grade stations. However, the observed bias and variability indicate that low-cost sensors should complement rather than replace reference-grade monitoring infrastructure.

Discussion

This study compared the performance of the Kunak AIR Pro and BAM 1020 to assess whether low-cost sensors could support air quality monitoring in NI. The results demonstrated moderate agreement between the two instruments, with evidence that the low-cost sensor could identify general PM2.5 trends but showed limitations in measurement accuracy when compared to the reference monitor.

Pearson's correlation analysis produced a positive relationship between the two sensors ($r = 0.369$), indicating that the Kunak AIR Pro was able to reflect some broad temporal variation in PM2.5 concentrations. However, this correlation was relatively modest and lies at the lower end of what may be considered acceptable for supplementary monitoring. This suggests that, while the low-cost sensor demonstrated some capacity to identify general pollution trends, its performance was not sufficiently strong to indicate close agreement with the BAM 1020 reference monitor. This supports the findings of Mukherjee et al. (2017), who emphasised that low-cost sensors require comprehensive real-world validation before large-scale deployment.

It also suggests that their greatest value may lie in deployment as part of a wider, validated sensor network, where multiple low-cost devices can provide improved spatial coverage and help build a more detailed picture of local pollution patterns, while reference-grade stations remain necessary for regulatory accuracy. Despite this modest correlation, low-cost sensors may still offer practical value in contexts where the primary objective is to improve spatial coverage and identify broad pollution patterns rather than provide regulatory-grade measurements. In NI, where fixed reference-grade monitoring stations are limited in number, the deployment of validated low-cost sensors could help identify localised PM2.5 hotspots and support data collection for initiatives such as PEACEPLUS and PEACE-AIR. Their value therefore lies less in replacing reference instruments and more in complementing them within a wider monitoring network.

The RMSE value of 4.02 $\mu g/m^3$ further demonstrates that notable differences existed between individual measurements from the two sensors. Considering that the WHO annual PM2.5 guideline value is 5 $\mu g/m^3$ (World Health Organization, 2021), an error of this magnitude is significant and may influence interpretation of exposure risk. This is particularly important in NI, where mean urban background concentrations are already above WHO recommendations but below current regulatory limits (DAERA, 2026). In such circumstances, relatively small measurement errors may affect policy decisions and public health messaging.

Bland–Altman analysis showed a mean difference (bias) of −1.80 $\mu g/m^3$, demonstrating that the Kunak AIR Pro generally underestimated PM2.5 concentrations compared to the BAM 1020 reference monitor. This finding is important because underestimation during periods of elevated pollution may reduce the effectiveness of interventions designed to protect public health. The wide limits of agreement also indicate variability in sensor performance, suggesting that agreement between the instruments was not consistent across all concentration levels.

The Bland–Altman plot further demonstrated increasing variability at higher PM2.5 concentrations, with several strong negative outliers observed. This suggests proportional bias, where the low-cost sensor becomes less reliable as pollutant concentrations increase. Similar concerns regarding sensor performance under varying environmental conditions have been identified by Polidori et al. (2017) and Liu et al. (2019), who found that calibration under representative field conditions is essential for improving accuracy. NI's variable meteorological conditions, including high humidity and changing weather systems, may further influence optical sensor performance and contribute to this variation.

Rainfall may also have influenced PM2.5 concentrations during the study period. Total rainfall in Armagh during April 2026 was 38.4 mm (Armagh Observatory and Planetarium, 2026), compared with a long-term average April rainfall of 55.67 mm (Met Office, 2021). As rainfall can contribute to the removal of airborne particles, these conditions may have had some influence on observed PM2.5 concentrations.

The findings are particularly relevant in the context of residential solid fuel burning, which the SAPPHIRE project identified as the dominant source of PM2.5 in many Irish residential areas (Wenger et al., 2020). Since pollution episodes associated with domestic heating often occur during evening periods and may be highly localised, the use of only a limited number of high-cost reference stations may underestimate local exposure. Low-cost sensors offer the potential to improve spatial monitoring coverage and better identify pollution hotspots that may not be captured by fixed monitoring infrastructure alone.

This has clear relevance to PEACEPLUS and the PEACE-AIR programme, which aim to improve cross-border environmental monitoring and evidence-based policymaking. The results of this study suggest that low-cost sensors could support wider monitoring networks across NI and the ROI, particularly where financial and logistical barriers limit the deployment of multiple reference-grade stations. However, the observed bias and variability indicate that low-cost sensors should complement rather than replace reference-grade monitoring systems.

A key limitation of this study was the relatively short monitoring period of two weeks, with one full day excluded due to BAM 1020 maintenance. This limited the range of meteorological conditions and pollution episodes captured during the study period. Seasonal variation, particularly during colder winter months when solid fuel burning increases, may produce different results. In addition, the study was conducted at a single monitoring location, which may limit wider generalisation across NI. It should also be noted that the data analysed in this study were collected during the first two weeks following deployment of the Kunak AIR Pro sensor. As this represented the initial operational period of the instrument, it is possible that early deployment or stabilisation effects may have influenced sensor performance. However, this could not be determined within the scope of the present study.

Despite these limitations, the study provides valuable locally relevant evidence in an area where limited published comparison studies currently exist. As sensor performance is strongly influenced by local environmental conditions, this NI-specific evaluation contributes useful evidence to support future monitoring strategies.

Conclusion

This study evaluated the performance of the low-cost Kunak AIR Pro PM2.5 sensor against the BAM 1020 reference-grade monitor at Armagh AQMS. The findings demonstrated that the low-cost sensor showed moderate correlation with the reference monitor and could identify general trends in PM2.5 concentrations. However, the RMSE and Bland–Altman analysis revealed consistent underestimation and variability in individual measurements, particularly at higher pollution levels.

These results indicate that while low-cost sensors have value for expanding spatial monitoring coverage and identifying localised pollution patterns, they currently lack the accuracy required to replace reference-grade monitoring for regulatory compliance purposes. Instead, they are best used as supplementary tools that enhance existing monitoring networks. For EHPs, this has practical relevance because validated low-cost sensors may support the identification of localised PM2.5 hotspots, help prioritise areas for further investigation, and provide additional evidence to inform local air quality management, public health advice and cross-agency interventions.

Given the health significance of PM2.5 exposure and increasing policy focus on stricter air quality standards, improving monitoring capacity is important for effective EH protection. This is particularly relevant in NI, where residential solid fuel burning remains a major source of PM2.5 and where localised exposure hotspots may not be fully captured by a limited number of fixed monitoring stations. Although the findings do not suggest that low-cost sensors are suitable for formal regulatory enforcement, they may still assist EHPs by helping to identify areas where additional investigation, community engagement or targeted intervention may be required, while also contributing to evidence-based policy development.

Overall, this study supports the use of validated low-cost sensors as part of a wider air quality monitoring strategy, particularly within initiatives such as PEACEPLUS and PEACE-AIR, where improved cross-border monitoring and stronger evidence-based decision-making are key objectives.

Recommendations

Based on the findings of this study, several recommendations can be made for future research and air quality monitoring practice.

Firstly, low-cost PM2.5 sensors should be used to complement rather than replace reference-grade monitoring stations. Their lower cost and ease of deployment make them valuable for increasing spatial coverage, particularly in residential areas affected by solid fuel burning, but regular calibration against reference monitors remains essential.

Secondly, future studies should involve longer monitoring periods across multiple seasons to capture a wider range of meteorological conditions and pollution events. Winter monitoring would be particularly important due to the increased influence of domestic solid fuel combustion on PM2.5 concentrations.

Thirdly, further comparative studies should be conducted at multiple sites across NI, including urban, rural and roadside environments, to improve understanding of sensor performance under different local conditions.

Since completion of this study, four additional Kunak sensors have been deployed at Armagh AQMS. This creates an opportunity for future research to compare the performance of all five low-cost sensors against the BAM 1020 reference monitor to assess inter-sensor consistency, repeatability and reliability within a multi-sensor monitoring network.

Finally, policymakers and EHPs should consider the integration of validated low-cost sensors into wider air quality management strategies under PEACEPLUS and PEACE-AIR. Improved monitoring coverage would support stronger evidence-based policy development, better identification of pollution hotspots and more effective public health protection across both NI and the ROI.

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Appendices

Appendix A: Monitoring Site and Sensor Installation

Kunak AIR Pro PM2.5 sensor at Armagh AQMS

Installing the Kunak AIR Pro PM2.5 sensor

BAM 1020 Particulate Monitor

Appendix B: Sample Data Preparation

	A	B	C
1	onc_mg_m	onc_ug_m3	
2	0.003	3	
3	0.004	4	
4	0.003	3	
5	0.003	3	
6	0.003	3	
7	0.006	6	
8	0.004	4	
9	0.006	6	
10	0.005	5	
11	0.004	4	
12	0.004	4	
13	0.004	4	
14	0.003	3	
15	0.001	1	

BAM mg/m^3 to µg/m^3 conversion

Appendix C: Statistical Output

	N	Minimum	Maximum	Mean	Std. Deviation
Diff	311	-19.81	8.17	-1.8031	3.59851
Valid N (listwise)	311				

Standard Deviation Calculations on SPSS

		RGsensor	LCsensor
RGsensor	Pearson Correlation	1	.369**
	Sig. (2-tailed)		<.001
	N	312	311
LCsensor	Pearson Correlation	.369**	1
	Sig. (2-tailed)	<.001	
	N	311	311

**. Correlation is significant at the 0.01 level (2-tailed).

Pearson Correlation Calculations on SPSS