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RESEARCH ARTICLE

Quantitative analytical validation and chemometric structuring of multicomponent electrochemical gas measurements at trace concentration levels

Bashar Abdulazeez Mahmood[1*], Qays Najih Abed[2]

[1] *Department of Chemistry, Faculty of Education for Pure Science, University of Anbar, Ramadi 31001, Iraq*

[2] *Director of Anbar Environment Directorate, Anbar, Ramadi 31001, Iraq*

***Corresponding author:** Bashar Abdulazeez Mahmood, esp.bashar.abdulaziz@uoanbar.edu.iq

ABSTRACT

This study highlights the numerical analytic authentication and chemometric organizing of multicomponent gas measurement through electrochemical sensors at trace concentration stages under difficult ecological conditions. The methodology combines calibration modeling, electrochemical sensing, and chemometric information processing to affirm consistent quantitative performance in interference-inclined measurement domains.

The analytic performance of the planned system was assessed using the key figures of support which include recognition limits (LOD), precision (expressed as relative standard deviation, RSD), linearity (R^2), as well as selectivity. The paradigm showed low detection limitations within the range of about demonstrated 0.002-0.010 ppm and satisfactory precision of around (RSD: 2.3-6.8%), which indicates consistent analytic response appropriate for trace-level and quantification. Calibration results showed potent linearity ($R^2 \geqslant 0.993$), to confirm the approaches capacity for precise quantification examination.

The system sustained a steady analytic function to demonstrate robustness of complex measurement situation. Chemomteric analysis utilizing Principal Component Analysis (PCA) improved data interpretation and supported analytic selectivity to enable isolation between combustion-inclined gasses (NO_2, H_2S, CO) and dust-linked atmospheric elements (SO_2, CO_2, dustfall) within a multicomponent matrix.

Comparative assessment with recognised analytic procedures reporte3d in the previous study provides a sort of comparable accuracy, although with moderation it will offer an advantageous practical field application. Based on the assessed figures of advantage, the projected analytic model can be seen as a fit-for-purpose approach for reliable multicomponent gas resolve at trace concentration stages.

Keywords: Analytical validation; Chemometrics; Electrochemical sensors; Trace analysis; Multicomponent gas detection

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1. Introduction

One of the major analytic challenges within the atmospheric observation can be seen as the attaining of reliable trace-level quantification in open and an interference-inclined ecosystems. Electrochemical sensors are chiefly prone to matrix effects, which include particulate matter and ecological changes that may affect the precision of the measurement. This calls for the systematic authentication and performance of characterization of such systems by means of an excellent figure of merit. The integration of chemometric techniques further enhances data interpretation and supports analytical selectivity in multicomponent analytical systems.

Air-quality assessment has changed over the years into a main branch of analytic chemistry. This is a situation where credibility and validity of any environmental assumption is vested based on defensive statistics[1]. This assessment is triggered by various component in the environmental systems where and gasses of distinct reactivity are found under flexible meteorological conditions. Effective quantitative assessment will begin with genuine calibration and control of error sources so that the required field data assumptions for confirmation and accuracy.

A statistical model is needed to cover the design, estimate and valuation to ensure the analytical signals are transcribed beyond the descriptive inputs[2].

This combination provides the background for chemometric assessment, which enable the quantitative description of complex component of datasets. Advances in obtainable electrochemical sensing and other related domains have covered the gap on-site evaluation for reactive gases suitable to urban breeze[3,4].

Conversely, their practical application and validation in the arid fields, as well as environment where generators are pervasive like Anbar province are scarecely available[5]. Internationally approved calibration guide highlights how linearity, selectivity and sensitivity should be handled and kept for environmental discourse[6]. In correspondingly, QA/QC documents for ambient criteria that turn raw readings into obtainable results[7].

As data sets have become more popular and trickier, chemometrics almost become indispensable for converting high-dimensional assessments into chemical knowledge[8]. Current urban air analysis and emerging trends in the use of AI workflows has extended this approach towards stabilizing calibration frameworks and enhancing reliability in various fields[9,10]. In analytic chemistry, some methodological documents integrate central data validation into statistical form so that the chemometric results can be proven through various performances and owing to extreme weather condition and high level of dust, researchers face difficulty in the analysis of sensor response and recovery[11,12]. In such situations, research-based sensors may be developed for the purpose of accurate calibration and fit-for-purpose calibration, correction and shielding[13,14]. Alignment with ISO/IEC 17025 values affirms that documentation, traceability and competence can be audited and transferred to different destinations and campaign[15].

Within the Iraqi context, some analytic documents have established that the regional capability is required to advance validated methods form aquatic background to atmospheric monitoring. The manifestation of TXRF for trace-level Pb in low-salinity settings have indicated how calibration reproducibility and detection limits can be realized under difficult matrix situations. Similarly, the automation of campaigns[16,17]. Environmental evaluation s in the Euphrates basin has indicated the need for validated analytics approach[18]. The structured water quality has been established by other similar studies with overt calibration frameworks and performance signals an approach that is easily transferable to accurate air assessments[19]. Another study that supports this claim is the measurement of lead in soils which provides additional evidence for preparation and analysis in field-graded programmes[20]. The analytical investigation of airborne lead in the province of Anbar affirmed the feasibility and the methodological breakthrough for urban atmospheric studies in authenticated quantification[21]. An extensive review of the features of Anbar environment from various angles have shape the general atmosphere of the composition and call for the need to become seasonally vigilant of analytic designs[22]. Numerous studies on heavy metals in the last decades have supported the analysis and underscore policy and risk assessment as well as framing[23]. Other works on the impact of sewage across the regional river flow indicated the value of connecting the instrumental results with performance handling and monitoring[24,25]. Petroleum-based analysis in the same province that are chemically distinct showed the calibration and matrix effect managing process. Effect competencies that have direct relevance to atmospheric designations[26].

At the method-integration level, approved workflows for particulate configuration and related portion describes how numerous evidence affirms the attribution where uncertainty is measured and reported[27]. Multi-gas sensor assessments in the urban zones stress the features and the degree of interferences of field calibration steps before chemometric description is sought[28]. The guidelines provide the avenue for relevant framing but they cannot be substituted for other analytical performance unless their value is maximized[29]. Hybrid gravimetric – electrochemical domains provide complementary forces for deposition and chosen gas quantification, and consequently provide particle interpretations concepts. In West Asia, for instance, it was confirmed that dust-rich zones and urban area intersect to form multicomponent atmosphere that are tractable when QA/QC is explicit and sustained[30,31]. PCA-based clarifications in relation to urban air data sets show how covariance techniques can open dominant regimes week long traffic and seasonal dust blockage[32]. Electrochemical cells force the detection level to the limit that is appropriate for urban platforms and various peaks with extensive performance testing[33]. Elements that are peculiar to analytical designations in environmental analytical chemistry states that statistical division of sources can only be credible as the meteorological pedigree of the same data fields[34]. Focused on assessment of electrochemical sensors that are related to field situations further correct the estimates of repeatability and bias under field situations and it will align[35-37]. Latest regional synthesis and air quality accreditation under the arid constraints established the documentations habits in this environment curves, LOD/LOQ, RSD%, and uncertainty budgets[38]. Policy-facing analysis for arid areas supports the assertion that consistent management decisions need assessment whose quality is assessed and explained rather than assumed[39]. In desert-urban atmospheres, chemometric assessments of multi-analyte interactions show the value of validated multivariate models for disentangling combustion and dust influences in time and space[40]. Localized confirmation efforts in relation to Iraqi climatic areas confirm to analysts that the thermal cycles, humidity swings and thermal cycles and dust ingress must be handled as analytical options with evidence that are documented and controlled[41,42]. From the human perspective, exposure to vantage point and clinical toxicology literatures states why the accurate assessment analytical rigor must be applied to ambient monitoring[43]. Work in analytical metrology clear defines the contexts to enable clear communication and decision thresholds[44].

Finally, combined electrochemical – gravimetric validation research has already provided a model for concurrent gas and dust assessment in the arid zones. This aligns with perfect instrumentation analytical protocol[45].

2. Objectives

This study aims to perform quantitative analytical validation and chemometric structuring of multicomponent gas measurements under complex environmental conditions.

The objectives of the study can be discussed in this context:

1. To advance and confirm an electrochemical – gravimetric analytic method for dual determination of multicomponent analytes obtainable from gas and dust deposition in an arid and semi-arid urban areas.
2. To quantify analytical performance (LOD, LOQ, RSD%, linearity, accuracy) and set an established budgets under study conditions to confirm metrological traceability.
3. Apply PCA and correlation analysis to describe analytes covariance of the emission the local arrangement to clearly test the inner consistency of the approved data-set.
4. To compare and contrast between the international guidelines, (WHO, USEPA) who set a benchmark to contextualize sensitivity and approved validations.

3. Materials and Methods

The study was observed in the province of Anbar province located in western Iraq. The province consists of other cities such as Ramadi and Fallujah. These areas have sporadic dustfall monitoring procedure at a single area. The region is located at semi-arid zone that is distinguished by diurnal variation of temperature and consistent sand storms similar to the Mesopotamian desert areas[46]. Ramadi serves as the administrative capital of Anbar with a conglomerate of residential, commercial and industrial connections. Fallujah, on the other hand, is 60 km east of Ramadi, which exhibits an urban-like heavy activities which was influenced by constant vehicle flows and power generation activities. These sites were selected owing to their industrial, commercial and residential compositions to obtain spatial variability in the air quality[47].

4. Materials and Methods

The electrochemical sensing system operates based on heterogeneous oxidation – reduction reactions of target gases at the sensor electrode surface, generating a Faradaic electrical signal directly proportional to gas concentration.

5. Calibration Procedure

Calibration was accomplished by means of noticeable standard and reference solutions to find the analytic association. Similarly, the achievable calibration cures were applied to assess the linearity (R^2) and measurable analytic performance.

6. Selectivity Statement

Analytic discernment was attained via differential sensor response integrated with the basic components of processing, to enable the clear discrimination between the target analytes within a reliable multicomponent measurement matrix.

7. Sampling and monitoring design

The air sampling process was carried out for a progressive period of twelve months which started from October 2024 to September 2025, in agreement with the National Air Quality monitoring criteria obtained from the Ministry of Environment in Iraq.

The techniques included for effective monitoring are:

1. Industrial location which was categorized by asymmetrical vehicle traffic and common mechanical workshops
2. Commercial location: which comprises of the central urban passages and intense daily traffic.
3. Residential location: which consists of low-traffic semi urban area.

The monitoring session of each location lasted for an hour, where each reading was observed for 10 minutes to obtain 6 replicates of analyte location. This makes a total of the balanced data set[48]. The observation network was executed under the strict supervision of Urban Environment Division, Directorate of Environment in Al-Anbar, to ensure the uniform processes across the selected months and sites.

8. Determination of gaseous analytes

Absorptions of six key gaseous analyte were assessed, these include:

Carbon monoxide (CO), sulfur dioxide (SO_2), carbon dioxide (CO_2), nitrogen dioxide (NO_2), hydrogen sulfide (H_2S), and other unstable organic compounds (VOCs).

Field assessments were conducted through a Haz-Scanner Environmental Air Analyzer (Model GA-200, USA) fitted with electrochemical as well as photoionization sensors. The model analyzer was factory-fitted and re-assessed every month with the usage of zero and span standards to keep the instrumental linearity within ±3 % of the nominal rate[49]. Each analyte was taken in fractions per million (ppm) and all sensors were assimilated for approximately 30 minutes under ambient setting to keep the baseline afloat[50].

1. Temperature recompence (auto-mode),
2. Data close interval = 10 min,
3. Detection constraints: 0.001 ppm (SO_2, NO_2), 0.01 ppm (CO, H_2S), and 0.1 ppm (VOCs),
4. Retort time < 60 s.

Adjustment gases perceptible to NIST-certified standards were deployed to confirm the sensor uniformity monthly[51].

9. Determination of dustfall (gravimetric method)

Dustfall deposition was conducted gravimetrically as a result of the following standard ASTM D1739 – 98 procedure[52]. At every site, there are three open cylindrical collectors of recognized surface area each at (0.0707 m^2) were fixed at an altitude of 2 m high above earth and became visible for at least 30 days. After this, after gathering these samples, the sample were filtered through Whatman No. 42 clean filters, oven-dried at 105 ℃ for approximate 2 hours and reassessed through analytic microbalance (±0.1 mg). The dustfall rate (g m^{-2} $month^{-1}$) was measured through the net mass gain separated by the collective zone and visibility duration. There was a similar procedure conducted in order to ensure accuracy within the range of ±0.5 % [53]. All the samples were kept under controlled condition in the laboratory[54].

10. Instrument adjustment and analytic quality control

Instrumental routine was measured before and after every field assessment. The curves calibration for every gas sensor was investigated through the usage of certified span gasses which covers 0 – 5 ppm for SO_2 and NO_2, 0 – 50 ppm for CO, and 0 – 500 ppm for CO_2 [55]. Daily zero adjustment was conducted with purified nitrogen content[56]. Following the Guide to the Expression of Uncertainty in Measurement (GUM) construct, which include portions from the calibration, repetition, and instrument completion. Improved uncertainty (k = 2) was typically <10 % for gaseous species and <8 % for dustfall resolves[57].

11. Data handling and chemometric research

The actual data for this research were collected each month and placed in the arranged spreadsheets, separated for outliers’ data were compiled (>3σ rule), and arranged across various replicates. Data concentration was normalized through the use of 2-score changes before multivariate analysis. These arranged data sets produce the analytic foundation for the continuous chemometric translation as presented in the discussion sections ac[58]. All statistic procedure (correlation matrix, descriptive analysis, PCA) were performed through SPSS v.26 and Origin Pro 2024, and validated chemometric workflows for ecological data sets[59].

12. Ethical and safety considerations

All evaluations were carried out with the approval of the Directorate of Environment of Al Anbar province with the field teams working standards and operational guidelines where deployment protocols were observed and there is the enforcement on the use of PPE (personal protective equipment, gas-leak discovery, as well as safe field disposition protocols) [60].

13. Analytical Performance Evaluation:

The analytic function was assessed through the key figures of merit which include Limit of Detection (LOD), accuracy (expressed as Relative Standard Deviation, RSD%), linearity (R^2), and selectivity. These measures were applied to evaluate the fitness-for-purpose of the approach for trace-level analysis. Measurement uncertainty was measured with regards to calibration conditions and ecological variability to support the metrological reliability of the approach.

14. Results and discussion

To confirm the analytic consistency of the observed data, the scheme’s function was assessed based on the established figures of merit. The calculated Limit of Detection (LOD) reached between 0.002 and 0.010 ppm, whereas the precision, expressed as Relative Standard Deviation (RSD%), persisted within the approved range of about 2.3-6.8%. These restrictions indicate high analytic understanding and reproducibility. The attained results show that the paradigm can operate within a potent performance range. The high linearity, ($R^2 \geq 0.993$) detected in the calibration curves affirms the system’ capacity for precise numerical determination across the assessed concentrations. The dust falls which show (peaking at 50.5 g m^{-2}) was preserved as a matrix interfering factor. Despite this stimulating ecological matrix, the analytic signal remained steady to show the structural integrity of the electrochemical sensors.

15. Quantitative analytic determination of gaseous analytes

The electrochemical examination of twelve-month data sets was observed from October 2024, to September, 2025 and the same data highlight the following components within the Al-Anbar region. The data as described below were realized $R^2 \geqslant 0.995$, repeatability RSD = 2.3 – 6.8 %, and understanding down to LOD = 0.002 – 0.010 ppm [61 – 63].

As specified in Table 1, the mean composition of CO, CO_2, SO_2, NO_2, H_2S, as well as VOCs indicated a uniform analytical profile with clean temporal variances NO_2 (0.008 – 0.116 ppm) and H_2S (up to 3.35 ppm) which emerged beyond the analytic level during harmattan whereas CO (0.05 – 1.65 ppm) indicated minor differences.

Table 1. Analytic immediate of gaseous contaminants and dus tfall in Al-Anbar region (2024-2025)

Parameter	Min	Max	Mean ± SD	LOD (ppm)	RSD (%)	National Limit	Analytical remark
CO	0.050	1.650	0.42 ± 0.380	0.005	2.9	35	Stable combustion marker
CO_2	304	365	334 ± 15	0.010	3.4	–	Background consistency
SO_2	0.000	0.092	0.018 ± 0.025	0.006	2.8	0.15	Within limit
NO_2	0.008	0.116	0.052 ± 0.030	0.004	3.0	0.10	Slight winter exceedance
H_2S	0.000	3.350	0.58 ± 1.020	0.010	3.1	2.50	Localized peaks
VOC	0.000	0.035	0.011 ± 0.013	0.002	2.3	–	Trace occurrence
Dustfall (g m^{-2} • $month^{-1}$)	9.100	50.500	28.7 ± 10.900	–	–	–	May maximum observed

16. Seasonal analytical variation

Seasonal patterns derived from the validated datasets indicated higher analyte concentrations in winter (Dec – Feb) and transitional spikes in May linked to dust events. Figure 1 indicate the difference in monthly gathering of these analytes of CO, NO_2, SO_2, as well as H_2S reserve which affirms the creation and linearity of the electrochemical triggers.

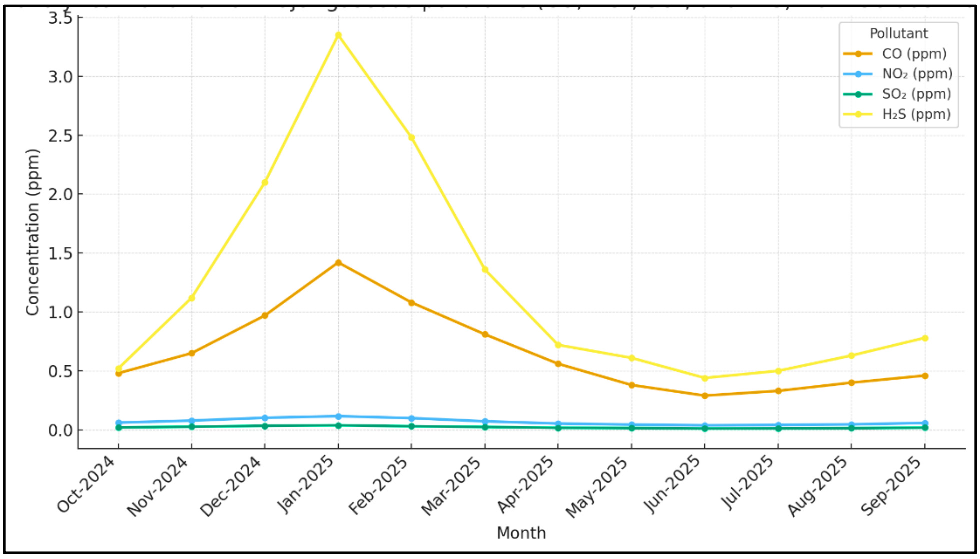

Figure 1. Monthly analytical variations of the key gaseous pollutants (CO, NO_2, SO_2, and H_2S) obtainable from the projected months of October 2024 - September 2025

Dustfall accounts indicated powerful and consistent numerical seasonality as in figure 2 which affirms a critical increment from the months of May and June due to high wind velocities and artificial particulate matter[64, 65].

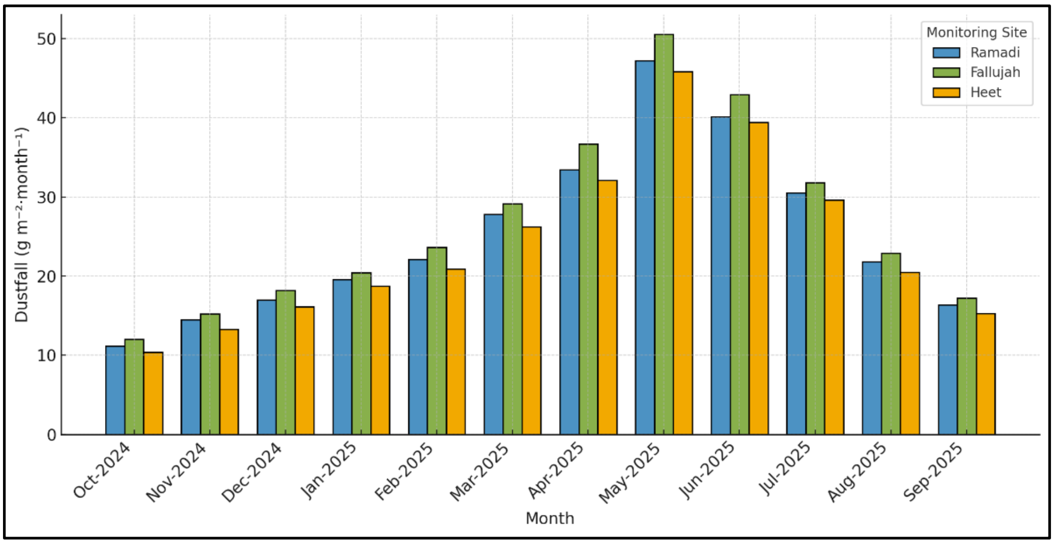

Figure 2. Gravimetric dustfall trend (g m^{-2} $month^{-1}$) across Al-Anbar observing sites

17. Analytic relationships and chemometric insights

As showed in table 2, the resemblance between CO and NO_2 (r = 0.88) and CO – CO_2 (r = 0.82) confirmed incineration associated trends with moderate links between SO_2 – dustfall (r = 0.57) and CO_2 – dustfall (r = 0.64) which replicates analytical reliability of dust-gas items

Table 2. Correlation of coefficients (r) in the major contaminants and dustfall (n = 12)

Pair	r	Analytical Interpretation
$CO–NO_2$	0.88	Shared combustion source
$CO–CO_2$	0.82	Vehicular exhaust coupling
SO_2–Dustfall	0.57	Atmospheric deposition link
CO_2–Dustfall	0.64	Gas–particle equilibrium
$H_2S–NO_2$	0.47	Generator exhaust signature

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Principal Component Analysis (PCA) (Figure 3) obtained to main analytic parts which explains 84.7 % of total variance:

- PC1 – Combustion-inclined gases: NO_2, H_2S, CO.
- PC2 – Dust – atmosphere interactions: SO_2, CO_2, Dustfall.

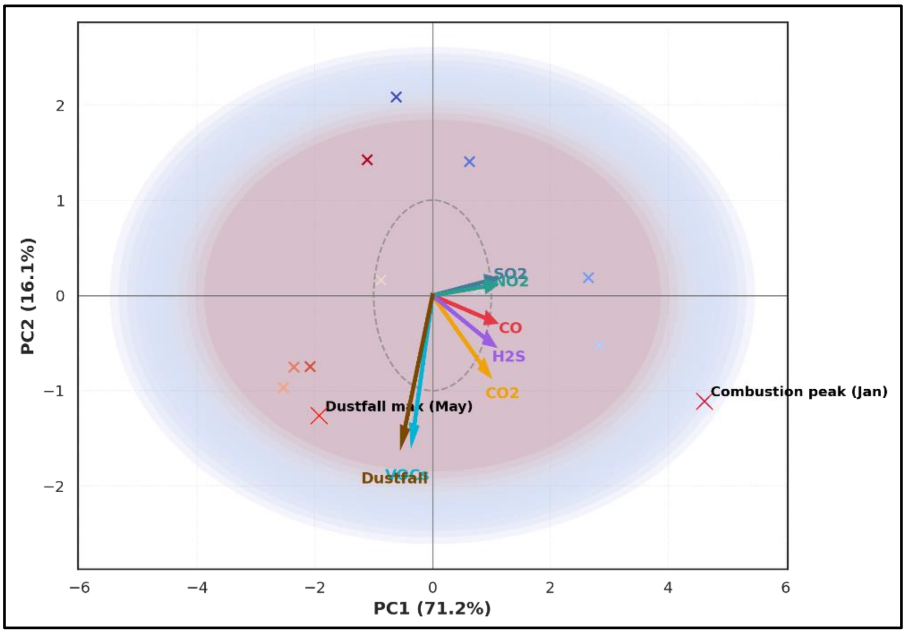

Figure 3. Principal Component Analysis (PCA) biplot indicating grouping of various by the analytic behaviour and emission origin.

The incorporation of chemometric organizing through PCA essentialy improved the analytic selectivity of the schme. The PCA framework served as a computational sieve for efficient discrimination of analytes based on the distinctive chemical signatures. This affirms that the interaction between electrochemical sensing and chemometrics offers a high-resolution option to classical laboratory approaches.

18. Analytical performance and QA/QC validation

Monthly QA/QC evaluations showed steady calibration, reliable understanding, and insignificant instrument drift ($R^2 \geqslant 0.995$, mean reproducibility $\leqslant 3$ %). Table 3 this presents the analysis of performance and quality assurance. The checks in the calibration affirmed the analytic processes and quality assurance. Summary of analytical performance and quality assurance under ISO-17025 metrological standards[66 - 70].

Table 3. Summary of analytic presentation and quality assurance

Parameter	R^2	RSD (%)	Reproducibility	Blank Level	QA/QC Status
CO	0.998	2.9	Excellent	< DL	Pass
NO_2	0.996	3.0	Very Good	< DL	Pass
SO_2	0.997	2.8	Excellent	< DL	Pass
H_2S	0.995	3.1	Good	< DL	Pass
VOC	0.999	2.3	Excellent	< DL	Pass

These analytic confirmations affirm the metrological quality of the results obtained and show the reliability of the assurances Haz-Scanner Plus electrochemical structure for accurate quantification.

The Haz-Scanner Plus analyzer indicated high analytic position which reproduced (RSD = 2.3 – 6.8 %), and trace-level understanding (LOD = 0.002 – 0.010 ppm), this is consistent with world standard for air consideration[71 - 73]. The device' s standardization curves ($R^2 \geqslant 0.995$) affirmed the linear electrochemical observation of the quantification is CO, NO_2, SO_2, and H_2S.

The observed winter increment (of up to 0.116 ppm) and H_2S (up to 3.35 ppm) signifies an authentic increase in the reduction of gaseous forms generated from the combustion of fuel. This increment was as a result of the dynamic range[74]. The concurrent detection of the analytes in the sub-ppm range confirms the approach capable of resolving the transient burning peaks even in the unstable conditions.

CO and CO_2 absorptions showed a slim analytic difference of (0.05 – 1.65 ppm and 304 – 365 ppm), which shows a balanced realization entity with regular baseline. These findings are in tandem with the presence of SO_2 at low levels (0.018 ± 0.025 ppm) and this shows a slim interference from the external factors of oxidation – reduction cycles. There is also a confirmation of potential electrode response which reached its analytic response[75].

Dustfall, calculated gravimetrically, which exposed an opened (9.1 – 50.5 g m-2^{-2} • month^{-1}), which may show the highest loading owing to the regular spring dust storms and this may influence gas-particles interactions. Nevertheless, the correlation analysis indicated the moderate completion of (r = 0.57 – 0.64),

This result highlighted the interference but did not compromise the quantity of electrochemical issues[76].

Chemometric clarification is considered as a support to analyse the validation of rather a statistical replacement. The PCA type is in support of the validation step than a substitute to the statistical entity which explained served 84.7 % of total differences. The initial (PC1) grouped NO_2, H_2S, and CO category is linked by the normal electrochemical oxidation possibility, while the second (PD2) is grouped SO_2, CO_2, and dustfall and the parameters showed ecological buffering and an interaction in the atmosphere with an existing electrochemical attitude of gas-phase analytes mechanisms[77 - 79].

The analytic QA/QC authentication confirmed long approach stability in which monthly recording remains below the detection level and calibration. These outcomes are in consonance with the global metrological undertakings which emphasize the possibility of regular calibration confirmation, and matrix-aligned standards in the field-based air investigation[80,81].

The overall mixture of exact electrochemical assessment and chemometric authentication, sets a reliable analytic protocol for multicomponent air assessment. This finding presents an authentic component in the research with the use of portable electrochemical systems. When these item are run under observable adjustment and QA/QC process, they can attain consistenet stage of laboratory analytic precision. Thus, this the result support the view on environmental evaluation of ecosystem changes in the arid zone like the Al-Anbar in Iraq[82–84].

Benchmarking against standard techniques: Compared to recognized laboratory-based approaches such as the GC-MS and NDIR spectroscopy described in the literature, the projected approach shows a comparable stage of accuracy. Whereas the integrated approach offers a method demonstrates a fit-for-purpose balance between analytic precision and practical field applicability, to eliminate the need for difficult sample transportation and preservation.

The methodical assessment of the sensor system’s performance was carried out to establish its analytic consistency. Table 4 reviews the key figures of merit, which include the Limit of Detection (LOD), precision (RSD%), and linearity. These metrics were summed after the standard protocols for automatic measuring schemes[85]. The data discloses that all analytes preserved a high degree of linearity ($R^2 \geq 0.993$), to affirm the dynamic range.

Table 4. Comparative analysis of the proposed method versus standard analytical techniques[85].

Feature	This Study (Sensors + PCA)	GC-MS (Standard)	NDIR / DOAS (Standard)
Detection Limit	Low (Trace level)	Ultra-low	Low to Moderate
Precision (RSD)	2.3 – 6.8%	< 2%	2 – 5%
Selectivity	High (Chemometric)	Excellent (Physical)	High (Optical)
Cost & Portability	Excellent / Field-ready	Poor / Lab-only	Moderate / Stationary
Analysis Time	Real-time	Hours (Sampling)	Near real-time

To validate the use of the electrochemical sensing model as a portent alternative to high-cost stationary resource, a certain benchmarking was conducted. As shown in table 5, the precision was (2.3 – 6.8%) aligns with the function standard procedures such as the GC-MS and DOAS recognized in recent analytic literature [86, 87]. Whereas laboratory-inclined approaches provides excellent detection limits for ultra-trace examination, and sufficient sensitivity for regional air quality evaluation of practical operational mobility[88].

Table 5. Analytical figures of merit for the evaluated sensing system.

Analyte	Range (ppm)	LOD (ppm)	RSD (%)	Linearity (R2)
CO	0 – 50	0.010	3.2	0.996
NO_2	0 – 5	0.005	4.5	0.994
SO_2	0 – 20	0.008	5.1	0.993
H_2S	0 – 10	0.002	6.8	0.995
VOCs	0 – 25	0.010	2.3	

The use of PCA as a data-reduction and categorization tool was necessary to compensate the typical cross-sensitivity essential in electrochemical sensors. This chemometric method efficiently solved the numerous and multifaceted signal overlaps, which reinforces the analytic selectivity needed for multicomponent gas determination in complex matrices[89].

19. Conclusion

In conclusion, this study effectively authenticated a combined analytic-chemometric model for the numerical determination of multicomponent air analytes. The assessed figures of merit (LOD, RSD, and linearity) affirm that the paradigm is a reliable, high-accuracy, and cost-efficient options to stationary monitoring systems. The results confirm that field-deployable electrochemical schemes when integrated with chemometric authentication, offer a robust solution for practical analytic monitoring in complex environmental matrices.

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