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EXPERIMENTAL STUDY ON CO_2 DETECTION IN INDOOR ENVIRONMENTS

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Abstract: *Indoor air quality monitoring, essential for maintaining healthy environments and for setting appropriate corrective measures, can be carried out using dedicated sensors or laboratory testing to detect pollutants such as CO_2 . This paper presents experimental results on CO_2 concentration in various indoor settings. The environmental measurements support efforts to position high-performance CO_2 sensors on the European market and align with current trends in sensor development. Sensor performance and inter-device consistency were evaluated using three devices: Sensors Europe GmbH – AGM50, Greisinger EBG-CO2-1R, and the experimental Nattive-Senz INO-SEN CO2.*

Key words: *indoor air quality, CO2 , Ventilation, Occupant health*

1. INTRODUCTION

Carbon dioxide (CO_2) in indoor environments has long been regarded as an essential indicator in the design and optimization of ventilation systems for residential and work spaces, as well as in the assessment of indoor air quality (IAQ). Pollutants such as carbon dioxide (CO_2) and suspended particles contribute to indoor air pollution at varying levels [5,6].

Currently, building designers use CO_2 concentration monitoring not only to evaluate air quality but also to calculate ventilation rates, employing CO_2 as a target gas in strategies for controlling outdoor and indoor airflows, while also considering its effects on the health and comfort of occupants. More recently, the measurement of CO_2 levels has also been associated with assessing the risks of airborne transmission of infectious diseases.

At the same time, increasing emissions—composed of various pollutant species, such as suspended particles and carbon dioxide (CO_2)—have harmful effects on the human cardiovascular and respiratory systems, potentially causing acute conditions and contributing to a reduction in life expectancy [7,8].

According to the World Health Organization (WHO), poor air quality contributed to 4.2 million deaths in 2016, of which approximately 17% were due to strokes and 26% to respiratory diseases. Numerous studies have shown that indoor air pollutant levels are two to four times higher than those found outdoors. In the United States, it is estimated that people spend an average of 22.25 hours per day indoors and 1.44 hours in vehicles or other means of transport, which significantly increases their exposure to pollutants.

Thus, indoor air quality represents one of the most significant global environmental health risks, a challenge that cannot be ignored. The situation in the European Union is similar, highlighting the universal nature of this issue.

In contemporary society, people spend the majority of their time indoors. The presence of a wide range of pollutants and contaminants in these enclosed environments has turned indoor air quality (IAQ) into a major concern [1].

In recent years, a positive trend has been observed in building design, focusing on reducing energy consumption and minimizing environmental impact [4]. Among the key factors used in evaluating building performance are thermal comfort, indoor air quality and

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ventilation, visual comfort, and acoustic comfort. These factors directly influence the health, comfort, and productivity of occupants in any indoor environment [2,3].

In addition, aspects such as spatial organization, the integration of natural elements into the built environment, building location, and accessibility to public or private services also contribute to the creation of a sustainable and health-supportive indoor environment.

Understanding indoor CO_2 concentrations is essential for several reasons, primarily related to human health, comfort, and environmental considerations. The most important factors include:

- Human Health: Elevated CO_2 levels can have both direct and indirect effects on health. Increased concentrations may cause headaches, dizziness, shortness of breath, and cognitive impairment. Prolonged exposure to high CO_2 levels can lead to more severe health issues.
- Ventilation: CO_2 monitoring is often used as an indicator of indoor air quality (IAQ). High CO_2 levels typically indicate inadequate ventilation. Proper ventilation is crucial for removing pollutants, ensuring a continuous supply of fresh air, and diluting contaminants, including airborne pathogens.
- Comfort: High CO_2 concentrations can contribute to a feeling of stuffiness and discomfort. Even when levels do not pose immediate health risks, occupants may experience discomfort and reduced productivity.
- Energy Efficiency: Managing CO_2 levels is also linked to energy efficiency. Maintaining adequate ventilation while avoiding excessive intake of outdoor air can help reduce energy consumption in HVAC (heating, ventilation, and air conditioning) systems. Balancing comfort and energy efficiency is essential.
- Environmental Impact: Excessive indoor CO_2 emissions contribute to the overall carbon footprint. By monitoring and controlling CO_2 levels, businesses and individuals can reduce emissions and support a more sustainable environment.
- Regulatory Compliance: In some regions, building codes and regulations set standards for indoor air quality and require CO_2 monitoring in spaces such as schools, offices, and healthcare facilities. Adhering to these standards is crucial for occupant safety and well-being.

2. INITIAL CONSIDERATION

For the sensor performance tests and inter-device trials, three instruments were used: Sensors Europe GmbH - AGM50, Greisinger EBG-CO2-1R, and the experimental Nattive-Senz INO-SEN CO2. The first device was considered the reference due to its high measurement accuracy, while the second was used as a comparison point for the experimental INO-SEN sensor. CO_2 concentration in ambient air is measured using the NDIR (Non-Dispersive Infra-Red detection) principle.

Infrared gas sensors based on Non-Dispersive Infrared (NDIR) absorption spectroscopy overcome the limitations of catalytic or electrochemical sensors, which are prone to contamination, aging, and have a short lifespan. Additionally, NDIR sensors provide high detection accuracy, a wide range of detectable gases, high reliability, and long service life, making them the optimal solution for monitoring CO_2 concentrations [9].

NDIR technology relies on the absorption characteristics of molecules in the infrared spectrum. When infrared radiation passes through a gas with specific absorption properties, the gas molecules absorb a portion of the radiation. This absorption relationship follows the Lambert-Beer law.

$$I = I_0(v) \cdot c^{-\alpha(v)CL} \quad (1)$$

Where:

- $I_{0(v)}$ represents the intensity of the incident beam,

- α(v) is the optical absorption coefficient of the target gas as a function of wavenumber (vv),
- C is the concentration of the target gas,
- L is the optical path length.

The concentration of CO_2 gas can be efficiently measured using the NDIR spectroscopic technique due to its strong absorption bands in the mid-infrared (MIR) region, which correspond to the fundamental vibrational and rotational energy transitions of the molecule. In addition to their intensity, the fundamental absorption bands of polyatomic gases in the MIR are less congested compared to their much weaker overtones in the visible (VIS) and near-infrared (NIR) regions, enhancing selectivity by reducing cross-sensitivity.

For instance, CO_2 exhibits a strong absorption at 4.26 μm (2350 cm^{-1}, Figure 1). This absorption band is unique, making it highly selective for CO_2 detection.

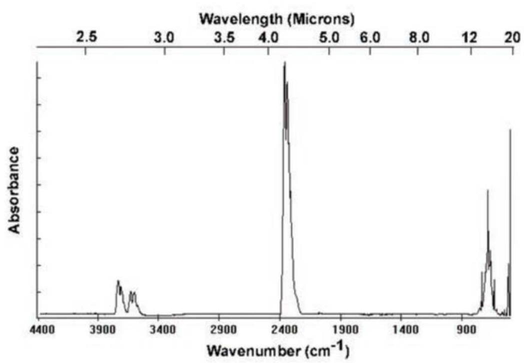

Fig. 1. The extinction coefficient spectrum of CO_2 calculated using the Spectraplot simulation tool [11]

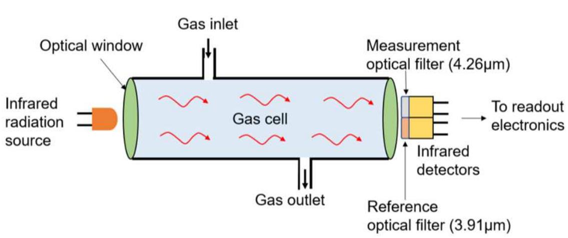

Fig. 2. Schematic of the operating principle of the NDIR CO2 concentration measurement configuration [11]

3. EQUIPMENT USED

3.1 Sensors Europe Gmbh, AGM50

The AGM50 analyzer, developed by Sensors Inc., a company founded in 1969 by the University of Michigan, is a reliable instrument for precise gas monitoring. With over 50 years of experience in designing gas and particulate pollutant measurement devices, Sensors Inc. operates its European headquarters and production facility in Erkrath, Germany.

The AGM50 utilizes an aspirated NDIR dual-beam principle with linearized output and compensation for temperature and pressure variations. The device offers high long-term stability, an improved signal-to-noise ratio, and a linear error of ≤1% of full scale (FS), with a lower detection limit of ≤0.5% FS. Its operational ranges include 0–50°C for temperature and 800–1200 mbar for pressure, ensuring accurate and consistent measurements across diverse environmental conditions.

3.2 Greisinger EBG-CO2-1R

Greisinger, a competence center for measurement devices, indicators, controllers, and temperature sensors, consolidates 37 years of expertise at its facility in Regenstauf, Germany. The EBG-CO2-1R analyzer is designed as a cost-effective alternative to reference analyzers, specifically for measuring CO_2 concentrations in greenhouses, ventilation systems, and indoor environments.

Key features of the instrument include:

- NDIR diffuse measurement principle
- Measurement range: 0–2000 ppm CO_2
- Measurement accuracy: ±50 ppm ±2% of the measurement range
- Temperature dependence: 2 ppm CO_2 / °C
- Signal output: EASYBus

This analyzer provides reliable and efficient CO_2 monitoring in applications where cost-effectiveness is a priority while maintaining sufficient precision for practical use.

3.3 Nattive-Senz, INO-SEN CO2

Nattive-Senz developed the INO-SEN CO_2 sensor, based on a thermopile detection principle with a 4.26 μm narrow-band NDIR filter and digital signal output via USB connection. As this sensor is experimental, the technical specifications used for both comparative measurements and statistical analysis were average values derived from the literature for similar devices.

The main estimated characteristics considered for the sensor are:

- Principle: Thermopile with NDIR filter – diffuse measurement
- Measurement range: 0–2000 ppm CO_2
- Measurement accuracy: ±50 ppm ±2% of the measurement range

4. EXPERIMENTAL CONDITIONS

Between July and August 2023, three sets of comparative measurements of indoor CO_2 concentration were conducted, with a minimum of 60 measurements per location, over periods of 3 and 4 consecutive days.

The measurements were carried out in different locations within UPT, including four distinct spaces: laboratories and a teaching office, using the previously described instruments.

The Sensors Europe AGM50 analyzer was considered the reference device due to its superior measurement accuracy. Sections 4.1 and 4.2 present the obtained results graphically, along with images showing the placement of the CO_2 measurement equipment in two of the four locations.

4.1 Comparative measurements Lab.N113

Figure 3 illustrates the placement of the three CO_2 measurement instruments in the N113 research laboratory at the Faculty of Mechanics, Politehnica University of Timișoara.

The technical specifications for the measurements are as follows:

- Laboratory area: 32 m²
- Occupancy during measurements: 2 persons
- Measurement period: 7–10 August 2023
- Data recording frequency: 1 reading every 5 minutes
- Data processing: hourly averages
- Total hourly average values recorded: 77 per instrument, 231 values in total

Fig. 3. Equipment placement in Lab. N113

Table 1

Daily average values of CO_2, Lab. N113 in ppm

	AGM50 ppm	EBG-CO2-1R ppm	INO-SEN CO2 ppm
7.08.2023	479.13	489.88	500.63
8.08.2023	474.67	485.25	495.29
9.08.2023	466.63	479.58	487.29
10.08.2023	467.31	467.31	477.38

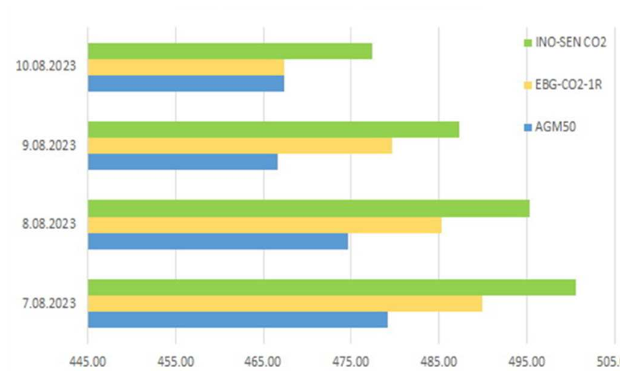

Fig. 4. Daily average values (24h) of CO_2, Lab. N113

4.2 Comparative measurements Office M302

Figure 5 illustrates the placement of the three CO_2 measurement devices in the faculty and PhD staff office, Room M302, Faculty of Mechanical Engineering, Politehnica University of Timișoara.

Technical specifications of the measurements conducted:

- Office area (Room M302): 25 m²

- Occupancy during measurements: 4 persons
- Measurement period: August 15–17, 2023
- Data recording frequency: 1 reading / 5 minutes
- Data processing: hourly average values
- Total hourly averages recorded: 57 per instrument, 171 in total

Fig. 5. Equipment placement in Office M302

Table 2

Daily average values of CO_2, Office M302, in ppm

	AGM50 ppm	EBG-CO2-1R ppm	INO-SEN CO2 ppm
15.08.2023	657.67	675.07	679.33
16.08.2023	625.83	647.25	650.13
17.08.2023	644.06	664.94	671.78

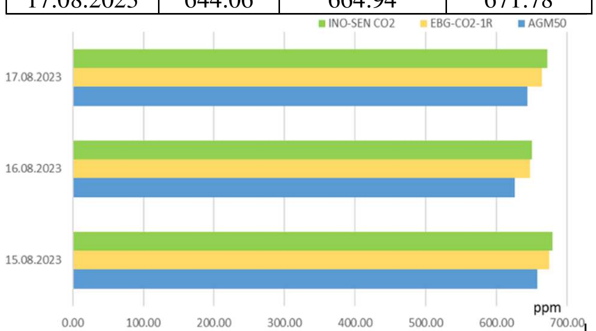

Fig. 6. Daily average values (24h) of CO_2, Office M302

4.3 Statistical Analysis of the Obtained Data

For the analysis of the results obtained from the inter-equipment trials, the methods specified in ISO 13528 were primarily applied. In this study, several statistical tests were used, including the Cochran test, model adequacy verification through the Fisher test (F-test, ANOVA methodology), reproducibility variance, between-sample variance, the SAP test for analytical precision verification, the ABSV test for acceptance of between-sample variation, as well as Z-scores, En-scores, and the Grubb test.

The repeatability of the experiments was assessed using the Cochran test, by estimating the experimental error and the variance of the dependent variable. Additionally, based on the reproducibility variance, the estimation variance of the regression coefficients was calculated, confirming the repeatability of the experiments. According to the Cochran test methodology, the number of repeated experiments is considered sufficient if the following condition is met:

$$G_{calc} < G_{tabel}$$

Cochran's test $$G = \frac{D^2{}_{max}}{\sum D^2{}_i} \quad (2)$$

For the present study, to perform the duplicate trials, 10 identical values measured by the reference analyzer Sensors Europe AGM50—considered the standard—were selected, along with the corresponding values obtained from the Greisinger EBG-CO2-1R and Nattive-Senz INO-SEN CO2 sensors. This resulted in a $G_{crit} = 0.602$.

The adequacy of the model was assessed using the Fisher test (F-test). A polynomial is considered suitable if, according to the ANOVA procedure, the test variables meet the required criteria. In this study, ANOVA was applied due to the experimental design and because it accounts for both statistical errors and the error of the comparison set—something not possible with the t-test. The analytical approach used corresponds fully to a one-way ANOVA.

Thus, for each dataset obtained from the three intercomparison exercises, the following were calculated in MS Excel:

- Analytical variation:

$$s^2{}_{an} = MS_{within} \quad (3)$$

- Between-sample variation:

$$s^2_{an} = \frac{MS_{between} - MS_{within}}{2} \quad (4)$$

$$MS_{between} = \frac{SS_{between}}{J - 1} \quad (5)$$

$$MS_{within} = \frac{SS_{within}}{(N - J)} \quad (6)$$

$$MS_{total} = \frac{SS_{total}}{N - 1} \quad (7)$$

- testul SAP – Sufficient Analytical Precision:

$$\sigma = \chi \cdot CV \quad (8)$$

$$CV = 2^{(1-0.5 \cdot \log C)} \quad (9)$$

$$SAP = \frac{s_{an}}{\sigma} \quad (10)$$

- testul ABSV - Acceptable Between Sample Variance:

$$\sigma^2_{all} = (0.3 \cdot \sigma)^2 \quad (11)$$

4.4 Competence Results from Comparative Measurements in Lab. N113 and Office M302

The results of the statistical analysis of CO_2 concentrations, obtained from comparative measurements between the three analyzers during August 7–10, 2023, in Laboratory N113, are presented in Tables 3 and 4.

Table 3. Selection of 10 reference values from the AGM50 analyzer out of a total of 924 readings, and comparison with values measured by the EBG-CO2-1R and INO-SEN CO_2 sensors. Location: Laboratory N113.

The results of the statistical analysis of CO_2 concentrations, obtained from comparative measurements between the three analyzers during August 15–17, 2023, in Office M302, are presented in Tables 5 and 6.

Table 6. Selection of 10 reference values from the AGM50 analyzer out of a total of 684 readings, and comparison with values measured by the EBG-CO2-1R and INO-SEN CO_2 sensors. Location: Office M302.

Table 3

Selection of 10 reference values from the AGM50 analyzer N113

	CO2 etalon	CO2 [ppm]	CO2 [ppm]
	550	545	557
Sample:	**AGM50 - etalon** CO2 etalon	**EBG-CO2-1R** CO2 [ppm]	**INO-SEN CO2** CO2 [ppm]
1	550	545	557
2	550	555	561
3	550	554	542
4	550	553	557
5	550	548	559
6	550	554	544
7	550	547	556
8	550	554	548
9	550	548	558
10	550	557	551
Media	**550.00**	**551.5**	**553.3**
u [ppm]	**5**	**50**	**50**

Table 4

Statistical Analysis of Data Homogeneity – Exercise in Laboratory N113

Testul Cochran	**Analytical variation**	**Between-sample variation**	**SAP (Sufficient Analytical Precision)**	**ABSV (Acceptable Between Sample Variance)**	Standard deviation EBG-CO2-1R	Standard deviation INO-SEN CO2
C	s_{an}^2	s_{sam}^2	s_{an}/σ	σ^2_{all}	σ^2_{UPT}	σ^2_{LIM}
0.176904	30.3667	258.1167	0.2114	519.84	4.09	6.63
ok, $G<G_{crit}$			ok, $s_{an}<0.5\sigma$	ok, $\sigma^2_{all}<c$		

Table 5

Selection of 10 reference values from the AGM50 analyzer M302

	CO2 etalon	CO2 [ppm]	CO2 [ppm]
	550	545	557
	AGM50 - etalon	**EBG-CO2-1R**	**INO-SEN CO2**
Sample:	CO2 etalon	CO2 [ppm]	CO2 [ppm]
1	690	702	711
2	690	684	692
3	690	695	688
4	690	699	708
5	690	705	698
6	690	695	687
7	690	697	685
8	690	688	697
9	690	698	695
10	690	695	686
Media	**690.00**	**695.8**	**694.7**
u [ppm]	**5**	**50**	**50**

Table 6

Statistical Analysis of Data Homogeneity – Exercise in Office M302

Testul Cochran	**Analytical variation**	**Between-sample variation**	**SAP (Sufficient Analytical Precision)**	**ABSV (Acceptable Between Sample Variance)**	Standard deviation EBG-CO2-1R	Standard deviation INO-SEN CO2
C	san2	ssam2	san/σ	σ2all	σ2UPT	σ2LIM
0.2048364	60.0944	510.8028	0.3324	416.16	6.16	9.07
ok, G<Gcrit			ok, san<0.5σ	ok, σ2all<c		

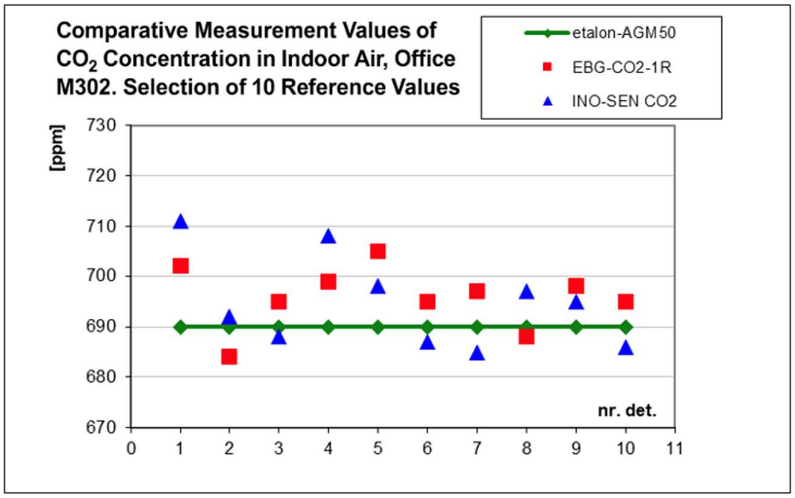

Fig.7 Comparative Measurement Values of CO_2 Concentration in Indoor Air, Office M302. Selection of 10 Reference Values.

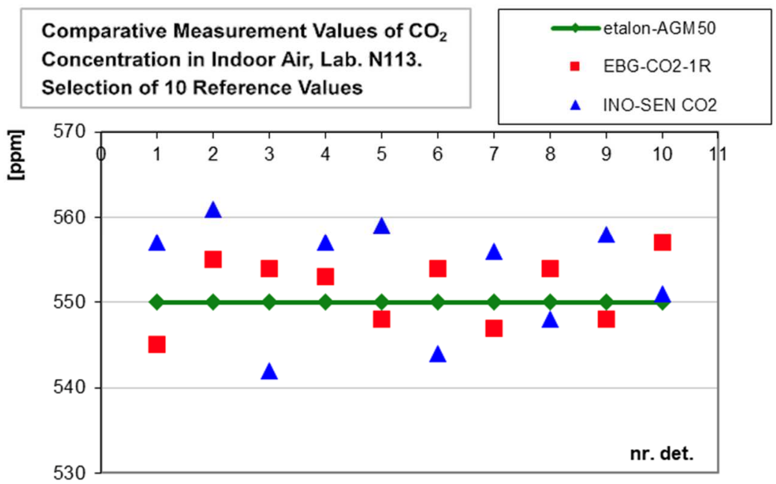

Fig.8 Comparative Measurement Values of CO_2 Concentration in Indoor Air, Lab. N113. Selection of 10 Reference Values.

Figure 8 illustrates the comparison of measured CO_2 concentration values in the indoor air of Laboratory N113, using the three analyzed instruments: Sensors Europe AGM50 (reference), Greisinger EBG-CO2-1R, and Nattive-Senz INO-SEN CO2. The reference analyzer AGM50 shows stable readings, while the other two sensors display slight variations, remaining close to the reference values. These results confirm the overall good performance and reliability of the tested sensors.

Figure 7 presents the comparative results of CO_2 measurements performed in Office M302 using the same set of instruments. The reference analyzer AGM50 was again used as a calibration benchmark. The values recorded by the EBG-CO2-1R and INO-SEN CO2 sensors show good correlation with the reference, with minor deviations attributed to differences in sensitivity and detection principles among the sensors. The results demonstrate consistent performance under real operating conditions.

5. CONCLUSION

This study aimed to perform a comparative evaluation of three CO_2 analyzers — Sensors Europe AGM50, Greisinger EBG-CO2-1R, and the experimental INO-SEN CO_2 developed by Nattive-Senz — under real operating conditions in two different locations within the Politehnica University of Timișoara.

The results indicated a good correlation among the measured values provided by the instruments, confirming the reliability of NDIR-based sensors for monitoring indoor CO_2 concentrations. The reference analyzer, AGM50, served as the benchmark for validating the other two devices, demonstrating superior stability and measurement precision.

The experimental sensor INO-SEN CO_2 exhibited satisfactory performance, with minor deviations compared to commercial analyzers, highlighting its potential for practical applications in indoor air quality monitoring.

The statistical analysis, conducted according to ISO 13528 and employing tests such as Cochran, ANOVA (F-test), Z-score, and En-score, confirmed the homogeneity and repeatability of the obtained data, validating the applied methodology.

In conclusion, the findings support the use of NDIR technology as an effective and accurate solution for CO_2 concentration measurement. Furthermore, the experimental INO-SEN CO_2 sensor can be considered a viable alternative for continuous ambient air monitoring, contributing to improved comfort, health, and energy efficiency in indoor environments.

Based on the comparative study of CO_2 concentrations in indoor environments, conducted in Laboratory N113 and Office M302 at the Faculty of Mechanical Engineering, Politehnica University of Timișoara, using three different instruments –Sensors EuropeAGM50 (reference), Greisinger EBG-CO2-1R, and the experimental INO-SEN CO_2sensor developed by Nattive-Senz – the following conclusions can be drawn:

- Sensor performance: All instruments provided comparable results, and statistical analysis of competence tests and repeatability confirmed the accuracy and reliability of the measurements. The INO-SEN CO_2 sensor, although experimental, proved suitable for monitoring CO_2 concentrations in both indoor and outdoor ambient environments.
- Relevance of CO_2 as an air quality indicator: Monitoring CO_2 concentrations remains a key parameter for evaluating indoor air quality, ventilation, occupant comfort, and for reducing potential health and productivity risks.
- The results support the use of NDIR sensors, including experimental devices, for precise and continuous CO_2 measurements in various environments, providing a solid basis for implementing air quality monitoring systems and optimizing ventilation strategies.

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Studiu experimental privind detectarea co_2 în medii interioare

Monitorizarea calității aerului din interior, esențială pentru menținerea unor medii sănătoase și pentru stabilirea unor măsuri corective adecvate, poate fi efectuată utilizând senzori dedicați sau teste de laborator pentru a detecta poluanți precum CO_2. Această lucrare prezintă rezultate experimentale privind concentrația de CO_2 în diverse medii interioare. Măsurătorile de mediu susțin eforturile de poziționare pe piața europeană a senzorilor de CO_2 de înaltă performanță și de aliniere la tendințele actuale în dezvoltarea senzorilor. Performanța senzorilor și consecvența între dispozitive au fost evaluate utilizând trei dispozitive: Sensors Europe GmbH – AGM50, Greisinger EBG-CO2-1R și dispozitivul experimental Nattive-Senz INO-SEN CO2.

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