SELECTION OF A SUITABLE CO_2 SENSOR FOR INDOOR AIR QUALITY ASSESSMENT

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Abstract

This article compares eight types of CO_2 sensors using NDIR technology for accuracy, response time, and acquisition costs. The experiment included static and dynamic tests in a chamber and a duct. The Testo 935 and Rotronic CL11/CP11 sensors showed high accuracy and fast response, while the Winsen MH-Z16 offered the best performance-to-cost ratio. Other tested sensors – NetAtmo, Comet S3532, LaskaKit SCD41 and MH-Z14 exhibited inaccuracies, making them unsuitable for scientific applications.

Keywords

CO_2 measurement, CO_2 sensors, pollutant measurement, experimental sensor comparison, accuracy, response time

INTRODUCTION

The measurement of CO_2 concentration has a wide range of applications in technical practice. In building services engineering, it is used in systems for controlling the performance of air handling units or as one of the indicators of indoor air quality (cleanliness). The use of sensors with the highest possible measurement accuracy is essential for air handling systems. Significant deviations can lead to a decline in indoor air quality or improper control of air handling units resulting in increased energy demand [1].

One of the parameters that can be determined using tracer gas concentration measurements is the local mean age of air (LMA). This parameter represents the mean time an air particle spends in a given space [2]. It is considered that stale air poses a greater risk to human health, as it accumulates harmful substances over time. Determining the age of air requires experimental measurements of the temporal changes in the tracer gas concentration at a specific point [2], [3], [4]. It is essential for the properties of the tracer gas to closely match the properties of air, including molar mass, which reduces the risk of errors caused by gas separation to minimize measurement errors. The most commonly used tracer gases are carbon dioxide (CO_2), sulfur hexafluoride (SF_6), methane (CH_4), and nitrous oxide (N_2O) [3], [5], [6]. The age of air can be calculated from changes in tracer gas concentration using an integral. For the decay (washout) method, the relationship is given by the equations (1) [2], [3]:

$$\mathrm{LMA} = \int_0^\infty \frac{C_p(t)}{C_p(0)}\, dt \tag{1}$$

Where *LMA* is mean age of air at a specific point, $C_p(t)$ is the concentration at time t and $C_p(0)$ is the initial concentration at time $t = 0$ seconds. The age of air is also one of the input parameters for evaluating ventilation efficiency, as shown in equation (2):

$$\varepsilon_{CH} = \frac{\tau_{nom}}{LMA} \tag{2}$$

Where τ_{nom} is the nominal air exchange time (s), whose inverse is defined as the air exchange rate (m^3s^{-1}), and *LMA* is the local mean age of air *(s)* [2], [7]. Ventilation efficiency indicates whether the air in the room is properly exchanged, providing optimal indoor air quality. The system is considered efficient if the ventilation efficiency $\varepsilon_{CH} \geq 1$.

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The accuracy of determining air age and ventilation efficiency directly depends on the precision of sensors and the measurement frequency. Using inaccurate sensors can lead to erroneous results which negatively affect energy consumption [1].

METHODOLOGY

It includes a description of the sensors, their wiring, and the definition of measurement experiments.

Tested sensors

Eight different types of sensors were tested: Comet S3542, Testo 935 Air quality probe, Rotronic CL11, Rotronic CP11, Winsen MH-Z14, Winsen MH-Z16, Laskakit SCD41, and NetAtmo Weather Station Indoor module.

All devices used operate on the principle of infrared spectroscopy (NDIR). This method measures CO_2 concentration by passing infrared light through a sample chamber containing air with CO_2, where the gas absorbs light at specific wavelengths, and the decrease in intensity of light reaching the detector is compared with a reference value, allowing the calculation of CO_2 concentration in the sample [8], [9]. The NDIR sensor diagram is shown in Fig. 1.

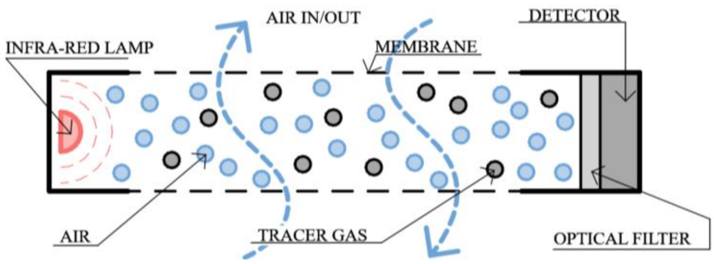

Fig. 1 NDIR sensor composition [9].

The testing involved measuring sensitivity and response time in two types of experiments described below. Prior to conducting the experiment, the Testo 935, Rotronic CL11, and CP11 sensors were calibrated according to the manufacturer's instructions in an outdoor environment to provide more accurate concentration readings. The sensor calibration value is automatically set to 400 ppm (particles per million), although the average concentration in 2024 was 422 ppm [10]. The CL11 sensor was disassembled, extended via a detachable cable with Dupont connectors as shown in Fig. 2, and used during the measurements.

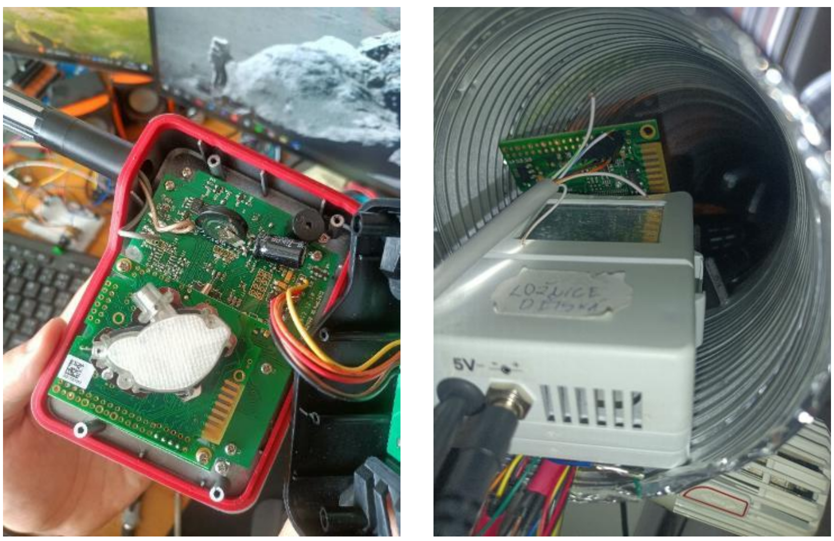

Fig. 2 Left: CL11 disassembly. Right: placement in the duct.

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Standalone sensors without manufacturer certification, automatic calibration, and service support, in a lower price range, were used in the measurement setup. Specifically, the Winsen MH-Z14, MH-Z16, and LaskaKit SCD41 sensors. These sensors were integrated into the measurement system through custom programming of an Arduino Mega microcontroller. The Winsen sensors communicated using a PWM signal, with the Arduino's PWM pin frequency limited to 500 Hz, while the LaskaKit sensor communicated via the I2C bus. The measured concentration using PWM (C_{ppm}) can be calculated from the ratio of the time of high output signal (T_H) to the time of the low output signal (T_L), as shown in equation (3) [11]. The measurement results can be obtained every second based on equation (3).

$$C_{ppm} = 5000 \cdot \frac{T_H - 2\,ms}{T_H + T_L - 4\,ms} \tag{3}$$

Tab. 1 summarizes the information about the sensors used – the CO_2 measurement range, the manufacturer-specified deviation in ppm, the percentage deviation from the currently measured value, the minimum adjustable reading time, and the approximate price in December 2024.

Tab. 1 Sensor specifications.

Sensor marking		CO_2 range	Deviation const. [ppm]	Deviation perc. (%)	Response time	Approx. cost (€)
Rotronic	CL11	400-10,000	30	5	1	596
	CP11	400-5,000	30	5	1	597
Winsen	MHZ-16	0-5,000	50	5	1	60
	MHZ-14	0-5,000	100	6	1	38
LaskaKit	SCD41	400-5,000	40	5	60	40
NetAtmo	Indoor module	0-5,000	50	5	300	79
Comet	S3532	0-5,000	50	3	10	219
Testo	935	0-5,000	50	3	1	622
		5,000-10,000	100	5		

Experiment preparation

12g CO_2 cartridges were used for the measurements to fill a sealed acrylic test chamber with a volume of 0.42 m^3 (dimensions 0.58 m × 0.59 m × 1.24 m). In addition, the laboratory windows were opened to minimize the potential increase in CO_2 concentration in the room caused by the presence of a person, gas leakage from the cartridge during filling, or imperfections in the sealing of the measurement chamber. CO_2 concentration was at the same time measured in the opposite corners of the laboratory and at the fan intake using Rotronic CL11 sensors to verify that no contaminated air was being drawn in from the laboratory or during the opening of the measurement loop. This sensor is also capable of measuring relative humidity and temperature. The fan in the measurement loop operated at full capacity, providing air exchange in the chamber approximately 150 times per hour.

During the measurement at the outlet pipe, the NetAtmo sensors were left inside the test chamber due to their size. The other sensors were placed in the pipe in the horizontal plane, filling approximately one-third of its height – they were placed in series to allow air to flow freely around them.

At the same time, several assumptions were made:

- A high air exchange rate provides rapid diffusion, i.e., the increase, mixing, and subsequent decrease in CO_2 concentration, and eliminates the influence of natural flow caused by potential temperature differences between surrounding surfaces in the test chamber.
- The mixing time of the air with the tracer gas is sufficiently long to provide complete mixing.
- The gas distribution across the pipe cross-section is uniform during the dynamic test, with no separation or accumulation in the sensor areas.

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Testing inside the chamber

CO_2 was mixed in the test chamber in a closed-loop circuit using a fan on the intake branch, while the exhaust branch was connected back to the fan intake. The air was mixed for 10 minutes to provide uniform distribution of CO_2 and stabilization of the concentration throughout the chamber. This time also allowed the sensors to stabilize their response to steady conditions. Subsequently, the exhaust branch was opened and led outside the laboratory. During the measurement, the sensors were placed close to each other in the interior of the chamber. The fan was operated continuously without interruption. A schematic diagram is shown in Fig. 3.

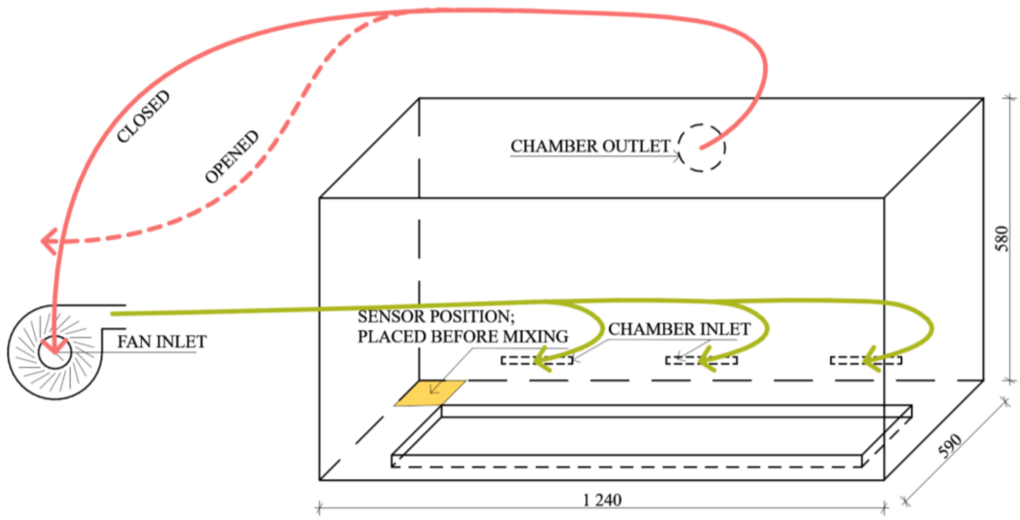

Fig. 3 Measurement scheme with sensors in the experimental chamber.

Testing inside the outlet pipe

Similar to the previous experiment, CO_2 was mixed in a closed measurement circuit, but without the presence of the sensors inside the chamber, as shown in Fig. 4. After the gas concentration stabilized, the fan was turned off, the sensors were placed into the outlet pipe branch, and the fan was turned on again. The objective was to measure the response time and sensitivity of the sensors to concentration changes from the initial to the high concentration and back to the initial/final concentration. The initial (and thus final) concentration refers to the CO_2 concentration in the laboratory which is the same or very close to the value outside.

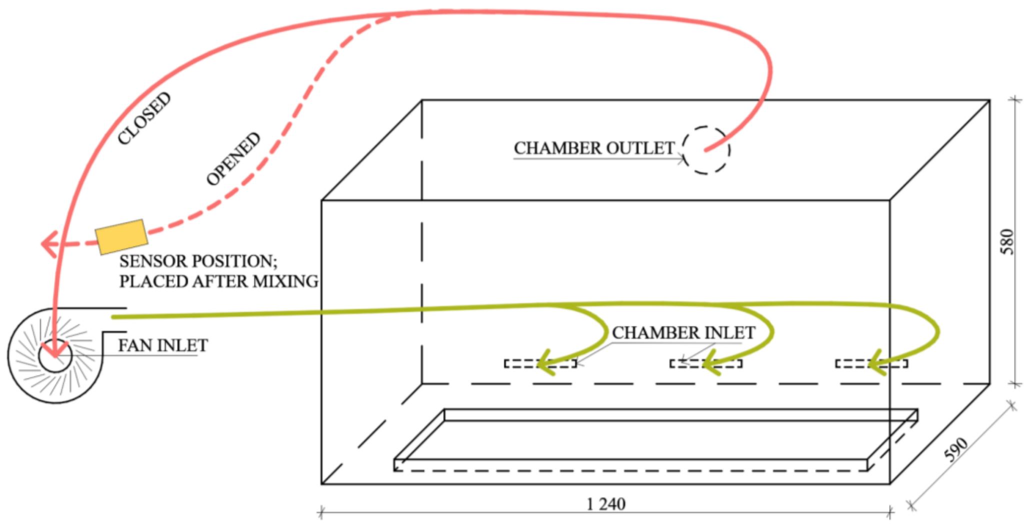

Fig. 4 Measurement scheme with sensors in the outlet pipe.

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Sensor comparison

The sensors with the apparent best results were compared with each other and evaluated using statistical tools such as the arithmetic mean in equation (4):

$$\bar{y} = \frac{1}{n}\sum_{i=1}^{n} y_i \tag{4}$$

Where $\bar{y}$ is arithmetic mean, n is the number of samples and y_i are the individual samples.

The median for an even number of values was calculated using equation (5):

$$\tilde{y} = \frac{y_{\left(\frac{n}{2}\right)} + y_{\left(\frac{n}{2}+1\right)}}{2} \tag{5}$$

Where $\tilde{y}$ is the median, n the number of samples, and y are the individual samples.

The root mean square error (RMSE) was calculated according to equation (6):

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n} (\hat{y}_i - y_i)^2} \tag{6}$$

Where n is the number of samples, $\hat{y}_1$ are the values of one sensor, and y_i are the values of the other sensors.

RESULTS

Results include static measurement in a closed chamber, a dynamic pipe test of the affordable sensors, and a dynamic pipe test of all the sensors.

Testing inside the chamber

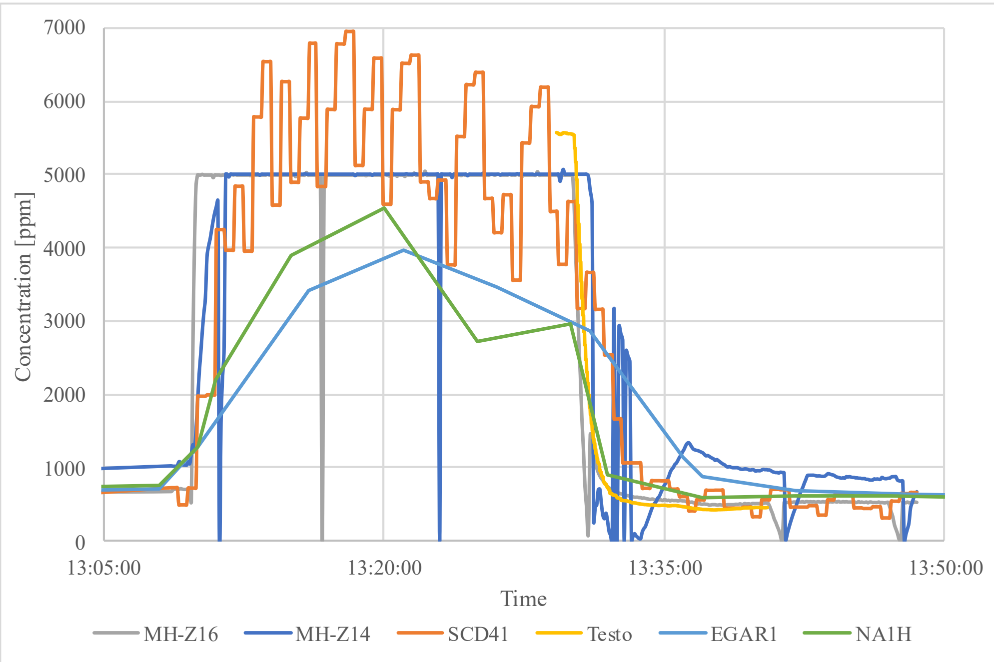

Fig. 5 Testing of sensors in a sealed chamber.

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Fig. 5 shows a comparison of the response of selected sensors resulting from one of the comparative measurements. The Winsen MH-Z16 and Testo 935 sensors exhibited relatively close agreement, while the MH-Z14 sensor had a slower response to a rapid decrease in the tracer gas. The LaskaKit SCD41 sensor showed significant fluctuations over time, with each measurement step taking several seconds. The NetAtmo sensors labeled EGAR1 and NA1H had slower responses to the increase in concentration, with the upper limit not being reached even after 20 minutes of gas exposure.

Dynamic testing of low-cost sensors in the duct

The three low-cost sensors – Winsen MH-Z16, Winsen MH-Z14, LaskaKit SCD41 – were compared in a more dynamic test with the reference sensor Testo, as shown in Fig. 6. It provided seemingly accurate and fast responses in the previous experiment. The MH-Z16 sensor closely follows the curve of the Testo 935 sensor. The MH-Z14 does not reach the maximum value; its curve approaches the final concentration in a manner similar to that of the Testo 935 and Winsen MH-Z16, but the measured concentration was overall higher by more than 500 ppm compared to the Testo 935. The SCD41 had a step-like pattern with results fluctuating between the MH-Z16 and MH-Z14 curves. It almost does not capture the sharp increase in concentration at the start of the measurement. The results fluctuated around the final concentration threshold.

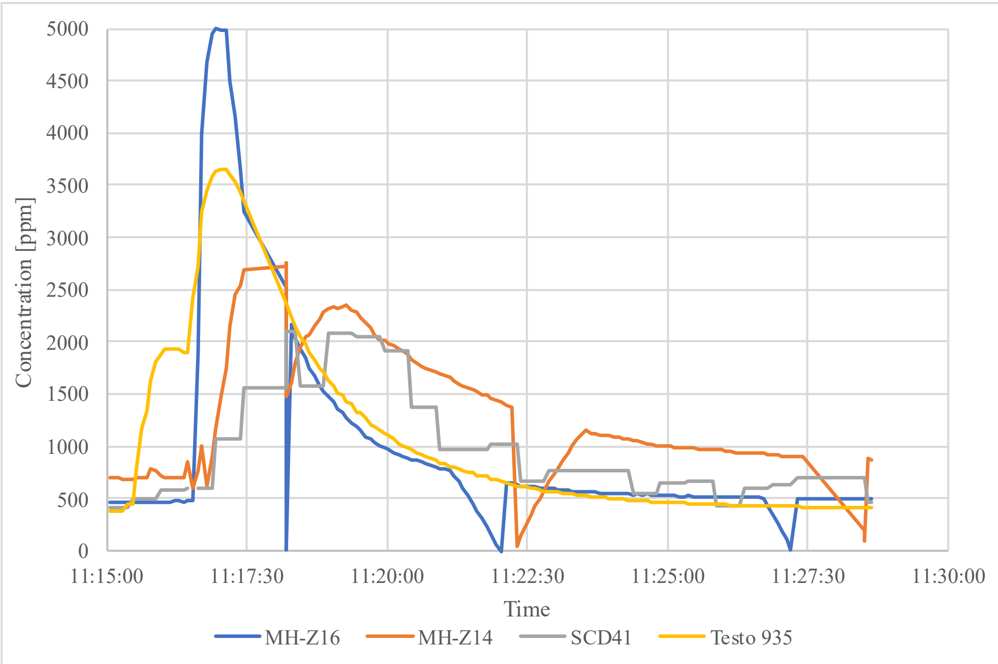

Fig. 6 Dynamic test of low-cost sensors in the pipe.

Dynamic test of all the sensors in the pipe

The comparison of the sensors in the dynamic test is shown in Fig. 7. A total of 5 Winsen MH-Z16 sensors were tested. They were purchased based on the results of the measurements mentioned in the previous sections. The entire setup was tested to compare the deviations between individual units. It was not possible to directly exhaust the outlet pipe to the exterior (the sensors placed inside the pipe) in this test. The agreement between the Testo 935 sensor and the Rotronic_CL11_outlet sensor (sensor on an extension cable inside the pipe) was very good, even at high concentrations. The Winsen sensors start to show excellent agreement in terms of shape with the curves from the upper limit of 5000 ppm which is the maximum for this sensor.

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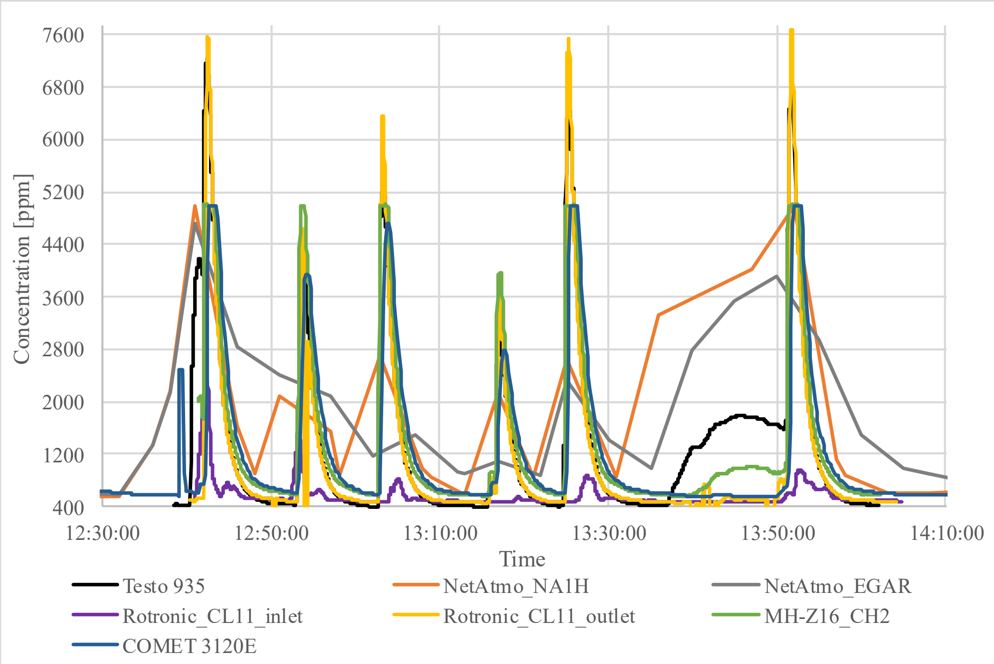

Fig. 7 Dynamic test of all the sensors.

The Comet sensor measured with a greater time delay and inaccuracy than the Testo and Rotronic sensors by approximately +150-250 ppm and the Winsen by approximately +50-100 ppm at the lower limit. The deviations rose to 1,000 ppm at the upper limit. The results show that the initial/final concentration is not the same for all sensors. The Winsen sensor measured an average of 566 ppm, Rotronic 484 ppm, Testo 424 ppm, and Comet 611 ppm after ventilating the test chamber following the last dynamic test. The measurement, shown in Fig. 7, with visible deviations in the curves, is specified in Fig. 8.

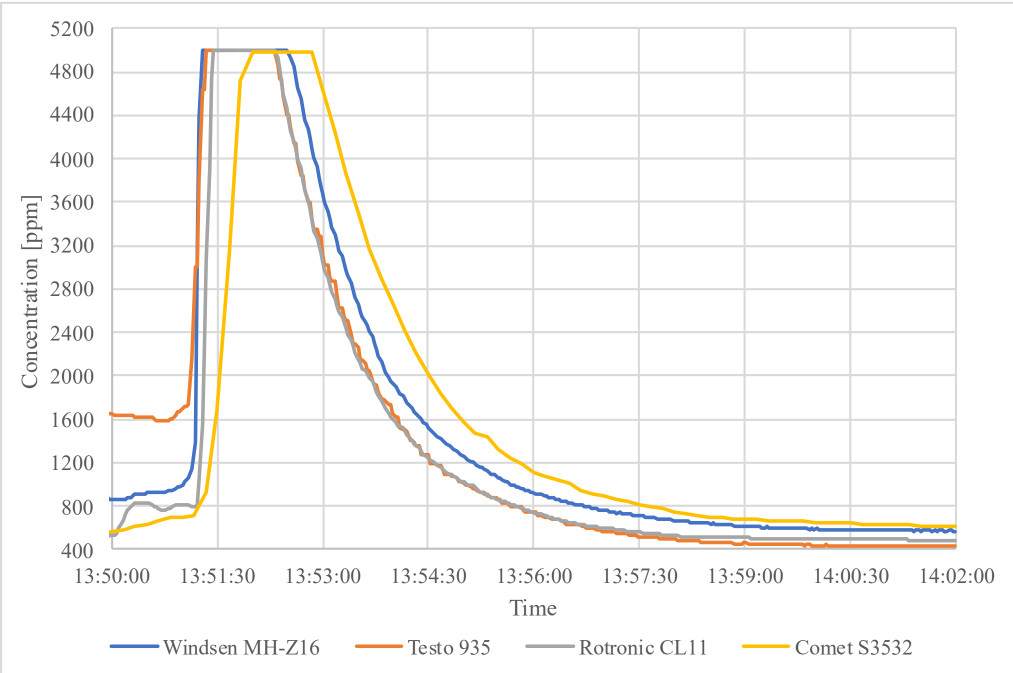

Fig. 8 Detail of the results of selected sensors from a single measurement.

The Winsen sensors were compared in six measurements, as shown in Fig. 7. In five out of the six measurements, they reached the highest possible measured concentration of 5,000 ppm. The average deviation between all Winsen

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sensors across all measurements was 67 ppm, with the median deviation being 21 ppm. This means that the average measurement error was 4.63%, and the median error was 2.5%.

The measured values of all Winsen sensors were averaged and compared with a single Rotronic CP11 sensor and the Testo 935. The evaluation is shown in Tab. 2.

Tab. 2 Summary of measurement results.

Sensor combination	Avg. dev.	Median dev.	RMSE	Avg. perc. error	Median perc. error
Winsen-Testo	*231*	*164*	*384*	*24%*	*23%*
Winsen-Rotronic	*212*	*128*	*328*	*18%*	*18%*
Testo-Rotronic	*263*	*58*	*451*	*16%*	*5%*
Winsen-Comet	*377*	*233*	*620*	*22%*	*20%*
Testo-Comet	*626*	*385*	*768*	*38%*	*34%*
Rotronic-Comet	*623*	*193*	*639*	*27%*	*26%*

By adding the median deviation to the Winsen-Testo and Winsen-Rotronic sensors to the lower values and reevaluating, the median deviation for Winsen-Testo becomes 41 ppm and 3%, and for Winsen-Rotronic 61 ppm and 6%. Comet was not evaluated because the deviation of the curves was inconsistent.

DISCUSSION

The increase in inaccuracies in NDIR sensors can be caused by varying temperature, humidity or aging [9], [12], [13]. The new sensors in the conducted experiment were Winsen MH-Z14, MH-Z16, and LaskaKit SCD41.

Rotronic

The Rotronic_inlet sensor detected a short-term increase in the concentration of the tracer gas at the beginning of each measurement cycle in the pipe in all 6 cases, reaching 1,000 ppm in 5 out of 6 cases. This was caused by handling the pipe – removing it from the fan, shifting it to a horizontal position, and installing sensors inside, which causes a small amount of CO_2 to be disturbed and "leak" onto the floor. Once the fan is turned on, the air reaches sufficient speed and is drawn out of the laboratory. This amount of tracer gas near the inlet only slightly extended the settling time of all sensors and did not have a significant impact on any particular sensor.

The Rotronic_CL11_outlet sensor occasionally lost signal, likely due to the extended cable and the sensitivity of the Dupont pins to mechanical vibrations in the outlet pipe caused by the rapidly flowing fluid.

The Rotronic sensors recommend a maximum recording rate of once every 30 seconds, but they can handle recordings every second

The Rotronic CP11 is not shown in Fig. 7. Its results were similar to those of the CL11, which would have cluttered the graph. It is the same device, just in a different casing. For the same reason, four other Winsen MH-Z16 sensors are missing.

Testo

The Testo sensor allowed for a 1-second recording interval, but it wrote the same value three times in a row – meaning it measures a maximum of once every 3 seconds.

The rise in the Testo data at the beginning of the measurement, shown in Fig. 6 between 11:14:30 and 11:16:30, was caused by inserting this sensor deeper into the pipe first. The rest was inserted as a fixed assembly afterward. Higher CO_2 concentrations were already present in the pipe.

When analysing the results, it can be seen that the Rotronic and Testo sensors calibrated outdoors often fell below the calibration limit of 400 ppm (measured even below the 380-ppm limit) after a rapid drop from a high concentration. However, it cannot be assumed that concentrations below 400 ppm can be achieved in urban environments, as the world average as of 2024 is 422 ppm [10].

Winsen

Connecting several sensors via PWM to a single Arduino board proved to be occasionally erroneous. In the chart shown in Fig. 5 a drop and subsequent increase (or vice versa) in the measured values of MH-Z14 and MH-Z16 can be observed, likely caused by a not quite suitable programming of the microcontroller, leading to data processing collisions in the processor. The more sensors connected to the board, the more frequent the signal dropouts (almost always in pairs). A separate programmed board was used for each sensor in the measurement shown in Fig. 7.

In addition to PWM, the MH-Z14 also supported UART connection. The measurement inaccuracy could be caused by an inappropriate communication type or signal conversion. Inaccurate results may also stem from mechanical damage or manufacturing defects. Only one unit was available.

CONCLUSION

Out of the 8 tested sensors, some proved to be completely unsuitable due to accuracy or response time. The purchase price also played a role in the selection. The evaluation is shown in Tab. 3. Acceptable values are marked with ✓, insufficient values with ×, affordability with ↓ and more expensive sensors with ↑.

Tab. 3 Sensor evaluation.

Sensor		CO_2 range	Accuracy + deviation, in ppm + %	Response time, in s	Purchase price
Rotronic	CL11	✓	✓	✓	↑
	CP11	✓	✓	✓	↑
Winsen	MHZ-16	✓	✓	✓	↓
	MHZ-14	✓	×	✓	↓
LaskaKit	SCD41	✓	×	×	↓
NetAtmo	Indoor module	✓	×	×	↓
Comet	S3532	✓	×	×	↑
Testo	935	✓	✓	✓	↑

All tested Winsen sensors showed comparable results, with a median deviation of 21 ppm and an error of 2.5%. The median error compared to Rotronic sensors was 128 ppm (RMSE 328 ppm) and compared to Testo sensors, it was 164 ppm (RMSE 384 ppm). Deviations were relatively consistent in these measurements. In contrast, the median error between Rotronic and Testo sensors was 58 ppm, but occasional significant deviations increase the RMSE to 451 ppm. The Comet sensor showed a median deviation in the range of 193–385 ppm depending on the compared sensor, and the shape of the concentration decay curve differed significantly from the Winsen, Testo, and Rotronic sensors. Errors range from 50–1,000 ppm depending on the concentration and the sensor were compared.

The Testo 935 and Rotronic CL11/CP11 sensors achieved high accuracy and fast response times, making them suitable for valid measurements. The Winsen MH-Z16 sensors offered a balanced ratio of accuracy, response speed, and cost, making them suitable for more extensive dynamic measurements. However, a disadvantage remains in the need for microcontrollers and their programming. Other tested sensors, such as the NetAtmo Indoor module, Comet S3532, Winsen MH-Z14, and LaskaKit SCD41, can be used in non-scientific applications, such as home monitoring, where accuracy and fast response are not critical.

All tested sensors use infrared spectroscopy (NDIR) technology, which is susceptible to inaccuracies due to temperature changes, high humidity, or sensor aging [9], [12], [13]. These factors may contribute to deviations. It would be beneficial to include additional measurement methods in future tests (e.g., electrochemical, photoacoustic sensors) for more accurate assessment or expand the sample of NDIR sensors by incorporating more types and manufacturers.

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The use of this method also limits the ability to verify the accuracy of sensors as declared by the manufacturers, as the actual CO_2 concentration cannot be precisely determined. In order to obtain at least an approximate assessment of sensor deviations from the manufacturer's specified accuracy, the medians of all measured values were used as the reference curve to compare individual sensors. The result is the following percentage match within the accuracy measurement range for the sensors: Winsen: 44%, Rotronic: 44%, Testo: 15%, and Comet: 25%. The resulting percentage match values were: Winsen: 88%, Rotronic: 50%, Testo: 38%, and Comet: 44% by including the median correction mentioned in the results section to the reference values of the Winsen-Rotronic and Winsen-Testo curves. It would be necessary to expand the tested sample and standardize the number of sensor types to achieve higher reliability for this method.

Future research will focus on the use of the Winsen MH-Z16, Testo 935 and Rotronic CL11/CP11 sensors to measure the decrease in CO_2 concentration at multiple points in the experimental chamber. This data will be used to calculate air age and evaluate ventilation efficiency. The findings will also contribute to the validation of computational fluid dynamics (CFD) simulations focusing on forced gas diffusion, which can be used to optimize the design of air handling systems and thus maintain the existing indoor environmental quality at lower economic and environmental cost.

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