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An integrated device for rapid analysis of indoor air quality in farms: the cases of milking parlors and greenhouses for leafy vegetables cultivation

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Abstract

The agricultural sector is responsible for polluting emissions originating from various sources, that impact on the environment and on human health. The negative effect of the emissions can have a greater effect if they originate in confined areas which can therefore bring gas concentrations to critical levels of tolerability for hosts (both workers and animals). In this regard, the contexts that can present major problems are attributable to the livestock activities and protected crop cultivations, in which agricultural machinery is used. To mitigate the emissions of polluting gases and improve indoor air quality, it is important to carry out effective monitoring procedures that can lead to the implementation of targeted corrective measures. For this purpose, it is necessary to use devices able to continuously detect the air gases concentrations in real-time. At the same time, the devices should be cheap, user-friendly and reliable. This study reports the application of a prototype device (integrated device for air quality measure – Indaqum) based on low-cost sensors to evaluate the performance of two different agricultural contexts and for which more insights are needed, the milking parlors and greenhouses for baby leaves vegetables cultivation. The statistical analysis shows the reliability of measures performed with Indaqum, compared to the reference measuring systems adopted (Drager tubes) resulting to properly measure NH_3, CO_2 and NO_2 air concentrations. In both the case studies examined, a good ventilation resulted essential to keep low gas concentrations in the air. Consequently, the cold periods of the year can be considered as the more critical.

Keywords

gas emissions, gas sensors, livestock activities, protected crop cultivations, baby leaf

1. Introduction

Monitoring the presence and concentration of air pollutants as well as the control of their emission sources is becoming increasingly important in several areas, among which the civil-social environments, industrial manufactories, transports and agriculture (EEA 2019a).

The analysis of air quality of a specific environment allows the identification and quantification of harmful compounds and the presence of human health-threating environmental conditions that primarily affect the workers' health. In particular, in the agricultural sector, the most important pollutants are ammonia (NH_3) and hydrogen sulfide (H_2S), followed by methane (CH_4) and carbon dioxide (CO_2), even if these lasts are judged as less relevant for health (Schenker et al., 1998). Furthermore, particulate matter (PM) and nitrogen oxides (NO_x) must be evaluated, as they play an important role for respiratory and cardiovascular diseases (Koolen and Rothenberg, 2019; Schenker et al., 1998). In addition, the greenhouse gases (GHG), NH_3, and sulfur oxides (SO_x) are harmful for the environment due to their role in climate change and soil acidification potentials (EEA 2019b, IPCC 2019).

Although several options are available to mitigate the emissions of polluting gases, substantial efforts are still necessary to reduce the atmospheric concentration of these gases and to maintain safe levels for people and the environment. Likewise, improvements in the monitoring technology are fundamental to reach the required knowledge and accuracy in the quantification of emissions in various environments (Insausti et al., 2020). This is required also for the agricultural sector, where livestock activities (Hou et al., 2015; Sajeev et al., 2018) and agricultural machineries (Lindgren et al., 2010) are counted among the main responsible for a significant share of the atmospheric emissions of harmful pollutants. Livestock is widely recognized as primary source of NH_3; in Europe, for example, 94% of NH_3 anthropogenic emissions (EEA, 2017) arises from this sector and about 75% derives from livestock manure management (Webb et al., 2005). Moreover, 14.5% of all anthropogenic GHG emissions (Gerber et al., 2013) derive from livestock supply chains.

Although emissions and air quality related to livestock contexts is thoroughly studied (EC, 2017) in some of them there is still a lack of data. For example, for milking parlors for dairy cattle, which host for many hours in addition to the animals also the operators and that in the few studies present have highlighted potential criticalities in air quality (Purdy et al., 2009). As regard the agricultural machineries, the emissions derived from engines exhaust gases emissions, are regulated accordingly with European directives (97/68/EC, 2010/22/EU, 2010/26/EU), that set emission restrictions (Lindgren et al., 2010). Agricultural machineries are mainly equipped with diesel engines and in the Italian agricultural sector, farms are commonly characterized by a broad range of machinery fleet compositions, including underused and outdated machinery (Bacenetti et al., 2018). The effect of exhaust gases could be worse if the tractors are used in a confined area, for example in a greenhouse, which in Italy is a very common condition for the cultivation of baby leaves. In Italy the fresh-cut market (mainly baby leaves) represents a large portion of the entire economic value of the fruit and vegetable market (Fusi et al., 2016). Baby leaves are cultivated in different geographical areas managed as protected crops with the soil covered by plastic tunnels. In this context, the level of mechanization is significantly high and the space for maneuvering can be small, thus requiring tractors to move in small in dimensions. Except for soil preparation operations, the engine powers are commonly quite low and the legislation on emissions’ regulation has been stricter for high-power ones (category 130-560 kW) (Directive 97/68/EC and five amending Directives adopted from

2002 to 2012) than for the low-power engines (18-37 kW) commonly present in greenhouses. In literature, several studies have focused on combustion emissions in open field conditions (Janulevičius et al., 2013; Lindgren, 2004; Lovarelli et al., 2018) while more insights are needed regarding exhaust gases emissions and air quality in greenhouses/confined or semi-confined environments.

The adoption of proper measurement methods and tools must be evaluated to allow the evaluation of emissions and of air quality continuously during the operating time. Sophisticated equipment are available mainly for scientific investigations, e.g. infrared photoacoustic systems to detect GHG in swine husbandry (Costa and Guarino, 2009) or ammonia in poultry house (Li et al., 2015), or Fourier-transform infrared (FTIR) spectrometers to measure ammonia in dairy barns (Janke et al., 2020).

These instruments are complex, and their use require qualified staff, but also expensive, making their use limited in time and space, despite the accuracy of measurements. At the opposite, the simplified equipment could be used but they are used mainly for occasional and punctual technical monitoring. Both types of instruments are not designed to carry out real-time, continuous, cheap and user-friendly measurements, providing a substantial contribution to the promptness of decision-making by allowing the rapid implementation of corrective actions.

The objective of this work is to monitor air quality in different agricultural contexts, using a specifically developed multiparameter prototype device (named Indaqum). With this device, it is possible to obtain a continuous, cheap and easy-to-interpret monitoring that provides the necessary information to actively control the working environments, with benefits operators, animals and the environment. The monitored contexts are milking parlors and greenhouses to produce baby leaf vegetables and they were firstly chosen in order to fill an important gap in literature data. Secondly, they were chosen to evaluate the robustness of the developed system and the interchangeability of its use.

2. Materials and Methods

Tests were performed in milking parlors of two dairy farms in Lombardy (Italy), farm A (Pavia province) and farm B (Lodi province) and in greenhouses for leafy vegetables cultivation in two farms in Lombardy, farm C (Brescia Province) and farm D (Bergamo province).

2.1 Experimental conditions

2.1.1 Milking parlors

Farm A with 92 milking cows had a double-7 herringbone milking parlor in a building with EW orientation. The milking parlor had a volume of 223 m^3 (3.8 m high, 10.7 m long and 5.5 m wide), and was equipped with a fan (diameter 1m) to extract the air from inside. The windows had a total area of 18 m^2, kept semi open. The floor was made of rubber, while a slatted floor was present in the milker pit. It was equipped with a holding area of 388 m^3 (4 m high, 10 m long and 9.7 m wide). The cows entered in the holding area were divided into 3 groups (42, 38, and 12 heads, respectively) and the maximum animal loading reachable was 0.18 animal/m^3.

Farm B with 140 milking cows had a double-10 herringbone milking parlor in a building with EW orientation. The milking parlor had a volume of 236 m^3 (2.4 m high, 18.2 m long and 5.4 m wide), and had no forced ventilation systems. The windows had a total area of 25 m^2 and were kept semi open. The floor was concrete, while a tiled floor was present in the milker pit. It was equipped with a holding area of 540 m^3 (5.5 m high, 18.2 m long and 5.4 m wide). The cows entered in the holding area were divided into 2 groups of equal number and the maximum animal loading reachable was 0.30 animal/m^3.

2.1.2 Greenhouses

The type of greenhouses considered were single span with a structure composed by half-arches made of galvanized steel tubes and covered with plastic film, with the front sides open. Every greenhouse used for the tests had a width of 8 m and height of 3.4 m, while the length was variable between 72 m and 96 m. Each greenhouse was divided in four humps of 1.8 m of width. In each farm the 3 main cultivation steps were monitored: soil tillage, sowing and harvesting. The machinery used in Farm C were: Harvest, ORTOMEC (STAGE II, year 2006); Sowing, SAME Frutteto 70 (STAGE n.a. year 1988) + homemade seeder; Soil tillage, SAME Silver 130 (STAGE I, year 2000) + spading machine Gramegna 2.7m. In Farm D were used: Harvest, Hortech (STAGE II, year 2006); Sowing, LANDINI Mistral 50 (STAGE II, year 2007) + seeder DEMASEMINATRICI 1.8 m; Soil tillage, DEUTZ FAHR Agrolux 70 (STAGE II, year 2008) + milling bed former COMEB 1.8 m. All the crops cultivated during the tests were baby leaf and in detail: rocket (*Diplotaxis tenuifolia*), lettuce (*Lactuca sativa* L. var acephala), spinach (*Spinacia oleracea*) and romaine lettuce (*Lactuca sativa* L. var. longifolia).

2.2 Environmental parameters

Weather conditions were also monitored in both systems. For internal ambient conditions, asensor with integrated data logger was used to measure and record the air temperature and relative humidity (HOBO U12 Temp/RH/Light/External DataLogger, Onset Computer Corporation, Pocasset, MA). For external weather conditions, data registered by nearby meteorological sites of a regional network were used (ARPAL, 2020).

2.3 Integrated device for air quality measure - Indaqum

The prototype of the integrated device air quality measures (Indaqum) has been designed to be easily integrated with different sensors both for the type of gas to be detected and for the transmission protocol. This configuration allows it to be used in contexts characterized by very different emission sources. The electrochemical sensors are installed on a multisensor board (Tecnosens srl) which could host up to six calibrated sensors. Other sensors can be connected singularly.

Powered up by either a battery or an external memory, Indaqum features a Silicon Labs EFR32MG13 micro-controller, running at 40MHz and supporting Bluetooth Low-Energy (BLE) connectivity.

Sensor data are collected from each sensor using the appropriate transmission protocol (UART or I2C, depending on the sensor), with a period configurable by the user. The multi-sensor board can mount up to six air quality sensors; indeed, the mounted sensors are automatically detected at system startup. All sensors are already calibrated, which makes measurements as accurate and reliable as those of any commercial solution. The installed sensors were: (i) electrochemical: GS+4NH3-100 for NH_3, range 0-100 ppm; GS+4NO2 for NO_2, range 0-30 ppm; GS+4NO for NO, range 0-250 ppm; GS-4CO CO, range 0-2000 ppm (DD scientific); (ii) NDIR sensors SENSIRION SCD30 for CO_2, range 400-10000 ppm.

An 8MB flash memory attached to the micro-controller via SPI is used to persistently store data. Each air quality record, consisting of one sensor reading for each available sensor at a given time, occupies 128 Bytes: this means that the flash memory can accommodate more than 65000 records (e.g., 18 hours with 1Hz sampling frequency). The battery slot is compatible with any USB power-bank, which allows Indaqum to operate for long time-frames (commercial power banks can reach 20000mA) or, in case of very long measurement sessions, to benefit from quick battery swaps or powered by electricity. The device can be controlled via the BLE interface, which is supported by all modern smartphones, computers and tablets. For efficiency and security's sake, we opted for a proprietary communication format (i.e., communication can happen only by using a proprietary application). The device comes with an Android application which allows users to set the sampling frequency; start and stop the sampling; erase the flash memory; and download the data in TXT, CSV and JSON format. Then, data can be shared by any mean supported by the smartphone (e.g., Google Drive, WhatsApp, e-mail, etc.).

2.4 Reference measurements

The Indaqum measurements were assessed by comparing them with those obtained with the reference measurements of the Dräger Short-term Tubes, coupled with Dräger-Tube pump Accuro.

Dräger Short-term Tubes used for milking parlor were: Carbon Dioxide 100/a, range 100-3000 ppm, Ammonia 0.25/a, range 0.2-3 ppm or Ammonia 2/a range 2-30 ppm; while for greenhouse: Carbon Dioxide 100/a, range 100-3000 ppm, Carbon Monoxide 2/a, range 0-300 ppm, Nitrous Fumes 0.2/a, range 0.2-6 ppm, Nitrogen Dioxide 0.1/a, range 0.1-30 ppm.

2.5 Experimental setting

In the 4 considered farms, 3 periods of the year with different weather conditions were monitored to assess the air quality and the functioning of Indaqum in cold (C), hot (H) and thermo-neutral (TN) climate conditions. In each period the tests were carried out for 3 days in the milking parlor, monitoring one of the two daily milkings (at 7:00 AM in Farm A and 2:00 PM in Farm B), while those in greenhouses were carried out for 1 day, monitoring 3 field operations (harvesting, sowing and soil tillage). Indaqum was set to record the value detected by the sensors every 5 minutes in the milking parlor and every minute in the greenhouse.

For the reference measurements, the tubes were used on air samples taken by filling 3 nalophan bags of approximately 30 L at regular intervals, filled with 3 pump strokes with a centrifugal pump. In milking parlor, the 3 bags were filled at intervals of about 10-15 minutes based on the duration of the milking operation. Instead, in the greenhouse the 3 bags were filled at intervals of about 1-7 minutes based on the distance traveled along the 4 humps of each tunnel. Each bag was analyzed with the specific tubes of the gas to be detected. All air quality measurements were carried out by placing Indaqum proximal to the head of the operator.

2.6 Data analysis

The same data analysis strategy was performed on data coming from both agricultural contexts (greenhouses and milking parlors). Firstly, the descriptive statistics relative to the results obtained using the reference instruments and Indaqum has been reported adopting a boxplot visualization.

Then, in order to define which is the most suitable statistical test to compare the performance of Indaqum with the reference device, the data distribution from each air qualitative parameter (CO_2, CO, NO_2, NO and NH_3) was analyzed applying the Kstest (One-sample Kolmogorov-Smirnov test). This test returns the decision for the null hypothesis (H0) that the data comes from a standard normal distribution, against the alternative hypothesis (H1) that it does not come from such a distribution. The test rejects the null hypothesis at the 5% significance level (Marsaglia et al., 2003). Afterwards, a rank correlation analysis with the corresponding significance (p-value) was performed using Kendall rank correlation coefficient (Kendall τ, a nonparametric measure of correlation) in order to verify the relation between the references and Indaqum outputs. Values of the τ correlation coefficient can range from –1 to +1. A value of –1 indicates that one column (reference or indaqum outputs) ranking is the reverse of the other, while a value of +1 indicates that the two rankings are the same. A value of 0 indicates no relationship between the reference and the Indaqum. Finally, for a better understanding of the practical applicability of the proposed technology, the estimation ability of the reference instruments was compared with the Indaqum output. To do that, the Passing-Bablok regression method (Passing & Bablok, 2009) was applied on the qualitative air parameters monitored (using the reference method and the integrated device) in both agricultural contexts (greenhouses and milking parlors). This regression method is particularly suitable for method comparison, since it is a symmetrical non-parametric technique, which can build regression models also when both variables (independent and dependent) have a non-negligible experimental error, differently from the least squares method. For statistically evaluating the similarity/diversity between these two independent estimations, slope and intercept of the fitted line were calculated, and a significance bivariate test was conducted. The null hypothesis (H0) was verified when the slope was not significantly different from 1 and, simultaneously, the intercept was not significantly different from 0, meaning that there were no significant differences between the two methods, at a 95% confidence level (Tugnolo et al., 2021).

The entire data analysis was performed in Matlab® environment, version 2019b (The MathWorks, Inc., Natick, MA, USA) using Passing and Bablok regression by Andrea Padoan (Jan 16, 2010) and in-house functions.

3. Results and discussion

3.1 Sensors validation

3.1.1 Milking parlor summary statistics

The boxplots in fig. 2 provide a visual comparison of summary statistics for CO_2 (fig. 2a) and NH_3 (fig. 2b) obtained from the reference instruments and Indaqum. The mean, median, the interquartile range, the data range were represented into the graphs. Moreover, the potential and extreme outliers (observations beyond the data range whisker length) were also statistically represented. By default, a potential outlier is a value that is more than 1.5 times the interquartile range away from the bottom or top of the box. Overall, comparable results were obtained in terms of data distribution using the reference and Indaqum. Concerning the reference measurements for the CO_2, the results showed a concentration range that varies from about 600 to 2000 ppm. Instead, the reference NH_3 values ranged from about 0.25 to 2.25 ppm

3.1.2 Greenhouse summary statistics

Concerning the greenhouse analysis, in fig. 3 the summary statistics for CO_2 (fig. 3a), CO (fig. 3b), NO_2 (fig. 3c) and NO (fig. 3d) obtained from the reference instruments and Indaqum was reported. Lower concentrations of CO_2 (from about 300 to 850 ppm) were detected compared to those obtained in the milking parlors, while for NO_2 the concentration range varied from about 0.1 to 0.6 ppm. Concerning the CO concentrations close to zero were obtained.

Focusing on the outcomes from Indaqum, very different concentrations were obtained for the NO estimation, compared to the reference.

3.1.3 Measurements methods comparison

Firstly, in order to highlight the data distribution for each qualitative parameter analysed with the references and Indaqum, a one-sample Kolmogorov-Smirnov test was performed. With this test, it was possible to notice for each parameter and method of analysis that the null hypothesis (H0) was rejected proving the non-normal distribution of the data (data not shown).

Therefore, a non-parametric test which does not require data normally distributed and measures the strength of dependence between two variables was performed using the Kendall rank correlation. Fig. 4 shows Kendall rank correlation results for the qualitative parameters measured in the milking parlors (fig. 4a) and in the greenhouses (fig. 4b). The correlation ranges from -1 (highly reverse correlation colored in dark blue) to 1 (highly direct correlation colored in dark red). Concerning the milking parlors, a high correlation was obtained with a $\tau=0.84$ ($p\text{-value}<0.05$) for both correlations of CO_2 and NH_3 with the reference against Indaqum.

In the greenhouses, high and significant correlation ($p\text{-value}<0.05$) was obtained for the paired comparison between the parameters CO, NO_2 and CO_2, for the reference against Indaqum. The NO outcomes showed a lack of correlation suggesting the need for future investigation to better implement the NO measurement into Indaqum.

Moreover, further correlation analyses were performed to explore the possibility to measure indirectly with Indaqum a specific gas without using its related sensor. However, a not highly correlations (even if significant) emerged from the comparison between different qualitative parameters suggesting the unfeasibility of Indaqum to perform an indirect estimation for an additional reduction of the production costs.

Therefore, considering the existence of a highly and positive linear correlation between the outputs from the reference and Indaqum, a Passing–Bablok regression was performed to verify the equality between the methods. Using a joint test on slopes and intercepts, the reference instrument and the integrated device were compared in pairs. In this case, only for the CO_2 evaluation, the results obtained from the milking parlors and from the greenhouses were merged in order to better verify the equivalence of the two methods for the quantification of CO_2. In fig. 5, the four Passing–Bablok regression lines are presented (solid blue lines) and the confidence interval at 95% is highlighted with dashed black lines. The bisectors of the quadrants (ideal lines) are represented, for comparison, as dotted red lines. Fig. 5a reports the comparison between reference CO_2 vs. Indaqum CO_2, fig. 5b between reference NO_2 *vs.* Indaqum NO_2, fig. 5c between reference CO *vs.* Indaqum CO and fig. 5d between reference NH_3 *vs.* Indaqum NH_3.

No statistical differences between the instruments were highlighted for the quantification of CO_2, NO_2 and NH_3 at a confidence level of 95%. Therefore, the null hypothesis (slope not significantly different from 1 and intercept not significantly different from 0) was accepted for all the paired comparisons except for the CO evaluation where the null hypothesis was rejected ($0.01 < p < 0.05$) demonstrating a non-linear relationship probably due to the very low concentration of CO detected in the greenhouses (Table 1).

Table 1

Passing–Bablok regression outcomes: comparison between reference and Indaqum for CO_2, CO, NO_2 and NH_3 quantification.

Air quality parameter	**Reference *vs.* Indaqum**	**Significant differences**
CO_2	$p > 0.05$, H0 accepted	No
CO	$0.01 < p < 0.05$, H0 rejected	Yes
NO_2	$p > 0.05$, H0 accepted	No
NH_3	$p > 0.1$, H0 accepted	No

3.2 Monitoring of the indoor air quality with Indaqum: milking parlor

As regards the tests carried out in milking parlors, fig. 6 shows mean values of NH_3 and CO_2 per each fraction of milking time averaged on the three days of monitoring per farm (farms A and B) and period (H, TN and C). In every farm the total milking time differed depending on milking routine and herd dimension. In farm A NH_3 ranged between 0.1 to 3.1 ppm and in farm B from 0.1 to 4.5 ppm, while CO_2 ranged between 507 to 2021 ppm in farm A and from 389 to 2509 ppm in farm B. The trends described in fig. 6 show that Indaqum in the milking parlor can detect even small variations in the concentration of NH_3 and CO_2.

The differences in air quality in the two milking parlors were attributable to the management solutions implemented by the two farms, in particular the ventilation (both natural and forced) and the animals loading in the milking parlor. In addition, also seasonality influenced the indoor ambient conditions. Table 2 reports the average temperature (T; °C) and Relative Humidity (RH ; %) both inside and outside to the milking parlor of the two farms for the periods H, TN and C. It emerges that in period H the two farms presented similar conditions for both T and RH inside and outside. Instead, in TN and C wider differences can be observed: T was slightly higher in farm B, while RH was much higher in farm A. These seasonal differences emerge also considering the gases emitted per period as reported in Table 3.

Table 2

Mean and standard deviation (SD) values of inside (milking parlor or greenhouse) and outside Temperature and Relative Humidity in the three periods monitored in all farms.

Farm	**Period**	**T (°C)**		**RH (%)**	
		outside	**inside**	**outside**	**inside**
		Mean ± (SD)			
A	**H**	29.0 ± (0.9)	27.9 ± (0.4)	59.7 ± (6.7)	58.6 ± (1.1)
	TN	10.5 ± (3.1)	14.6 ± (0.2)	100.0 ± (0.6)	83.1 ± (0.9)
	C	5.2 ± (3.0)	10.5 ± (1.2)	100.0 ± (0.0)	87.2 ± (2.9)
B	**H**	32.7 ± (0.6)	30.3 ± (0.6)	57.5 ± (2.8)	58.4 ± (3.1)
	TN	14.9 ± (1.1)	18.9 ± (1.7)	88.6 ± (14.7)	80 ± (4.8)
	C	6.8 ± (1.1)	12.2 ± (1.7)	52.5 ± (0.8)	71.7 ± (5.0)
C	**H**	23.4 ± (2.5)	26.2 ± (0.2)	80.8 ± (10.2)	68.9 ± (0.2)
	TN	12.1 ± (0.3)	17.8 ± (0.2)	99.6 ± (0.1)	66.7 ± (0.2)

	C	2.3 ± (2.7)	10.2 ± (0.5)	99.5 ± (0.1)	63.2 ± (2.29)
D	**H**	30.1 ± (1.3)	31.6 ± (0.3)	54.3 ± (7.9)	60.7 ± (1.4)
	TN	14.9 ± (0.3)	21.1 ± (0.3)	69.9 ± (0.8)	65.9 ± (0.9)
	C	8.1 ± (0.1)	14.7 ± (0.8)	96.3 ± (3.1)	60.4 ± (0.8)

Table 3

Mean and standard deviation (SD) values of CO_2, NO_2 and NH_3 measured by Indaqum in the three periods monitored in all farms.

Farm	**cultivation steps**	**Period**	**CO_2**	**NO_2**	**NH_3**
			mean ± (SD)		
A	-	**H**	894 ± (169)	-	0.99 ± (0.33)
		TN	1050 ± (383)	-	1.06 ± (1.22)
		C	1435 ± (432)	-	1.37 ± (1.06)
B	-	**H**	909 ± (442)	-	2.27 ± (1.47)
		TN	1518 ± (842)	-	1.62 ± (1.24)
		C	1312 ± (635)	-	0.57 ± (0.26)
C	**harvesting**	**H**	461 ± (43)	0.19 ± (0.05)	-
		TN	458 ± (30)	0.20 ± (0.04)	-
		C	545 ± (74)	0.28 ± (0.08)	-
	sowing	**H**	386 ± (4)	0.17 ± (0.04)	-
		TN	446 ± (4)	0.17 ± (0.07)	-
		C	545 ± (31)	0.22 ± (0.07)	-
	tillage	**H**	407 ± (25)	0.16 ± (0.05)	-
		TN	588 ± (170)	0.42 ± (0.32)	-
		C	636 ± (116)	0.31 ± (0.16)	-
D	**harvesting**	**H**	472 ± (51)	0.17 ± (0.06)	-
		TN	534 ± (29)	0.19 ± (0.03)	-
		C	582 ± (78)	0.19 ± (0.10)	-
	sowing	**H**	396 ± (12)	0.22 ± (0.08)	-
		TN	470 ± (8)	0.22 ± (0.06)	-
		C	462 ± (5)	0.15 ± (0.04)	-
	tillage	**H**	488 ± (96)	0.29 ± (0.02)	-
		TN	719 ± (82)	0.26 ± (0.03)	-
		C	620 ± (148)	0.13 ± (0.07)	-

In period H, farm A switched on forced ventilation, allowing the extraction of air from the loading area and milking parlor. The NH_3 concentration during milking increased slightly, while CO_2 remained constant around 900 ppm. In this period, the entrance of animals in the loading area did not influence the gas trends. Instead, in farm B the NH_3 concentration increased during the milking finally reaching higher levels (4.5 ppm) than farm A. This occurred because farm B had no forced ventilation system that supported the air exchanges. Furthermore, the number of animals per group in farm B was higher than in farm A, and this also explains the higher peaks achieved. The effect related to the absence of forced ventilation can be observed on the trend of CO_2 concentrations of this farm. In particular, CO_2 increased (max 1830 ppm) at the entry of the two groups of animals and decreased with the progress of milking and the consequent exit of animals.

In period TN the gas concentration trend was similar to the period H in both farms. In general, NH_3 was lower and CO_2 was higher due to the differences in internal climate. The main difference can be seen in farm A due to a fault of the forced ventilation system on one day of measurement. This problem became evident on NH_3 concentration, with a peak (1.8 ppm) after the entrance of the second group of animals.

In period C farm A had the forced ventilation turned off. The absence of ventilation and the small dimensions of the milking parlor of farm A negatively limited the air exchanges, therefore NH_3 trend showed higher values than in the other periods and in particular two peaks at group entrances (max 3.1 ppm). The same occurred for CO_2 concentration even if no peaks can be observed. In farm B most of the openings were closed during period C; however, NH_3 concentrations were lower (max 1 ppm) than period H and TN, but also lower respect to period C of farm A. This can be due to a lower RH inside and outside the parlor that fastened NH_3 removal (Yin and Zhang, 2020). As regards CO_2 concentration, the same trend of the other monitored periods was observed.

From fig. 6 some general indications can be defined. As widely known, NH_3 emission is influenced by temperature and humidity. Moreover, the effect of ventilation must also be considered since it influences the emission rate (Rong et al., 2010), although this does not necessarily lead to an increase in air concentrations because the natural or forced ventilation favors its removal from the building (Bleizgys and Bagdoniene, 2016; Herbut and Angrecka, 2014).

Very few air quality data are available in literature about milking parlors, and most of them focus on particulate matter and dust (Purdy et al., 2009). However, some considerations can be done, also taking into account other parts of the cowsheds. For both the monitored farms, the results on NH_3 concentrations are comparable to what was found in literature. In naturally ventilated dairy cowsheds were reported average values of 1.5 – 2.4 ppm for NH_3 (Janke et al., 2020; Samer et al., 2012), and more widely of 0.5-8.5 ppm, depending on the measurement seasons, with increasing values at higher temperatures (Wu et al., 2012).

The effect of ventilation and of the animal loading in the milking parlor is also noticeable on CO_2 concentrations. Peaks are evident when ventilation lacks and in concomitance of the animals entry in the waiting areas. Increased CO_2 concentrations emerge with temperature decreases, which is also reported in literature relating to cowsheds where CO_2 can vary between hot and cold period between 450-800 ppm to 600-1000 ppm (Samer et al., 2012) or between 904-1052 ppm (Wu et al., 2012).

3.3 Monitoring of the indoor air quality with Indaqum: greenhouse

As regards the tests carried out in greenhouses for baby leaves growth, fig. 7 shows the values of CO_2 and NO_2 per each farm (farms C and D), period (H, TN and C) and field operation (harvesting, tillage and sowing). In every farm, each operation lasted from about few minutes (sowing and tillage) to about one hour (harvesting), and no clear trend can be observed in the different operations, farms and monitored periods.

In farm C, NO_2 ranged between 0.0 to 1.0 ppm and in farm D from 0.0 to 0.5 ppm, while CO_2 ranged between 400 to 1000 ppm in farm C and from 400 to 1200 ppm in farm D. These trends show that also in this case Indaqum can detect even the small variations in the concentration of NO_2 and CO_2.

Differently from the milking parlor, the interpretation of the results is more complex because of the interaction of several factors. For example, each operation was performed with:

(i) different tractors characterized by different engine age, exhaust gases emissions limits (stage) and engine power,

(ii) different seasonality (see table 3),

(iii) a total of three/four ways forth and back, therefore the exhaust gas pipe - that is directed towards the soil or laterally on the tractors working in greenhouses - can have either hit the side of the greenhouse or the central space, thus dissolving the exhaust gases differently in the space,

(iv) different timing during the day, therefore some operations were carried out with the engine warmed up or not (tractor just started),

(v) different power requirements depending on the coupled machinery, therefore influencing the engine speed and torque and finally the exhaust gases emission,

(vi) no control of air fluxes that can have affected the measurement of the emissions in the different parts of the greenhouse.

In table 3 are reported the average environmental conditions of temperature (T; °C) and relative humidity (RH; %) inside and outside the greenhouse per farm in the 3 periods H, TN and C. In farm C, T was generally lower than in farm D, while RH was quite similar in both farms for the whole monitored periods.

Considering fig. 7, the peaks in emissions can be mainly observed during TN and C, when air temperatures were low. Instead, in period H, the high air temperatures both inside and outside the greenhouse can have reduced air fluxes and favored the engine warming-up, reducing the peaks of emissions to air. In almost all operations can be observed two main trends: either the measurement shows constant values for the 3-4 ways forth and back of each period (for example, tillage operations in C and sowing operations in TN) or some peaks can be observed in correspondence of the proximity to the sides of the greenhouse. Therefore, air fluxes and sides proximity seem to be the two main variables affecting the emission of the monitored gases. In addition, respect to the engine characteristics, the machinery present on the farms were quite old. Also this aspect can have affected the results, because the oldest emission stages such as the one of the tractor used during sowing in farm C were characterized by emissive limits much higher than the newer engines (10-100 times more) (Dieselnet, 2021).

4. Conclusions

The results of this study show that the Indaqum prototype, developed to monitor air quality, performed properly for the measurement of NH_3, CO_2 and NO_2. Its monitoring behavior is comparable to the reference measurement system. Moreover, in the tests carried out in the milking parlor and in the greenhouse, Indaqum allowed to detect even the small variations in gases concentration in air, compared to the reference systems. This achievement is promising for the future use of Indaqum as an active control device of the internal environment of agricultural structures, and in particular as a support tool to avoid the onset of undesired air quality conditions. Its adoption can be coupled with the automated starting of ventilation systems as well as with the cleaning or removal of effluents in barns when critical/undesired conditions are detected. Indaqum can therefore be included within the framework of Precision Livestock Farming devices.

In the future, the duration of the sensors installed in Indaqum and adopted in hostile environments such as agricultural ones will need to be further investigated, especially in terms of prolonged exposure to dust, humidity and gases.

Considering both the monitored environments, a good ventilation resulted essential to keep gas concentrations in the air low. Consequently, the cold periods of the years can be considered as the more critical. However, the increasing use of electric engines in greenhouses will possibly eliminate the problem of such emissions in the air in semi-enclosed environments. In this case, future measurements of the presence of dust will be also needed.

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