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Assessment of a Low-Cost Portable Device for Gas Concentration Monitoring in Livestock Housing

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Abstract: The increasing regulatory pressure to monitor and reduce GHG emissions and air pollutants requires cost-effective methods for their surveillance. The most common techniques used for scientific investigations into gas concentration monitoring in barns are accurate but expensive and require complex maintenance. This research study analyzed the potential use of low-cost portable measurement devices for the measurement of ammonia (NH_3) and carbon dioxide (CO_2) concentrations in an open dairy barn. A comparison between the gas concentrations acquired at different heights from the floor by using portable devices and those acquired by a photoacoustic infrared multigas spectroscope (i.e., reference measurement) in the same sampling locations was carried out to determine the precision of the low-cost portable devices. The performances of the low-cost portable devices were statistically analyzed by application of the one-way analysis of variance, correlation analysis, and regression analysis. The results showed a significant difference between the gas concentration values at various heights from the floor for both NH_3 and CO_2. The correlations between the concentrations acquired by the low-cost portable devices and the INNOVA were statistically significant ($r = 0.83$; $p < 0.001$) for gas concentrations monitored at 0.4 m from the floor. Compared with the reference measurement device, the low-cost devices were effective at the monitoring of NH_3 concentrations at 0.40 m from the floor; however, they underestimated the concentrations in the barn at increasing heights from the floor, and the device was not adequate for CO_2 concentrations. In detail, the relative measurement error of the low-cost devices compared to the INNOVA was reduced close to the floor during NH_3 concentration measurements. Within these limitations, this device may be useful for monitoring the NH_3 concentration in the barn and assessing variations in the NH_3 concentrations mainly related to the animal occupied zone. Further efforts are needed in this field of research to identify a low-cost device that can simplify emission estimation from open dairy barns.

Keywords: low-cost sensors; portable device; environmental monitoring; gas concentrations; dairy barn; photoacoustic infrared spectroscope

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1. Introduction

The relevant role of agriculture in climate change was underlined in the Paris Agreement under the United Nations Framework Convention on Climate Change (UNFCCC) in 2015, which deals with issues such as food production, security, and GHGs emissions [1]. Specifically, 92 countries included the livestock sector in order to achieve their national reduction emission targets [2]. Although Europe has implemented policies for improving air quality (e.g., Directive 2008/50/EC, Directive 2010/75/EC, and Directive 2016/2284/EU), the text *A Europe that Protects: Clean Air for Al'* [3], adopted by the European Parliament on 13 March 2019, emphasizes that the costs of air pollution control in Europe are significantly lower in the agricultural sector than in other sectors where more stringent emission controls have already been implemented. In Italy, emissions from farms are assessed by a monitoring and control plan carried out by the farmers through the utilization of regional guidelines [4]. However, Italian law on emissions into the atmosphere requires in the cattle sector that only dairy houses with over 200 heads have an emission authorization (D.Lgsl. n. 152/2006 [5]; D.Lgsl. n. 128/2010 [6]). For a lower number of livestock units, there is no control on emissions, though high levels of gas concentrations are likely to be reached for both large and small herds [7,8].

Livestock activity has a significant influence on environmental balance both locally and globally (in terms of air and climate quality, water and soil quality, biodiversity, and landscape quality) [9]. The effects of emissions impact not only the environment but also other fields, as they can affect animal welfare and farmer safety [7,10–12].

The increasing regulatory pressure to reduce GHG emissions and air pollutants requires cost-effective methods to allow their regular surveillance. In this context, the monitoring of air pollution is the basis for the application of efficient emission mitigation strategies [13].

According to Wang et al. [14], the available technologies for measuring gas concentrations can be subdivided into three categories: (a) rapidly responding sensors that provide concentrations over time (e.g., electrochemical cells, chemiluminescence, fluorescence, photoacoustic spectroscopy, and long path optical instruments); (b) cumulative concentration devices that carry out only time-averaged values (e.g., denuders, passive samplers, and adsorption bottles); and (c) instantaneous devices that give snapshot measurements. The operating principles, advantages, limitations, and costs of these technologies were classified in a study by Hassouna et al. [15].

One of the most common techniques used for scientific investigations into gas concentration monitoring in dairy barns is photoacoustic infrared multigas spectroscopy. In the literature, several research studies have measured the gas concentrations in NV dairy barns by using photoacoustic infrared spectroscopes [16–22]. Photoacoustic infrared spectroscopy is based on analyses of the acoustic waves produced from gases that are exposed to radiation [23,24]. Among the most commonly used devices, the photoacoustic infrared spectroscope (INNOVA, Lumasense Technology, Denmark) is a widespread technology for the continuous measurement of gas concentrations, but the cost of the instrumentation and routine maintenance is too high [14]. In detail, the purchase price of this kind of equipment and the cost of routine maintenance are relatively high, and, thus, these devices are not suitable for environmental control carried out by farmers. Generally, the use of this instrument is for scientific purposes, in particular, for determining emission factors under specific barn characteristics and constraints (e.g., barn structure, climatic conditions, barn management, and herd size), which requires long-term measurements [25]. Therefore, the use of several instruments during the same period in more than one barn requires higher costs and more complex maintenance than for low-cost devices.

However, simplified measurement systems are emerging; these are equipped with less accurate sensors than scientific instruments, yet they boast much lower costs, easier usage, and the possibility of monitoring several points continuously at the same time [26].

Based on the background described above, the purpose of this research study was to validate innovative low-cost devices for gas concentration monitoring. The following objectives were pursued by investigating the performance of each low-cost device against an advanced photoacoustic infrared spectroscope: (i) to study the profiles of the gas concentrations acquired by the two instruments; (ii) to assess the performance of the low-cost device; and (iii) to identify their potential use in an open dairy barn.

2. Materials and Methods

2.1. Description of the Barn

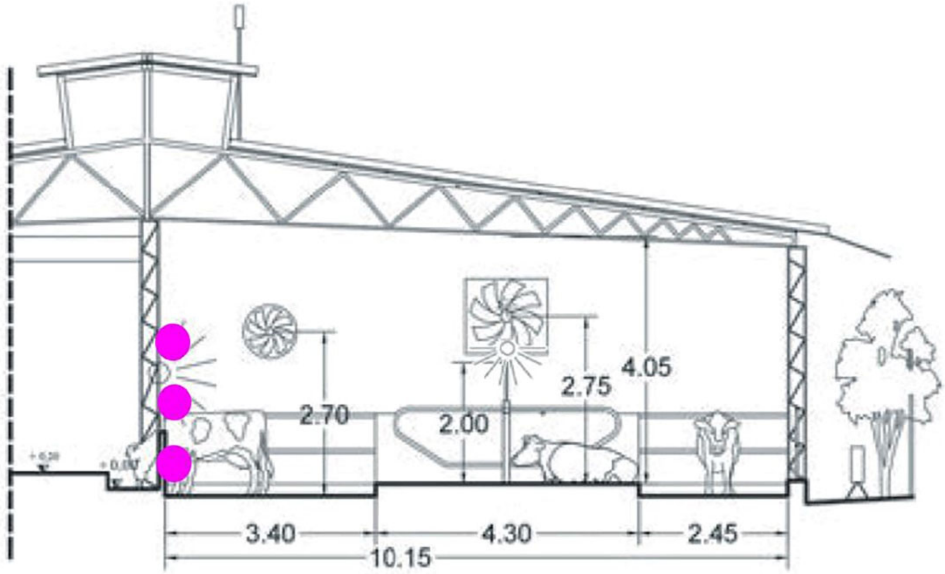
The site of the experiment was located in the province of Ragusa (Southern Italy), which is a geographical area with the highest number of dairy barns in the Mediterranean Basin. The data were acquired in a cubicle free-stall dairy barn from 11th to 18th June 2021.

The open structure (Figure 1) was defined by three completely open sides and one side closed by a continuous wall with four small openings. The rectangular plan (i.e., 55.50 m long and 20.80 m wide) was covered by a concrete floor with a roof made of fiber-reinforced corrugated concrete panels. The heights at the ridge vent and the eave were 7 m and 4 m, respectively.

Figure 1. Indoor view of the barn characterized by completely open sides.

The different functional areas can be distinguished in the plan view of the barn (Figure 2): the feeding area, subdivided into the feeding alley, manger, and feeding passage; the resting area with 64 head-to-head cubicles in two rows and three pens; the service alley for herd management; offices; and boxes for calves, located on the southwest side.

(**a**)



(**b**)

Figure 2. Position of sampling points in the barn. In the plan view of the barn, (**a**) the localization of the sampling pole was located in the central area of the barn. The section of the barn (**b**) shows the vertical distribution of the sampling points in the sample pole at different heights from the floor.

In addition to the fact that the natural ventilation of the indoor space was assured by the open structure, the barn was equipped with sprinklers and fans in the feeding alley and a fogging system with fans in the resting area. The fans located in both the resting area and the feeding alley had tilt angles of 20° from the horizontal plane. In detail, the fans in the resting area had a rotation axis located 2.75 m from the floor along the longitudinal axis of the barn, whereas the fans in the feeding alley had a rotation axis 2.70 m from the floor and parallel to the longitudinal axis of the feeding alley.

Fifty-seven Friesian cows were milked twice a day—once in the morning and once in the afternoon. The floor of the barn was made of concrete and was cleaned by a tractor with a scraper every morning. A mixed ratio was delivered at 12 a.m. for ad libitum consumption. The barn was equipped with a cooling system made of fans located in both the resting area and the feeding alley. The fans operated every 20 min to move air in the barn. Moreover, during milking sessions, the cooling system was switched off.

2.2. Measurement Devices

The measurements of the NH_3 and CO_2 concentrations were continuously carried out at three sampling locations (SLs) located in the central area of the barn along a vertical axis (Figure 2). The first, the second, and the third SLs (i.e., hereafter named SLA, SLB, and SLC, respectively) were located 0.40 m, 1.55 m, and 2.70 m from the floor, respectively. The data were acquired from 9 to 14 April 2022.

The measurements were carried out by using three low-cost portable devices (SKY2000-M2, Digitron Italia, Ferentino (Fr), Italy) and a photoacoustic infrared multigas spectroscope as the reference measurement device (Lumasense Technology A/S, Ballerup, Denmark). In each SL, a small box contained the sampling points for both the low-cost and reference devices (Figure 3). An air filter was attached to the end of each sampling tube to keep the sampler free of particles. Each sampling point was attached to a sampler tube in PTFE (polytetrafluoroethylene) linking the sampling point to the measurement device.

The three low-cost devices were portable instruments suitable for continuous measurement of the gas concentrations of NH_3 and CO_2. Each low-cost device had an internal sampling pump linked to a sampler tube with an air filter to allow air sampling. In detail, the measurements of the NH_3 concentrations were carried out by a chemical sensor in the low-cost device characterized by a range of 0–100 ppm, a resolution of 0.01 ppm, and a precision of 2%FS. The CO_2 concentrations were measured by an infrared sensor enclosed in the low-cost devices characterized by a range of 0–4000 ppm, a 1 ppm resolution, and a precision of 2%FS. The measurement frequencies were 2 min and 30 s for both gases. The calibration of each instrument was performed by the company just before the measurement activity. The beginning of the measurement was synchronized for all three devices in order to acquire the gas concentrations at the same time for the three different SLs.

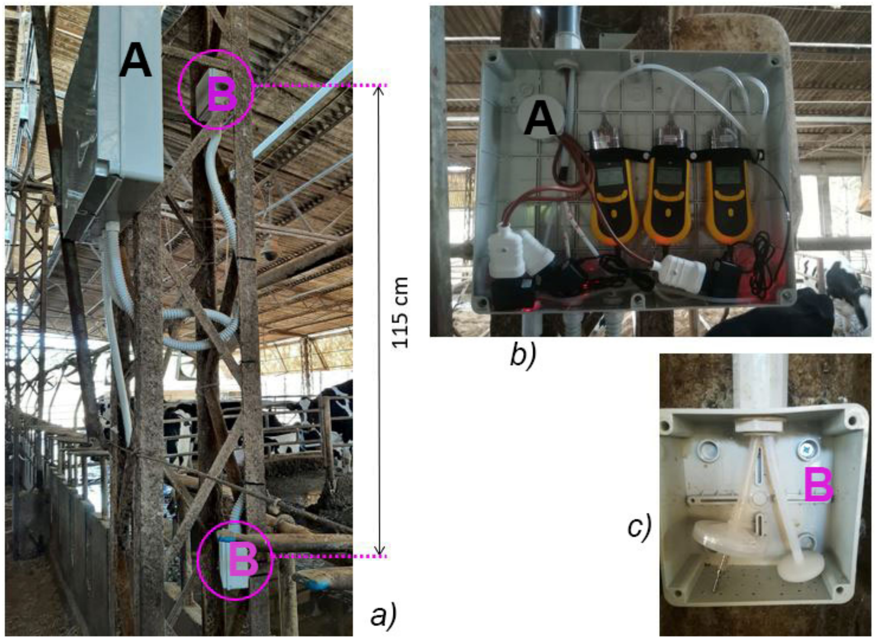


Figure 3. Installation of the low-cost system in the barn (**a**) with a large box (A) to contain the three low-cost measurement devices and small perforated boxes (B) to contain the sampling points for the measurements. The distance between two different consecutive sampling points was 1.15 m (**a**). In the large box (**b**), three low-cost measurement devices were installed. In the small boxes (**c**), the sampling points for the measurement are shown. In detail, each small box contained the sampling tubes for both the low-cost and reference devices. Each sampling tube was equipped with an air filter.

The reference instrument INNOVA was a photoacoustic analyzer composed of a Multigas Monitor mod 1412 i and a multipoint sampler 1409/12. The system has 3 inlet channels and tubes that connect each channel to the multipoint sampler 1409/12 and to the respective sampling location. The device is able to perform simultaneous measurements of different gases (i.e., NH_3 and CO_2), but not contemporaneously in all SLs. Based on evidence reported in the study by Rom and Zhang [23], the measurement cycle (i.e., composed by the numerical sequence of the SLs) was optimized to reduce bias related to the detection of the very different concentrations (i.e., high and low concentrations) between two adjacent SLs. According to the findings described in a recent study by D'Urso et al. [27], three repetitions of measurement for each SL were recorded by the instrument before switching to the following SL. The gas concentrations were continuously acquired according to a measurement cycle established before the experiment (i.e., SLA, SLB, and SLC). The SITs used for the experiments were Normal (5s). The detection limits, declared by the manufacturer, are as follows: 0.2 ppm for NH_3 and 1.5 ppm for CO_2. The INNOVA was calibrated before the measurement campaign by the company.

2.3. Data Processing and Statistical Analyses

The data on the NH_3 and CO_2 concentrations acquired by using the low-cost devices and the data acquired by the INNOVA were organized in a spreadsheet based on the time of the day and the location in which the measurement was carried out (i.e., SLA, SLB, and SLC). A specific dataset was implemented by carrying out computations of the relative measurement errors $\varepsilon_i(\%)$ of the low-cost devices, according to the following relation:

$$\varepsilon_i = \frac{|GC_{rif} - GC_i|}{GC_{rif}} \times 100 \ (\%)$$

where GC_{rif} (ppm) is the reference value of the gas concentrations acquired by the INNOVA analyzer, and GC_i (ppm) is the gas concentration value measured by the low-cost devices. The reference value for the gas concentrations was obtained by the mean value of the gas concentration between the second and the third repetitions for NH_3 and CO_2 [27].

Moreover, correlation analyses were carried out between the NH_3 concentrations and the CO_2 concentrations acquired by means of the two instruments at different heights from the floor. Moreover, a linear regression was carried out for a correlation factor r higher than 0.8. To deepen the statistical analyses, a one-way analysis of variance (ANOVA) was applied to assess the occurrence of significant differences between the gas concentrations at different heights for both the NH_3 and CO_2 acquired by the two instruments. Finally, a post-hoc analysis was carried out for each ANOVA, and the mean values were separated by Tukey's honestly significant difference at $p < 0.05$.

3. Results

3.1. Gas Concentrations

Based on the results of the ANOVA (Table 1), the gas concentrations acquired at different SLs were significantly different, showing an uneven distribution of gas along the vertical axis of the barn. In detail, the NH_3 concentrations measured by the reference device decreased from the floor to the roof of the barn. In detail, the NH_3 concentrations acquired at SLA were significantly different ($p < 0.001$) than those acquired at SLB and SLC, with the highest NH_3 concentration measured at 0.40 m from the floor in SLA. The same significant differences were found for the NH_3 concentrations acquired by the portable devices, with the highest NH_3 concentrations found in SLA. However, the mean values of the gas concentrations in SLB and SLC measured by the portable devices were lower by about 1 ppm than those acquired by the reference instrument. With regard to the CO_2 concentrations, the results of the ANOVA showed that the lowest gas concentration was detected in SLB, whereas there was not a significant difference between the gas concentrations in SLA and SLC. This result was not found by the portable devices that recorded the highest CO_2 concentrations in SLC. In detail, based on the ANOVA, the gas concentrations measured in SLA, SLB, and SLC were significantly different ($p < 0.001$), with a decrease in the gas from SLC to SLA. Moreover, the results obtained by using the portable devices showed an underestimation of the gas concentrations in SLA and an overestimation of the gas concentrations in SLB and SLC.

Table 1. Results of the ANOVA ($p < 0.05$) carried out for gas concentrations of NH_3 and CO_2 at three groups of sampling locations (i.e., SLA, SLB, and SLC) for each gas.

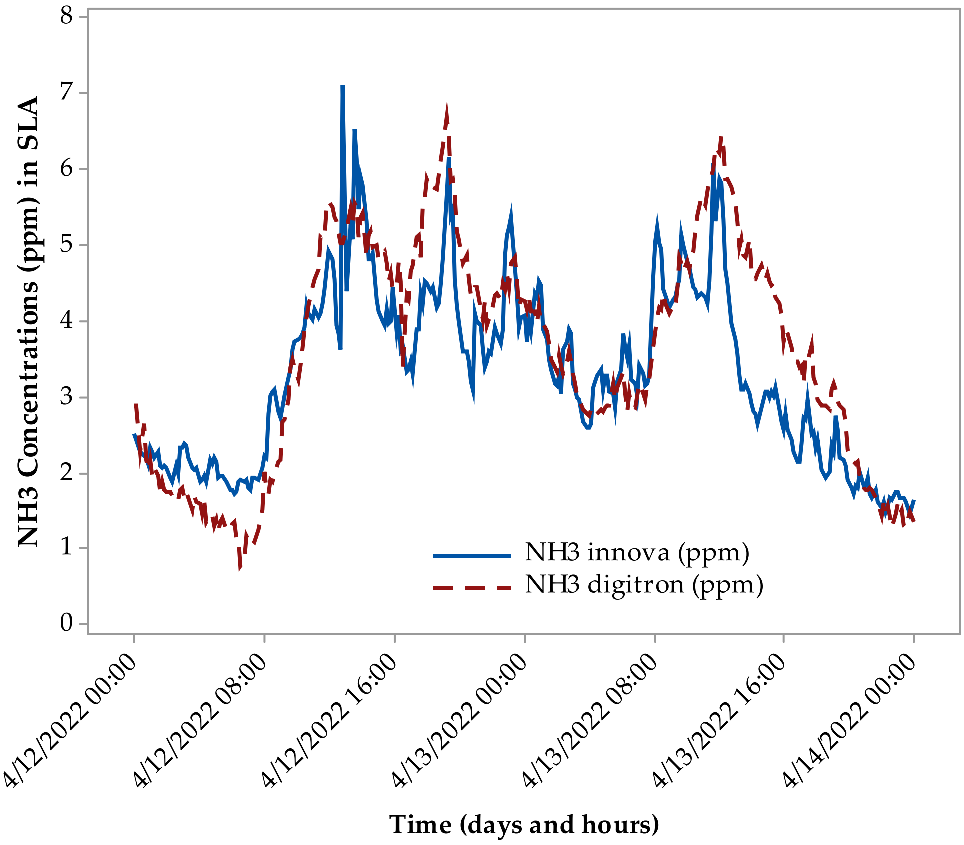
SL	Mean of NH_3 INNOVA Analyzer (ppm)	Tukey's Post-Hoc Test		SL	Mean of NH_3 Portable Device (ppm)	Tukey's Post-hoc Test	
A	3.51	A		A	3.63	A	
B	1.71		B	C	0.77		B
C	1.69		B	B	0.68		B

SL	Mean of CO_2 INNOVA Analyzer (ppm)	Tukey's post-hoc test		SL	Mean of CO_2 Portable Device (ppm)	Tukey's post-hoc test		
C	598.62	A		C	779.6	A		
A	596.44	A		B	575.59		B	
B	558.95		B	A	444.83			C

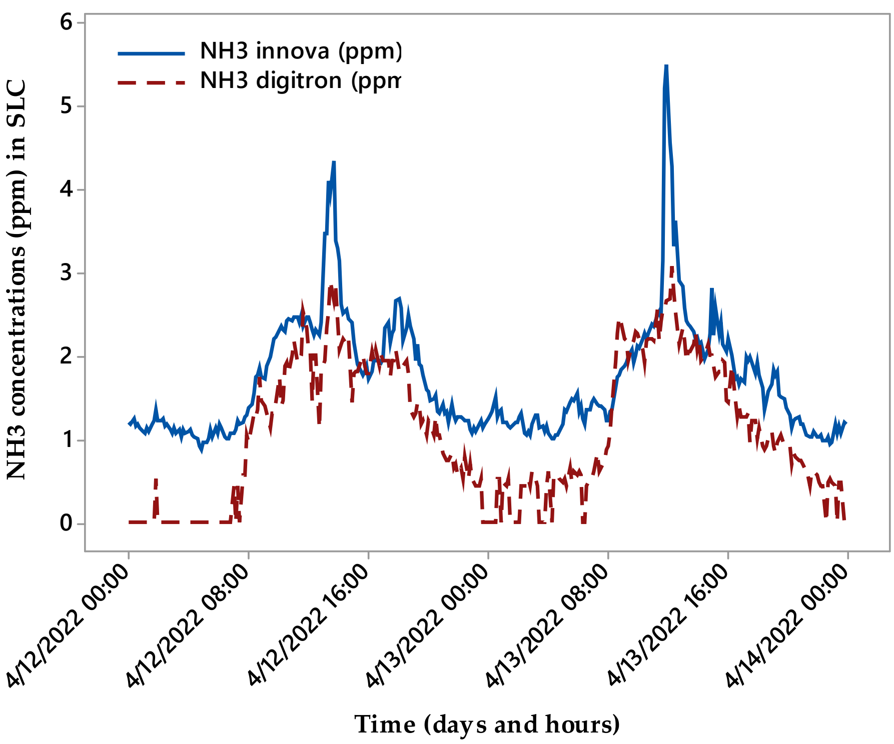
Rows with a different letter (A, B, C) are significantly different.

The correlation analyses carried out between the gas concentrations acquired by the INNOVA and the portable devices were significant ($p < 0.001$) for all of the heights from the floor considered for both NH_3 and CO_2. However, the Pearson correlations of the NH_3 concentrations measured by the INNOVA and the NH_3 concentrations measured by the portable devices were 0.83, 0.48, and 0.66 for SLA, SLB, and SLC, respectively. Regarding the measurements of the CO_2 concentrations, the Pearson correlations of the measurements by the INNOVA and the measurements by the portable devices were 0.18, 0.57, and 0.41 for SLA, SLB, and SLC, respectively. Therefore, a good level of correlation (Pearson coefficient > 0.7) was found only in SLA for NH_3.

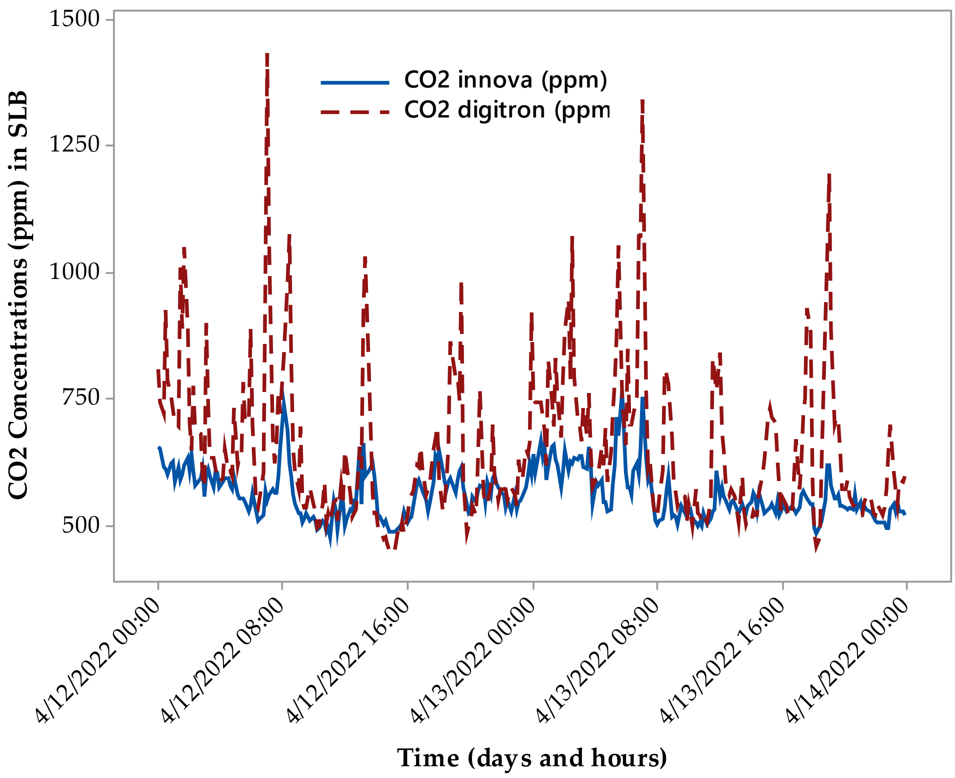
Figure 4 shows the trend of gas concentrations having r > 0.5, acquired at different SLs by using the two measurement devices. A good fit was found between the NH_3 concentrations acquired by the reference and the portable device (Figure 4a) with an overestimation of the NH_3 concentrations for the portable devices, especially after the peaks of the NH_3 concentrations. The graphs show that the NH_3 concentrations acquired by the portable devices were lower for SLs located at a greater height from the floor (Figure 4b), thus underestimating the values in comparison to the INNOVA device, whereas the CO_2 concentrations acquired by the portable device at 1.55 m from the floor were higher than those of the reference (Figure 4c).


NH3 Concentrations (ppm) in SLA
8
7
6
5
4
3
2
1
0
NH3 innova (ppm)
NH3 digitron (ppm)
4/12/2022 00:00
4/12/2022 08:00
4/12/2022 16:00
4/13/2022 00:00
4/13/2022 08:00
4/13/2022 16:00
4/14/2022 00:00
Time (days and hours)

(**a**)


NH3 concentrations (ppm) in SLC
6
5
4
3
2
1
0
NH3 innova (ppm)
NH3 digitron (ppm
4/12/2022 00:00
4/12/2022 08:00
4/12/2022 16:00
4/13/2022 00:00
4/13/2022 08:00
4/13/2022 16:00
4/14/2022 00:00
Time (days and hours)

(**b**)



(**c**)

Figure 4. Trends of gas concentrations having r > 0.5 during two days of measurements. In detail, the graphs show NH_3 concentrations acquired in SLA (**a**) and SLC (**b**) and CO_2 concentrations acquired in SLC (**c**) by using the two measurement devices.

Based on the outcomes, the NH_3 concentrations acquired by the INNOVA and the NH_3 concentrations acquired by the low-cost devices were strongly correlated in SLA. The linear regression model, which was applied to describe the relationship between the NH_3 concentrations acquired by the two devices, is shown in Figure 5. The regression equation ($p < 0.001$ and $R^2_{adj} = 68.6\%$) is as follows:

$$NH_{3\ portable\ device}(ppm) = 0.371 + 0.926\ NH_{3\ INNOVA\ analyzer}(ppm)$$

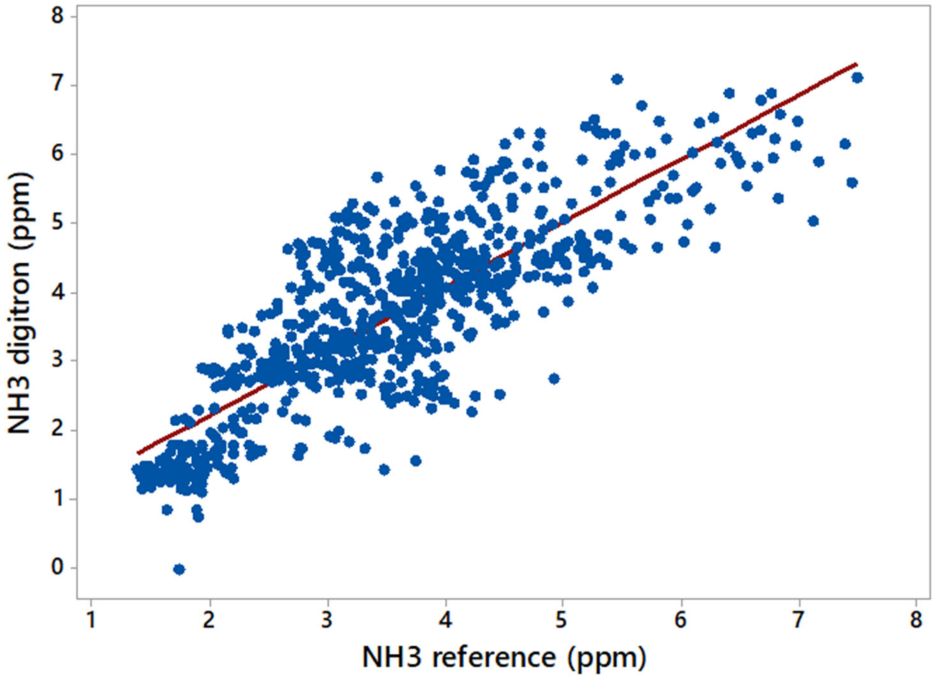


Figure 5. Linear regression analysis between NH_3 concentrations (ppm) acquired by the INNOVA analyzer (reference) and NH_3 concentrations (ppm) acquired by the low-cost device in SLA.

3.2. Analysis of the Measurement Errors

The results of the ANOVA (Table 2) showed that the position of the SLs significantly influenced the relative error of the gas concentrations for both NH_3 ($p < 0.001$) and CO_2 ($p < 0.001$). In detail, the lowest error for the portable devices was recorded during the measurement of the NH_3 concentrations in SLA. There was not a significant difference between the error of gas computed in SLB and those in SLC. In these two groups, the NH_3 concentrations were underestimated by about 60% when the measurement was carried out by the portable devices. With regard to the CO_2 measurements taken by portable devices, the results showed that the error computed at SLB was the lowest, whereas the absolute value of the error measurement for CO_2 was about 30%. In detail, the portable device underestimated the measurements in SLA and overestimated the measurements in SLC.

These results were also represented in the boxplot reported in Figure 6a,b. Moreover, it was also found that the relative error carried out by the portable devices in SLC had the highest variability for both NH_3 (Figure 6a) and CO_2 (Figure 6b). This latter finding is valuable for suggestions related to protocols applied in open dairy barns.

Table 2. Results of the ANOVA ($p < 0.05$) carried out for the relative error ε_i (%) related to measurements of the gas concentrations of NH_3 and CO_2 at the three sampling locations (i.e., SLA, SLB, and SLC) by using the portable devices.

SL	**Mean of Error for NH3 Portable Device (%)**	**Tukey's Post-Hoc Test ***	
A	3.39	A	
C	−59.20		B
B	−59.33		B
SL	**Mean of error for CO2 portable device (%)**	**Tukey's post-hoc test***	
C	28.82	A	

B	1.90	B	
A	−24.47		C

* Rows with a different letter (A, B, C) are significantly different.

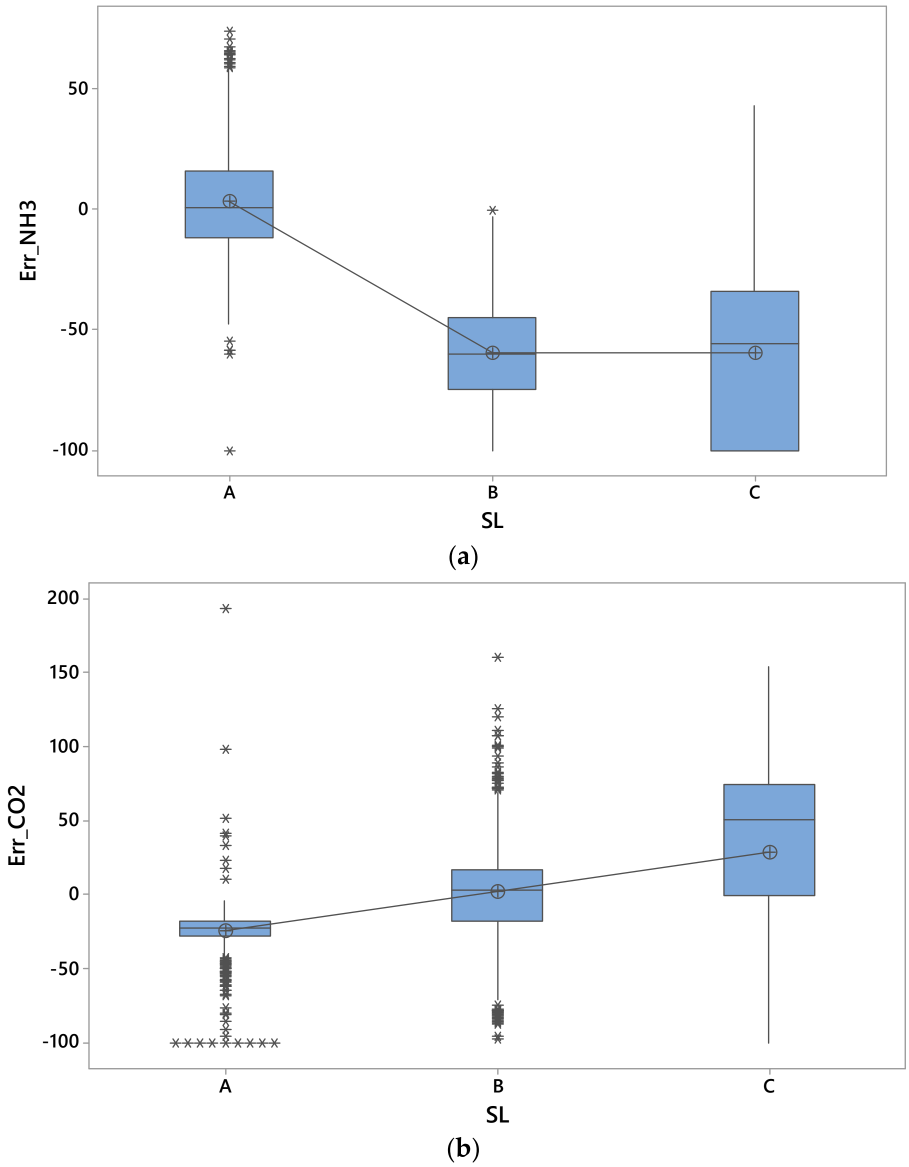


Figure 6. Boxplots of the error of gas concentrations for measurements carried out at SLA, SLB, and SLC by portable devices for both NH_3 (**a**) and CO_2 (**b**). The symbol * identify outliers.

4. Discussion

4.1. Gas Concentrations Measured by the Reference Instrument

The gas distribution analyzed in this study was heterogeneous in the barn, as was found in other studies in the literature [25,28]. Based on the measurements acquired by the INNOVA analyzer (i.e., reference), the vertical pattern found in this barn is different compared to that found by Mendes et al. [29]. In detail, in the study by Mendes et al. [29] it was found that the variability of the NH_3 concentrations increased from the animal occupied zone (AOZ) to the top of the barn, whereas CO_2 decreased from the floor to the top of the barn. These results were found for a mechanically ventilated dairy barn.

In the present study, the vertical pattern of the gas concentrations was described for an open dairy barn. The results showed how the highest gas concentrations were acquired at floor level, which was lower along the vertical axis of the barn, and the highest CO_2 concentrations were recorded at the top of the barn.

One of the influencing factors on gas distribution is the place where gaseous production occurs. As described in the study by Baldini et al. [30], the NH_3 concentration is mainly produced at floor level in the AOZ, and then NH_3 rises upward very quickly due to its bulk density (equal to 0.66 kg/m^3 in standard conditions). Since NH_3 is lighter than air (a bulk density of 1.293 kg/m^3 in standard conditions), the movement of the gas tends to be located upward along the vertical axis. However, the presence of the air flux of the fans modifies the flow pattern of the air in the barn and, consequently, modifies the gas concentrations in the air because it moves NH_3 toward the outdoor environment, increasing the dilution of the gas and, thus, its distribution in the barn. In detail, the tilt angle of the fans provided ventilation at about 1.55 m from the floor in the AOZ, where SLB was located. In addition to the fans that smooth the concentration gradients inside the barn [31], another factor is the prevailing air direction, which is related to the downwind orientation of the building; therefore, even in the absence of fan activation, there is always a dilution of gas concentrations along the longitudinal axis of the barn due to the builder's choice of barn orientation.

Regarding the CO_2 concentrations, the main difference compared to NH_3 is that the CO_2 concentrations are mainly produced from animals in the AOZ, where SLB was located. Since the gas concentrations are diluted at that location due to the fans and the main air direction, the CO_2 concentration was the lowest in SLB, as can be found in the results of Table 1.

4.2. Performance of the Portable Device

The results of this study show that the analyzed portable device was found to be affordable only for measuring the NH_3 gas concentrations in SLs located close to the floor of the barn. However, it is well known that chemical sensors, such as those used as measurement analyzers in the portable devices to measure NH_3, suffer from saturation [32]. In fact, the results of the experiments carried out in this study (Figure 4a) showed a shift in the values of the NH_3 measurements; this effect produced overestimation at high values of the measured gas concentrations (Figure 4a).

With regard to the NH_3 measurements carried out in SLB and SLC, the high influence on the value produced by the air velocity and the distance of the source of production, both mentioned in Section 4.1, produced a reduction in NH_3. In detail, the portable devices underestimated the measurement by about 1 ppm for values of NH_3 below 2 ppm.

The results of the analysis on the measurements by portable devices are not satisfactory for CO_2 because the instrument produced high errors compared to the reference. Moreover, although the correlation between the CO_2 concentrations measured by the INNOVA analyzer and those measured by the portable device in SLB was 0.57, Figure 4c shows that the sensor for CO_2 was not accurate for application in dairy barns because the measurement value was overestimated. In detail, based on the matching of the monitored data with direct observation of herd management, it was found that the CO_2 concentrations increased quickly when the groups of cows were moved to the milking parlor; this CO_2 increase in the environment may be attributed to the movement of the air and also to a decrease in the performance of the infrared sensors due to ambient particulate matter. In this regard, further experimental analyses are required to confirm this conclusion.

Since CO_2 is generally used as a tracer gas to estimate emissions in this barn typology [33–35], the CO_2 measured by the Digitron is not adequate for this purpose because it increases uncertainty in the estimation.

Therefore, the use of the portable device can be reduced to gas concentration monitoring rather than emission estimation. The potential use of the Digitron device is thus related to the monitoring of NH_3 concentrations, especially when carried out by farmers. In fact, portable devices, thanks to their cheaper price compared to other instruments, can be acquired by farmers to measure gas concentrations in their barns. In fact, selfmonitoring of the barn environment by the farmer may provide information on exceeding the safety thresholds [13] for workers in the barn. Another application of the portable device may be the verification of the gas presence in the air to assess the application of mitigation strategies as well as the welfare conditions of the cows; in fact, in the literature, it was found that welfare conditions are related to animal breeding conditions [12,36].

The use of low-cost devices for monitoring purposes is not still common among farmers due to reduced information on safety regulations, but their application may increase awareness of the risks in livestock barns. Moreover, an effective design and fine-tuning of the low-cost devices may be promising as well for emission estimation with the consequence that current databases, models, and emission factors, based on all of the above data related to northern European contexts [37], can be updated.

5. Conclusions

The outcomes of this research study highlight that the specific barn structure, characterized by the absence of perimeter walls, influenced indoor conditions with effects on the distribution of gas concentrations along the vertical axis of the barn. Moreover, the presence of the cooling systems in both the feeding alley and the resting area was another factor that influenced gas distribution because it contributed to moving the air along the longitudinal axis of the barn.

This research study was carried out to assess the application of a low-cost device (SKY2000-M2, Digitron Italia, Ferentino (Fr), Italy) for monitoring NH_3 and CO_2 in open dairy barns. Statistical analyses were carried out to find out the relations among the acquired gas concentration values by applying a rigorous approach. Based on the results, the portable device could be used for the monitoring of NH_3 concentrations, whereas the device is not accurate enough for CO_2 to be adequate for the purpose.

The monitoring of gas concentrations at the housing level will make it possible to support farmers with barn management in order to increase the environmental performance of the farm as well as to improve animal welfare and quality of production. The use of low-cost devices for scientific purposes, provided that a specific design and fine-tuning are carried out, may be useful to investigate the emission production in contexts characterized by different barn typologies, housing systems, climatic conditions, and mitigation strategies that have not been investigated yet. Moreover, the application of low-cost devices may contribute to the estimation of emission factors in order to update emission inventories from the livestock housing systems monitored.

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