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Ammonia and greenhouse gas emissions from slatted dairy barn floors cleaned by robotic scrapers

Alessandro Chiumenti[1], Francesco da Borso[1], Andrea Pezzuolo[2*], Luigi Sartori[2], Roberto Chiumenti[1]

[1]*Department of Agricultural, Food, Environmental and Animal Sciences, University of Udine, Udine, Italy*
[2]*Department of Agroforesty and Landscape, University of Padova, Legnaro, Italy*

**Corresponding author: andrea.pezzuolo@unipd.it*

Abstract

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The design of animal housing and manure management systems are key factors in livestock farming. Frequent removal methods, in fact, allow for the reduction of gasses produced from fermentations of the organic matter contained in manure, that affect animal welfare and farmer health and are emitted from animal housings into the atmosphere as a consequence of ventilation. The present study aims to evaluate the performance of a Robotic Scraper (RS) operating on the floors in a full-scale, operative free-stall dairy barn. The research is focused on the evaluation of gaseous emissions from the two types of floors (concrete and rubber mat coated), and with and without RS operation. The floors with rubber coating demonstrated higher emission rates of ammonia (NH_3), carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) compared to the uncovered concrete floors, both before and after RS operations. The operation of RS, furthermore, determined significant reduction of greenhouse gasses (GHG) but did not have relevant effect in terms of NH_3 emission, which reduced only of 1.4% from concrete floors, but increase of 12.7% from rubber coated floors.

Keywords: animal housing; manure management; automatic cleaning systems; pollutant gasses; animal behaviour

The agriculture sector contributes significantly to the emission of pollutant gasses such as ammonia (NH_3), methane (CH_4), carbon dioxide (CO_2), and nitrous oxide (N_2O) (Monteny et al. 2006; Aneja et al. 2007; Basso et al. 2016; Pezzuolo et al. 2017a). In fact, in Europe approximately 80% of NH_3 emissions responsible for acidification of soil originates from livestock production (Webb et al. 2005; Boscaro et al. 2017); CO_2, CH_4, and N_2O, furthermore, are the most crucial greenhouse gasses (GHG) associated with livestock production systems (IPCC 2006; Cabaraux et al. 2009; Boscaro et al. 2015; Pezzuolo et al. 2015).

Manure management is an essential factor in livestock farming and special attention should be paid to all procedures, including removal of manure from animal houses, manure storage, treatments, and finally, land spreading (Chadwick et al. 2011; Pezzuolo et al. 2017b). The layout of animal housing and manure removal techniques, also have a relevant impact on indoor conditions of animal housings (Braam et al. 1997; Hamelin et al. 2010; Pereira et al. 2011; Da Borso et al. 2017). In fact, frequent manure removal allows minimization of the fermentations of the organic matter, reduces the volatilization rate of noxious gasses, reduces GHG emissions, and ultimately reduces the risk of severe lameness of dairy cows (Wu et al. 2012; Chapinal et al. 2013).

In Italy, automatic manure scrapers on solid floors are the most utilized equipment in dairy barns. Introduced with the main objective of re-

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ducing manual labour, automatic scrapers are installed in alleyways along the cubicles and the feed barrier and are frequently activated by a timer. A positive environmental effect, such as a demonstrated decrease of ammonia emissions is also obtained (Buck et al. 2013). However, the operation of mechanical devices for the removal of manure results in high energy consumption combined with wear of parts along with the tendency to show limited efficiency in terms of rapid and complete removal of liquid fractions. For this reason, currently in modern free stall farms, the solution with slatted floor and hydraulic removal of liquid manure, collected in channels underneath, is preferred (Chiumenti 2004). These systems show lower efficiency, however, in the removal of solids that tend to accumulate on the surface of the floor with eventual compaction and clogging of the openings of the slatted floor, and consequently, the reduction of its functionality. A possible solution to these problems is the utilization, as in the solid floor, of mechanical scrapers with negative impacts in terms of energy demand and costs.

Robotic scrapers (RS), instead, represent the most recent introduction among cleaning systems offered on a commercial scale. The RS are mainly used on slatted floors in order to facilitate the removal of the solid fraction of manure from the pavement which, otherwise, reaches the removal channels underneath with more difficulty than urine (Markus, Thorsten 2013). This innovative solution has not been studied thoroughly, especially with regard to environmental aspects.

The aim of the present study was to assess the environmental performance of a RS in terms of gaseous emissions from the slatted floor in a full-scale, operational dairy farm in Northern Italy.

MATERIAL AND METHODS

Animal management and experimental design. Test were performed in a full-scale, operative dairy farm in late winter into spring for a total of six months, in compliance with the daily operating activities of the farmer.

The dairy farm is located in Longa di Schiavon, Vicenza, North-Eastern Italy, with an average of 140 milking cows and 110 heifers. The yearly average milk production is 9,550 l per head, and animals are fed once a day by total mixed ration.

Fig. 1. Detail of the robotic scraper operating on the concrete slatted floor

The structure of the barn has a metal frame without side walls in order to improve air circulation in the hot months.

High volume, low speed fans are installed on the roof to enhance the comfort of animals in the summer. The roof is insulated and features a top-central opening.

The floor of the alley is completely slatted and partially lined with rubber mats. Manure is collected in channels located underneath, and the removal of manure is performed once a day by recirculation of manure from the storage tank. Liquid manure from a storage tank is flushed into channels under slatted floor, removing the fresh manure collected underneath the floor of the barn.

The floor of the animal housing is kept clean by an automated scraping system represented by a robot model Discovery (Lely, the Netherlands) which is self-propelled and powered by electric motors connected to a 12V gel battery. The robot (Fig. 1), performs the cleaning of the floor by means of an inclined scraper installed in the front of the machine that functions by pushing manure against the floor allowing it to fall through the openings. The advance speed is 9–18 m/min, and the operating width is 880 mm. The machine features an ultrasonic sensor for guidance along the walls and is accompanied by a front ring for direction change when a frontal object is detected.

Data collection. Ambient temperature and humidity were monitored in the centre of the stable (Fig. 2) by a portable meter Model 3000 (Kestrel, USA). The emissions of pollutant gasses such as ammonia (NH_3), methane (CH_4), carbon dioxide (CO_2), and nitrous oxide (N_2O) were determined in order to assess the environmental benefits of the

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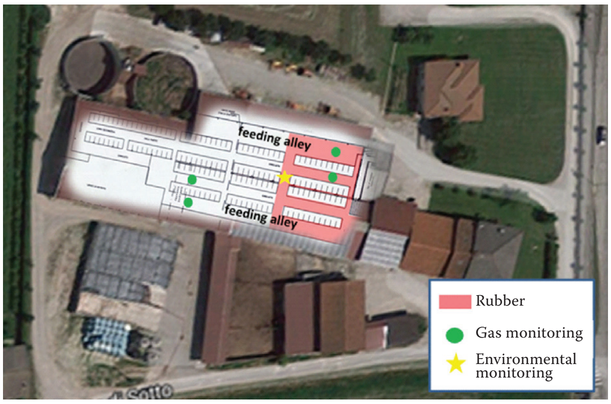

Fig. 2. Layout of the farm and location of gas monitoring and environment monitoring points, with detail of the rubber floor

RS. Considering that the objective was to assess the emissions from the floor, not from the entire barn, the emissions of these gaseous compounds were determined directly from the slatted floor by the closed chamber method, a method widely documented in literature and used to measure the emissions from various emitting surfaces, including solid or liquid (Sommer et al. 2004; Chiumenti et al. 2007, 2009, 2015; Horowitz et al. 2013; Park et al. 2014). The closed chamber method is based on the determination of the increasing rate of gas concentration versus time inside a chamber positioned on the emitting surface, avoiding any influence of air fluxes. The concentration typically demonstrates a linear increasing trend followed by a saturation phase as depicted in the example reported in Fig. 3.

The specific flow of the monitored gas (F_{gas}), also defined as emissivity (mg·m^{-2}·h^{-1}), is obtained by the following equation:

$$F_{gas} = \frac{dC}{dt} \times \frac{V}{A}$$

where: dC – variation of the concentration of the monitored gas in the time interval (mg·m^{-3}); dt – time interval (h); V – inner volume of the static chamber (m^3); A – base area of the chamber, and hence, the emitting area (m^2)

The chambers used to cover the surface of the floor were made of Polyethylene (PE) with a volume of 0.029 m^3 and dimensions of 0.33 m width, 0.50 m length and 0.18 m height with an area of 0.165 m^2 (Fig. 4). The dimensions of the chambers were comparable to other studies reported in literature: Baldini et al. 2012, for example, utilized a static chamber with a base of 0.174 m^2. Concentrations of gasses were determined by two photoacoustic multi-gas analysers (BK1302 Bruel & Kjaer, Denmark) sampling air from the chambers by PTFE pipes. PE was adopted in several preliminary tests proved to be reliable considering the high emissivity of the surface (covered with manure and urine), the limited measuring time (about 10 min) and the limited internal surface compared to the covered emitting area. The sampling points are reported in Fig. 2. This method was considered more practical and accurate in the operative conditions of the analyses compared to other methods, such as the ventilated tunnel. In fact, we declined to implement the ventilated tunnel for the following reasons:
- necessity of sucking air from a "clean ambient", which excludes a barn with animals;
- waiting until a stable air flow is reached, which determines longer measuring times (which can be a problem operating in a farm with animals);

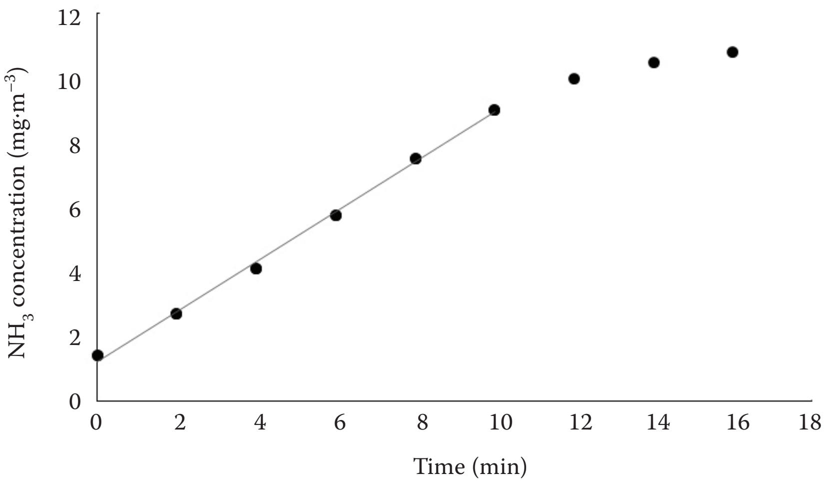

Fig. 3. Typical concentration plot used for the determination of the emissivity by the closed chamber method

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Fig. 4. The photoacoustic gas analyzers (a) and the static chambers (b) used to determine the emissions from the floor. It is possible to see the PE paddings used to close the openings of the slatted floor

– a tunnel over a slatted floor determines the suction of air from the channels underneath the floor; therefore, negatively affecting the measurements.

The measuring locations were chosen according to floor type and in the same area of the barn (same group of animals) in order to avoid variables. To asses a comparison of scraped and non-scraped conditions, the farmer must stop the robot and isolate the animals to allow for the recording of the measurement. It should also be considered that the livestock can consume the sampling pipe, trample the instruments and chambers, as well as the researchers. This type of intrusional activity must comply with farmer's daily operational activities.

Preliminary tests. The static chamber measurement method implemented on a slatted floor determines the aspiration, through the openings, of gasses originated by the manure collection tank located under the surface. In normal conditions, emissions are derived from the floor and from the openings, but to determine the emissions from the floor, openings must be closed. The emissions from below, in fact, are part of the system but are not influenced by the action of the RS. For this reason, preliminary tests were focused on the evaluation of the contribution to the emissions sorted by the solid portion of the slatted floor in comparison to the combination of the emissions from the floor and those deriving from the manure collection channels located underneath. It was possible to determine the contribution solely of the solid portion of the pavement by closing the openings by special PE foam paddings in order to isolate the floor from the tanks (Fig. 5). Preliminary tests were performed on conventional floor (concrete), with continuous presence of animals and without scraping of manure.

Robotic scrapers tests. After the preliminary phase, measurements were always performed by closing the openings with the objective of evaluating the emissions solely from the solid surface of the floor. In order to evaluate the effect on the emissions sorted by the RS, measurements were made immediately after the cleaning and at 5 h from scraping. It was not possible to extend measurements to more than 5 h of pause of the scraper as this would have resulted in an excessive accumulation of manure produced by animals requiring manual cleaning operations. This is a difficulty related to the fact that the monitoring was performed on a full- scale, operational farm, with the possibility of obtaining operative results, but also with the necessity of allowing the farmer to complete his tasks efficiently. Measurements were performed in the alleys in different locations of the barn (Fig. 2)

Fig. 5. Detail of the rubber liner used on top of the slatted floor in some areas

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in order to compare the effect of the RS on *concrete* floor and on the floor lined with *rubber* mat.

Descriptive statistical analysis was adopted considering that it was not possible to determine the emission on several parcels of floor because of the need of compromising with the activity of the farmer and with animal welfare. The measurements were performed in two selected areas, homogeneous in terms of animal load, with 3 repetitions for each detection. The data provided represents average measurements in the various locations.

RESULTS AND DISCUSSION

Manure was characterized by the total solids content (TS) of 8.5%, a volatile solids content (VS) of 85.3%TS, a pH of 7.34 and total nitrogen concentration of 3,500 mg·l^{-1}.

The tests were performed with ambient temperature ranging from 18°C to 22°C and air humidity from 47.8% to 56.0%.

Preliminary tests

The fluxes of monitored gasses from the entire surface, including slats and slots (f + t), resulted higher than fluxes solely from slats (f) (Fig 6). This result can be explained considering that manure temporarily stored in the channels determines the emission of NH_3 deriving from urine degradation, and, furthermore, is subject to fermentations with the production of NH_3 and N_2O, due to the degradation of organic nitrogen of proteins, accompanied by CO_2 and CH_4 derived from the anaerobic degradation of the organic fraction (figure 6).

In fact, average NH_3 comprehensive emission resulted in 12.8 mg·h^{-1}·m^{-2}, while the emission rate from the floor resulted in an average of 7.4 mg·h^{-1}·m^{-2}. For this gas, it is evident that the contribution of the emission from channels is relevant, 42.2% in particular, as consequence of the volatilization of NH_3 in gaseous form present in manure. The global emissivity of NH_3 measured in the alleys with slatted floor resulted slightly lower than that reported by Baldini et al. (2012) in the range 14.1–15.8 mg·h^{-1}·m^{-2}. The emission rate of CH_4 from floor and tank showed average of 39.9 mg·h^{-1}·m^{-2}, while, emission rate from the floor resulted of 17.9 mg·h^{-1}·m^{-2} corresponding to 44.9% of the total. This gas is typically formed as consequence of presence of organic matter subject to anaerobic fermentations in stored manure.

As far as N_2O is concerned, average emission rates were 0.43 mg·h^{-1}·m^{-2} (from the floor) and 0.75 mg·h^{-1}·m^{-2} (from the floor and the tank). These differences appeared to be significant for all gasses except CO_2, which showed emission rate of

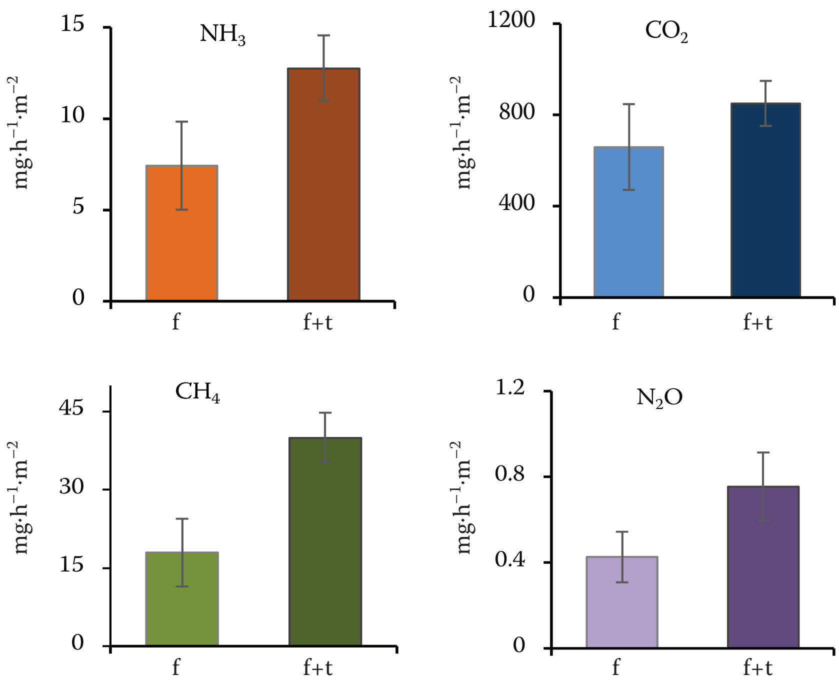

Fig. 6. Emission rates from the solid slats of the floor (f) and global emissions from the slotted floor and manure tank underneath (f + t); the vertical bars represent standard errors

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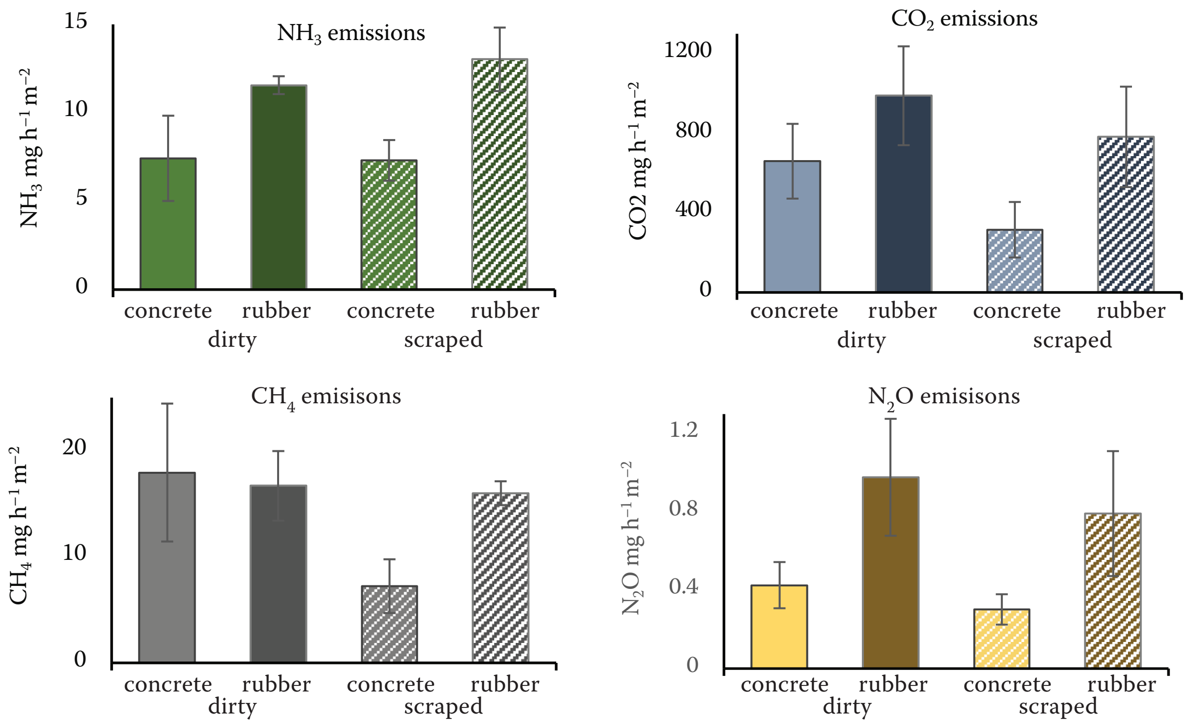

Fig. 7. Emission rates from concrete and rubber coated concrete floors, with RS not operating (dirty) and immediately after the cleaning (scraped); the vertical bars represent standard errors

659.5 mg·h^{-1}·m^{-2} to 850.5 mg·h^{-1}·m^{-2} from floor and floor + tank, respectively.

Furthermore, emissivity data of different gasses demonstrated a wider range of variability in the measurements performed with closed openings as consequence of the variable quantity of manure present on the surface.

Robotic scrapers tests

The operation of the RS did not determine significant effects in terms of NH_3 emission reduction (Fig. 7). The emissivity from scraped concrete floor ranged from 4.8 to 11.0 mg·h^{-1}·m^{-2} with average of 7.3 mg·h^{-1}·m^{-2} compared to a range from 2.0 to 15.2 mg·h^{-1}·m^{-2} with average of 7.4 mg·h^{-1}·m^{-2} of the same type of floor without scraping. On rubber coated floor, instead, the operation of the RS determined an increase of the emissivity from average of 11.6 mg·h^{-1}·m^{-2}, with max. of 12.5 mg·h^{-1}·m^{-2} and min. of 10.5 mg·h^{-1}·m^{-2}, to an average emissivity of 13.0 mg·h^{-1}·m^{-2}, with maximum of 15.6 mg·h^{-1}·m^{-2} and min. of 8.9 mg·h^{-1}·m^{-2} after scraping. As a matter of fact, the use of scrapers can increase NH_3 emissions as reported by Sommer et al. (2006), because the thin layer of slurry retained by the floor is a significant source of NH_3.

The emission rate of CO_2 from concrete floor before RS operation ranged from 228.9 to 1,246.7 mg·h^{-1}·m^{-2}, average of 659.5 mg·h^{-1}·m^{-2}, and from 80.9 to 1,046.8 mg·h^{-1}·m^{-2}, with average of 315.1 mg·h^{-1}·m^{-2} after cleaning. Alternatively, for the rubber coated floor, the emission rate of CO_2 before RS operation ranged from 475.0 to 1,467.0 mg·h^{-1}·m^{-2}, with average of 988.6 mg·h^{-1}·m^{-2}, and from 387.5 to 1,351.0 mg·h^{-1}·m^{-2}, with average of 781.8 mg·h^{-1}·m^{-2} after scraping.

RS operation determined significant reduction of emissivity only on the concrete floor, in relation to CO_2, with a reduction of 52.2% compared to a reduction of 20.9% in the case of the rubber floor and to CH_4, with a reduction of 59.7% compared to 4.1%.

In detail, the emission rate of CH_4 from the concrete floor before RS operation ranged from 3.9 to 39.8 mg·h^{-1}·m^{-2}, with average of 17.9 mg·h^{-1}·m^{-2}, and from 2.1 to 16.1, with average of 7.2 mg·h^{-1}·m^{-2} after cleaning. However, for the rubber coated floor, the emission rate of CH_4 before RS operation ranged from 10.7 to 23.7 mg·h^{-1}·m^{-2}, with average of 16.7 mg·h^{-1}·m^{-2}, and from 13.6 to 18.0 mg·h^{-1}·m^{-2}, with average of 16.0 mg·h^{-1}·m^{-2} after scraping.

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Concerning N_2O emissions, reductions from 0.43 to 0.30 mg·h^{-1}·m^{-2} and from 0.98 to 0.79 mg·h^{-1}·m^{-2} were observed in concrete and rubber coated floors, respectively, corresponding to reductions of 30.2% and 19.4%.

For the monitored gasses, except for CH_4, emissivity resulted higher in the areas equipped with the floor covered with rubber mat, both in the duration of operation or pause of the RS. Furthermore, the operation of the RS systems seemed to accentuate the difference between the two floors, in favour of the uncovered concrete type.

These indications are in contrast with the results obtained by other authors (Baldini et al. 2012) that present, on the contrary, that the use of rubber mat on a solid concrete floor of walking areas could enhance the cleaning efficiency of the conventional scrapers. However, Baldini et al. (2012) monitored the emissions from a rubber floor resulting more smooth than concrete, retaining less liquid (containing ammonia) than in concrete.

In our case, instead, the rubber floor was less uniform, presenting channels that, on one side, prevent livestock from slipping, and on the other side, retain liquid (containing ammonia) and hence emissions are increased.

In general, furthermore, scientific literature is lacking in experimental results concerning the slotted floor covered with rubber mat. As previously cited, the variability of data did not provide for underlining significant differences before or after RS operations. It is evident, however, that besides NH_3, RS cleaning operation determined positive effects specifically on the floors not covered by rubber.

CONCLUSION

The purpose of the present study was to evaluate the environmental performance of a Robotic Scraper (RS) in terms of emission of gasses from the slatted floor.

The reduction of emissivity determined by the operation of RS resulted more profoundly on concrete floor for, in respective order: CH_4, CO_2, and N_2O. Rather, the operation of RS did not demonstrate any significant reduction of the emissions of NH_3. The RS, in reality, scrapers mainly the solid fraction and determines the spreading on the entire surface of the urinary fraction, thereby increasing the exposure to air for prolonged periods.

The portions of the floor equipped with rubber cover indicated higher emissivity, that could be explained as a consequence of the prolonged drying times, increase of roughness of the surface due to aging of the material, and lastly, a higher use by cows for ambulation, with consequent increased deposit of manure. An aspect that should be subject to further investigation is the eventual difference in temperature of the different type of floors.

The RS system exhibited, in general, promising potential in terms of reduction of GHG from the floor of livestock housings. In the future, the study should focus on further aspects, including energy consumption, the interaction with animals, and the microbiological quality of milk in comparison to traditional cleaning systems.

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