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Original article

Emissions of ammonia, nitrous oxide, methane, carbon dioxide and water vapor in the raising of weaned pigs on straw-based and sawdust-based deep litters

Baudouin NICKS*, Martine LAITAT, Marc VANDENHEEDE, Alain DÉSIRON, Claire VERHAEGHE, Bernard CANART

Service d'Hygiène et Bioclimatologie, Faculty of Veterinary Medicine, University of Liège, 4000 Liège, Belgium

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Abstract — Five successive batches of 40 weaned pigs were raised on deep litter of sawdust or straw without changing the litter in between batches. The quantity of litter dry matter utilized in the two cases was 5 kg per pig. The concentrations of gases were measured 8 times, at about one-month intervals, for 6 consecutive days and the ventilation flow was recorded continuously. Pig raising on sawdust-based litter differed from that with straw by an emission of 2.6 times less ammonia (0.46 vs. 1.21 g per pig per day), 2.1 times less methane (0.77 vs. 1.58 g per pig per day), 3.9 times more N_2O (1.39 vs. 0.36 g per pig per day), 4% more CO_2 (481 vs. 463 g per pig per day) and 21% more H_2O (1126 vs. 933 g per pig per day). All differences were significant. About 58% of the nitrogen excreted by the pigs was recovered in the gas form and for the two litters, about 79% in the form of N_2.

weaned pig / ammonia / nitrous oxide / methane / carbon dioxide

Résumé — Emissions d'ammoniac, de protoxyde d'azote, de méthane, de gaz carbonique et de vapeur d'eau lors d'élevage de porcelets sevrés sur litière accumulée de paille et de sciure. Cinq lots successifs de 40 porcelets sevrés ont été élevés sur une litière accumulée de paille ou de sciure sans que la litière ne soit changée entre les lots. La quantité de matière sèche de litière utilisée a été dans les deux cas de 5 kg par porcelet. Les concentrations en gaz ont été mesurées 8 fois à environ 1 mois d'intervalle durant 6 jours consécutifs et le débit de ventilation a été enregistré en continu. L'élevage des porcelets sur litière accumulée de sciure s'est différencié de celui sur litière accumulée de paille par une émission d'environ 2,6 fois moins d'ammoniac (0,46 vs. 1,21 g par porcelet par jour), 2,1 fois moins de méthane (0,77 vs. 1,58 g par porcelet par jour), 3,9 fois plus de N_2O (1,39 vs. 0,36 g par porcelet par jour), 4 % de plus de CO_2 (481 vs. 463 g par porcelet par jour) et 21 % de plus

* Correspondence and reprints
Tel.: 00 32 4 366 41 45; fax.: 00 32 4 366 41 22; e-mail: Baudouin.Nicks@ulg.ac.be

d'H_2O (1126 vs. 933 g par porcelet par jour). Toutes les différences sont significatives. Environ 58 % de l'azote (N) rejeté par les porcelets était sous forme gazeuse et, pour les deux litières, à raison de 79 % sous forme de N_2.

porcelet sevré / ammoniac / protoxyde d'azote / méthane / gaz carbonique

1. INTRODUCTION

The collection of wastes in the form of solid manure with litter presents various environmental advantages compared to liquid slurry such as: a reduction in the weight of wastes collected [21–23], a decrease in the amount of nitrogen in the wastes [17, 21, 24] and a decreased olfactory nuisance [3, 10, 14]. The weight reduction, which can reach 80% for deep litters of sawdust, is the result of the evaporation of almost all the water in the wastes [23, 24]. The diminution of the nitrogen content of the wastes results in the emission of atmospheric nitrogen (N_2), ammonia (NH_3) and nitrous oxide (N_2O) [13, 15].

N_2 emission does not have any negative influence on the environment, but that does not hold true for NH_3 and N_2O. NH_3 is well known as a toxic gas irritating the respiratory tract and plays an important role in acid deposition [8]. N_2O is one of the so-called greenhouse gases and has an atmospheric warming potential 310 times greater than that of CO_2 [2]. The quantification of the emissions of these three gases from deep litters is of prime importance for determining the importance of their effect on the environment.

The transformation of organic material in litters is also accompanied by the release of carbon in the form of carbon dioxide (CO_2), methane (CH_4) and other organic gases [16]. CO_2 and CH_4 both contribute to the greenhouse effect, with the atmospheric warming potential of CH_4 being 21 times greater than that of CO_2 [2].

The use of deep litter is quite different depending on whether the litter is sawdust or straw. Those composed of sawdust can be subjected to regular aeration by spreading and mixing the waste over all the area occupied by the pigs [14, 18]. Such a task is not possible with straw-based litters, since the manure is too compact [19].

Little data is currently available on the emissions of gases from deep litters utilized in pig production, with most of the results referring to ammonia emissions from pig houses with slatted floors where wastes are collected in the form of slurry [7, 9, 20]. The aim of this study was to quantify the emissions from deep litters composed either of straw or of sawdust. Such data are needful to evaluate the effects of rearing pigs on deep litters on air pollution.

2. MATERIALS AND METHODS

2.1. Experimental rooms

Two identical rooms with an area of 30 m^2 and a volume of 103 m^3 were arranged to house 40 piglets on a deep litter of sawdust in one and on straw in the other one. The area accessible to the pigs was 21.6 m^2, that is 0.54 m^2 per animal. Each room was ventilated with an exhaust fan and the ventilation rate was adapted automatically to maintain a constant ambient temperature. Fresh air entered through an opening of 0.34 m^2 which was connected to the service corridor of the building; the outside air was thereby prewarmed before entering the experimental rooms.

The air temperatures of the two rooms and the corridor were measured automatically every hour. The ventilation rates were measured continuously and the hourly means were recorded with an Exavent apparatus

(Fancom®) with an accuracy as specified by the manufacturer, of 35 $m^3 \cdot h^{-1}$, i.e. 1% of the maximum ventilation rate of the fan.

2.2. Animals and feed

In each room, five successive batches of 40 pigs were raised on the same litter, without changing the litter in between batches. All the pigs originated from the same farrowing herd and were divided into two homogeneous groups according to sex and body weight. The pigs were fed ad libitum. Upon their arrival, they were given a transition feed (baby starter) which after 5 to 10 days was gradually replaced by a post-weaning feed (starter). Crude protein, lysine and crude fiber contents measured for the baby starter were, respectively, 17.2, 1.18 and 4.0% and those for the starter 18.1, 1.24 and 4.4%. The pigs were weighed individually at the beginning and at the end of the experimental period. The quantities of feed ingested and water consumed were determined per batch.

2.3. Characteristics of the litters

Before the arrival of the first animals, a 30-cm layer of litter was installed in each pen. The quantities utilized were respectively 2440 kg of sawdust with dry matter (DM) content of 41% and 402 kg of wheat straw (88% DM). The sawdust was mostly composed of particles with a diameter of 0.2 to 2.0 mm, which represented 80% of the weight. Depending on the cleanliness of the pigs, supplementary amounts of straw were provided regularly, which was not necessary with the sawdust-based litter.

A 30 cm sawdust depth is a minimum to get a temperature increase into the litter, an increase required for the beginning of an in situ composting process. A 30 cm depth represents an amount of sawdust of 61 kg per pig place (2440 kg per 40 places). This amount is very high so, to decrease it and to lower the litter cost per pig, it is recommended to keep the same litter for several batches. One could fear sanitary problems but if all the pigs of the successive batches come from the same farrowing herd, the risk is limited and can be easily controlled. With straw, it is also recommended to keep several batches on the same litter in order to decrease the litter cost per pig. Of course with this technique, the gaseous emissions resulted both from the aging of the litter and from the evolution of the mass and metabolism of pigs during their stay.

About every 10 days, wastes from the pigs raised on sawdust were dispersed over all the area of the pen and incorporated manually, which was not done with the straw-based litter. In addition, to avoid an excessively high concentration of dust in the air, it was necessary to moisten regularly the sawdust-based litter. The amount of water added was 0.4 L per pig per week.

In each pen, the temperature of the litter was measured at a depth of 20 cm, 2 times a week in 4 spots. At the end of the experiment, the litters were weighed and analyzed.

2.4. Measurement of gas emissions

The concentrations of gases in the air in the two experimental rooms and the corridor supplying fresh air were measured with an apparatus from Innova Air Tech Instruments (1312 Photoacoustic Multi-gas Monitor) equipped for the measurement of NH_3, N_2O, CH_4, CO_2 and H_2O. The air in the experimental rooms was sampled upstream of the exhaust fan and that of the corridor at 1 m from the air inlet.

Because of technical problems encountered at the start of the experiment, it was not possible to measure gas concentrations during the stay of the first batch of pigs. Subsequently, the concentrations were measured 6 times at about one-month intervals and for 4 or 6 consecutive days respectively. The 6 series of measurements occurred in the middle of the stay of the second batch, the beginning and the end of the stay of the third, the middle of the stay of the fourth batch and at the beginning and end of the stay of the fifth batch.

In the absence of data for the first batch, a complementary study was conducted on a single batch of pigs by utilizing the same rooms and the same quantities of fresh litter, which was utilized at the start of the main experiment. In this complementary study, the emissions of gases were measured at the beginning and at the end of the stay of the pigs. The results were considered as equivalent to those which would have been obtained in the main study and the means were calculated taking into account the 8 series of measurements. The performance of the piglets in the complementary study was of the same order of magnitude as those obtained in the main study and are not presented.

The Multi-gas monitor was programmed by conducting a cycle of 3 measurements every half-hour, once every 10 minutes, the air being sampled successively in the room with the straw-based litter, the room with the sawdust-based litter and the corridor. So, for each localization, 2 air samplers were analyzed per hour.

The emissions were calculated on an hourly basis taking the hourly concentration as the average of the two measurements performed per hour at each location. The emissions were expressed in $mg \cdot h^{-1}$ utilizing the following formula:

$$E = D \times (C_i - C_e)$$

with D, the hourly mass flow ($kg\ air \cdot h^{-1}$); C_i and C_e the concentrations of gas in the air of the room or corridor ($mg \cdot kg^{-1}$ dry air).

The mean emissions per pig per day were calculated for each series of measurements. The cumulative emissions of nitrogen (Nc) in the form of NH_3 and N_2O were determined using the relation $Nc = 14/17 \times NH_3$ emission $+ 28/44 \times N_2O$ emission.

In order to estimate the N_2 emissions, the nitrogen balance was calculated taking into account the litter nitrogen content and the N incorporated by the pigs. The pig N retention was calculated from the daily weight gain and protein content of that gain [7].

2.5. Statistical analyses

For each batch the differences in emissions with regards to the litter utilized (straw or sawdust) were tested using an analysis of variance with one criterion (nature of the litter) for batches 2 and 4 and by utilizing an analysis of variance with 2 criteria, the nature of the litter (1 d.f.) and time of measurements (1 d.f.) for batches 1, 3 and 5, for which 2 series of measurements were available (at the beginning and at the end of the stay of the pigs).

The differences among batches were tested by taking the data of batches 1, 3 and 5 and comparing them 2 by 2. The data were treated separately for the piglets raised on straw and on sawdust, on the basis of an analysis of variance with 2 criteria: time of measurements (1 d.f.) and batch (1 d.f.).

The combined data obtained with the 5 batches were compared by utilizing an analysis of variance with 2 criteria: the nature of the litter (1 d.f.) and time of measurements (7 d.f.).

3. RESULTS

3.1. Climatic characteristics of the rooms

The mean air temperature was 23.7 °C in the room with the straw-based litter (Lst), 23.0 °C in the room with the sawdust-based litter (Lsa) and 18.9 °C in the corridor bringing in fresh air. Between the successive batches, there was no significant difference in the room temperatures. Because of the disposition of the two rooms in the building, thermal leakage through the walls was greater for Lsa compared to Lst. That is the reason for which the ventilation flow, being controlled by a thermostat, was systematically a little lower in Lsa than in Lst, with means (± SD among batches) of 537 ± 120 and 587 ± 118 $m^3 \cdot h^{-1}$, respectively.

3.2. Performances of the pigs

Table I presents the performances of the animals. The average daily gain (ADG) was 399 g, the feed conversion ratio 1.79 and the quantity of water consumed 2.56 $L \cdot kg^{-1}$ of feed, without any significant differences between the piglets raised on straw or sawdust.

3.3. Characteristics of the litters

The total amount of straw used for the rearing of the 5 batches was 1148 kg. Overall, 5.74 kg of straw per pig raised was required (1148/200 pigs), or 5 kg of straw DM, a value equivalent to the amount of DM of sawdust utilized per pig in the other room. The same amount of manure was removed from the two rooms, that is 3380 kg or 16.9 kg per pig at 31.5% DM for the straw based litter and 37.5% for the sawdust based litter (Tab. II). The straw-based litter contained more nitrogen than that of sawdust (+30%) and a much greater proportion of NH_4^+-N (14.3 vs. 2.5%). The average temperature of the litter was 36.0 °C with the straw and 34.4 °C with the sawdust. A temperature greater than 30 °C was observed in the two litters 4 weeks after the arrival of the first batch of pigs.

3.4. Gas emissions

Table III displays the mean values of gas emissions expressed per pig and per day. Pig raising on sawdust differed from that on straw by a 2.6 times lower emission of NH_3 ($P < 0.001$), 2.1 times lower for CH_4 ($P < 0.001$), 3.9 times greater for N_2O ($P < 0.001$), 21% more H_2O ($P < 0.001$) and 4% more CO_2 ($P < 0.05$). N emissions in the form of NH_3 and N_2O (NH_3-N + N_2O-N emissions) were not statistically different with regards to the room of origin.

The analyses conducted for each batch show that the differences in emissions with

Table I. Effect of type of litter on performance of piglets (mean + SD among batches).

	Straw	Sawdust
Number of pigs[1]	200	200
Initial weight (kg)	7.65 ± 0.31	7.65 ± 0.32
Final weight (kg)	24.63 ± 2.77	24.81 ± 2.13
Losses (%)	2.5 ± 0.9	2.5 ± 0.9
Daily weight gain (g)	397 ± 40	402 ± 28
Length of stay (days)	42.6 ± 2.1	42.6 ± 2.1
Feed conversion ratio	1.80 ± 0.04	1.79 ± 0.04
Water drunk (L) per pig per day	1.86 ± 0.19	1.81 ± 0.25
per kg of feed	2.61 ± 0.20	2.50 ± 0.26

[1]: 5 successive batches of 80 piglets per batch, 40 raised on sawdust and 40 on straw.

Table II. Composition of the litters at the end of the experiment.

	DM (%)	Total N ($g \cdot kg^{-1}$)	NH_4^+-N ($g \cdot kg^{-1}$)	C ($g \cdot kg^{-1}$)	pH
Straw	31.5	12.4	1.77	87	8.1
Sawdust	37.5	9.4	0.24	91	8.4

DM: dry matter; N: nitrogen; NH_4^+-N: ammonium nitrogen; C: carbon content.

regards to the type of litter were significant for each of them except for the emissions of NH_3 in batch 1, of CO_2 for batches 2, 3 and 5 and of H_2O for batch 4.

The comparison of the emissions from batches 1 and 3 shows that all the differences were significant ($P < 0.05$), with the exception of those for NH_3 and CO_2 in the room with straw. The differences between batches 3 and 5 were also for the most part significant ($P < 0.05$), with the exception of the emissions of CO_2 in the two rooms and those of CH_4 and H_2O in the room with the sawdust-based litter. This indicates that all types of emissions did not develop in the same way with the aging of the litter. Some increased regularly, as for example, the emissions of CH_4 in the straw room, while others such as the emission of N_2O in the room with sawdust increased during the first period (from batch 1 to 3) and decreased subsequently (from batch 3 to batch 5).

The analysis of the daily development of the emission of N_2O showed that the watering of the sawdust-based litter was accompanied by a rapid and substantial increase of 300 to 800% for this gas, which then fell gradually back to its initial level after 1 to 2 days. The wetting of the litter did not have any effect on the emissions of the other gases.

In the room with the straw, the supply of fresh straw induced a rapid lowering of the concentration of NH_3 to about 50%, which returned to the initial level after 12–24 h.

Table IV shows the nitrogen balance. About 58% of the nitrogen excreted by the pigs was recovered in the form of gases, and for the two litters about 79% in the form of N_2.

4. DISCUSSION

The weight of the manure collected at the end of the experiments, that is 16.9 kg per pig, and the quantity of N contained in the wastes, an average of 185 g N per pig for the two litters, confirmed previous results which showed a reduction of up to 80% of the mass of wastes produced and from 50 to 60% of the nitrogen content compared to the collection of wastes in the form of slurry [23, 24]. The values taken for reference for this comparison are a production of 80 L of slurry per pig with a total N content of 440 g [26].

The emission of NH_3 from piggeries with slatted floors is estimated to be 23% of excreted nitrogen [7]. In this experiment, the N-excreted was 418 g per pig. Thus, one would have expected a rate of production of 117 g per pig (with pigs raised on slatted floors). Yet, it was only 20 g per pig from the sawdust-based litter and 52 g per pig from the straw-based litter. With fattening pigs, Hoy et al. [11, 12] and Kermarrec [15] showed, respectively, a reduction of 35 and 50% of the emissions of NH_3 in pig raising on sawdust-based litter compared to that on slatted floors. Our data show that this reduction may be even more substantial; however, one should not generalize the results obtained with weaned pigs to the raising of fattening pigs.

The quantity of N lost from the litters in the form of gases was 248 g per pig with straw and 265 g with sawdust. In the two

Table III. Gas emissions (per pig and per day) in the raising of 5 batches of weaned pigs on deep litter of straw or on sawdust: mean values, RSD and test for statistical difference between the litters (T).

		Straw pen	Sawdust pen	RSD	T
Batch 1 n = 2 BW = 17.1	NH_3 (g)	0.98	0.85	0.056	NS
	N_2O (g)	0.00	0.44	0.022	***
	N_c (g)	0.81	0.98	0.046	*
	CH_4 (g)	0.98	0.45	0.058	***
	CO_2 (kg)	0.48	0.53	0.011	**
	H_2O (kg)	1.00	1.24	0.019	***
Batch 2 n = 1 BW = 14.6	NH_3 (g)	1.62	0.29	0.144	***
	N_2O (g)	0.33	1.74	0.178	***
	N_c (g)	1.54	1.35	0.174	NS
	CH_4 (g)	0.85	0.51	0.055	**
	CO_2 (kg)	0.40	0.43	0.021	NS
	H_2O (kg)	0.77	1.11	0.080	*
Batch 3 n = 2 BW = 15.3	NH_3 (g)	0.79	0.18	0.022	***
	N_2O (g)	0.63	2.40	0.392	**
	N_c (g)	1.05	1.67	0.246	NS
	CH_4 (g)	1.26	1.01	0.068	*
	CO_2 (kg)	0.43	0.45	0.009	NS
	H_2O (kg)	0.73	0.94	0.064	*
Batch 4 n = 1 BW = 16.0	NH_3 (g)	0.69	0.17	0.062	***
	N_2O (g)	0.51	1.88	0.266	**
	N_c (g)	0.90	1.34	0.166	NS
	CH_4 (g)	2.10	0.46	0.042	***
	CO_2 (kg)	0.50	0.45	0.014	*
	H_2O (kg)	0.95	1.02	0.056	NS
Batch 5 n = 2 BW = 17.9	NH_3 (g)	1.57	0.45	0.068	***
	N_2O (g)	0.43	0.86	0.052	***
	N_c (g)	1.57	0.92	0.062	***
	CH_4 (g)	2.52	1.12	0.064	***
	CO_2 (kg)	0.41	0.43	0.012	NS
	H_2O (kg)	0.94	1.06	0.026	**
Batch 1 to 5[1] n = 8 BW = 16.2	NH_3 (g)	1.21	0.46	0.031	***
	N_2O (g)	0.36	1.39	0.099	***
	N_c (g)	1.23	1.26	0.067	NS
	CH_4 (g)	1.58	0.77	0.028	***
	CO_2 (kg)	0.46	0.48	0.006	*
	H_2O (kg)	0.93	1.12	0.021	***

n = number of series (6 days per series); BW = (initial body weight + final body weight)/2 (kg); [1] mean for 8 series of measurements; NH_3: ammonia; N_2O: nitrous oxide; Nc: cumulative emissions of ammonia nitrogen and nitrous oxide nitrogen; CH_4: methane; CO_2: carbon dioxide; H_2O: hydrogen oxide; RSD: residual standard deviation; *: $P < 0.05$; **: $P < 0.01$; ***: $P < 0.001$; NS: not significant.

cases, 79% of the N was emitted in the form of N_2. The remaining 21% was divided into 17% NH_3-N and 4% N_2O-N with the straw-based litter, and 6% NH_3-N and 15% N_2O-N with the sawdust-based litter. It is probably the state of aeration that accounts for this difference, being higher in the sawdust-based litter compared to that with

Table IV. Nitrogen balance of the raising of 5 batches of pigs on a straw-based and a sawdust-based deep litter (g N per pig).

	Supply-N		Retained-N	Litter-N	Gas-N		
	Litter-N	Feed-N			NH_3-N	N_2O-N	N_2-N
Straw	40	850	432	210	43	10	195
Sawdust	7	850	432	160	16	38	211

N: nitrogen; NH_3-N: ammonia nitrogen; N_2O-N: nitrous oxide nitrogen; N_2-N = supply N- (retained-N + litter-N + NH_3-N + N_2O-N).

straw. Kermarrec [15] has shown that the aeration of sawdust-based litter strongly stimulates the release of N_2O. N_2O is rarely included in the analyses of emissions from slurries since it is often considered negligible. Kermarrec [15] noted, however, for fattening pigs a production of 0.73 $g \cdot day^{-1}$. This value is higher than that observed in this study with the straw-based litter (0.35 $g \cdot day^{-1}$) and lower than that measured with the sawdust-based litter (1.40 $g \cdot day^{-1}$). The increase in emissions of N_2O after moistening the litter, as observed in the present study, is also mentioned by Kermarrec [15].

The emissions of CH_4 can originate directly from the digestive tract of pigs, but also from the anaerobic decomposition of wastes. The production by the pigs is related to the amount of gross energy intake [5, 25] of which about 0.6% is eliminated in that form [5]. On the basis of a feed gross energy content of 16.6 $MJ \cdot kg^{-1}$ and on a consumption per pig of 715 $g \cdot day^{-1}$ in this experiment, an emission of 1.3 $g \cdot day^{-1}$ could be expected. In piggeries with partially slatted floors for weaned pigs, CH_4 emissions are estimated to be 11 $g \cdot day^{-1}$ per pig [6], which provides evidence of a substantial production within the slurry. The comparison of this value with that obtained in the room with the sawdust-based litter, that is 0.77 $g \cdot day^{-1}$, suggests that, in this case, this gas must originate essentially from the digestive tract of the animals. On the contrary, the comparison with the value for the room with the straw, that is 1.58 $g \cdot day^{-1}$, suggests that this litter produces CH_4 but much less than slurry. In addition, the emission of CH_4 in the room with the straw increased regularly with time, that is with the aging of the litter, which was not observed with other gases. Indeed, the emissions of CO_2, H_2O and, to a lesser extent, NH_3 appeared to be much more linked to the animal activity than to the age of the litter, with N_2O emissions behaving more randomly.

CO_2 emissions at the beginning, in the middle and at the end of the stay of one batch of pigs were respectively, on average for the two litters, 294, 447 and 668 g per pig; those of H_2O were 566, 962 and 1538 g per pig. There is a relationship between animal metabolism and CO_2 production. About 45×10^{-7} $m^3 \cdot s^{-1}$ (16.2 $L \cdot h^{-1}$ or 688 $g \cdot day^{-1}$) of CO_2 are generated for each 100 watt of energy produced by a pig [4]. For piglets of 10, 15 and 20 kg, the thermoneutral heat production is estimated at 49.3, 66.2 and 81.5 W, respectively [1, 4] and thus the CO_2 production at 339, 456 and 561 $g \cdot day^{-1}$. These values are of the same order of magnitude as those determined in the present study, which indicates that the respiration of the animals is the principal source of CO_2 in the rooms.

The production of water vapor by animals depends altogether on their weight and the ambient temperature. The minimal production at weights of 8, 15 and 25 kg can be estimated to be respectively 110, 177 and 269 $g \cdot day^{-1}$, with the maximum values being about 4-fold higher [1]. The results of this study do not allow the differentiation between the contributions of water from the animals and from the litter. However, the weight of the wastes collected shows that nearly all of the water from the wastes is evaporated, which is not the case when wastes are collected in the form of slurry.

In conclusion, the evaluation of the impact of pig raising systems on the environment is particularly complex. Because none are perfect, some positive aspects of one system compared to another is inevitably accompanied by negative aspects. Thus, it is very difficult to establish objective balances. The comparison between the use of sawdust or straw for deep litter shows that sawdust contributes less to NH_3 emissions and thus to acid deposition but more to the greenhouse effect.

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