Effect of an Acidifying Diet Combined with Zeolite and Slight Protein Reduction on Air Emissions from Laying Hens of Different Ages

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ABSTRACT The objectives of the study were to evaluate the effectiveness of a reduced-emission (RE) diet containing 6.9% of a $CaSO_4$-zeolite mixture and slightly reduced CP to 21-, 38-, and 59-wk-old Hy-Line W-36 hens (trials 1, 2, and 3, respectively) on egg production and emissions of NH_3, H_2S, NO, NO_2, CO_2, CH_4, and non-CH_4 total hydrocarbons as compared with feeding a commercial (CM) diet. At each age, 640 hens were allocated, randomly to 8 environmental chambers for a 3-wk period. On an analyzed basis, the CM diet contained 18.0, 17.0, and 16.2% CP and 0.25, 0.18, and 0.20% S in trials 1, 2, and 3, and the RE diet contained 17.0, 15.5, and 15.6% CP and 0.99, 1.20, and 1.10% S in trials 1, 2, and 3. Diets were formulated to contain similar Ca and P contents. Average daily egg weight (56.3 g), average daily egg production (81%), average daily feed intake (92.4 g), and BW change (23.5 g), across ages, were unaffected by diet ($P > 0.05$) over the study period. Age effects were observed for all performance variables and NH_3 emissions ($P < 0.05$). In trials 1, 2, and 3, daily NH_3 emissions from hens fed the RE diets (185.5, 312.2, and 333.5 mg/bird) were less than emissions from hens fed the CM diet (255.1, 560.6, and 616.3 mg/bird; $P < 0.01$). Daily emissions of H_2S across trials from hens fed the RE diet were 4.08 mg/bird compared with 1.32 mg/bird from hens fed the CM diet ($P < 0.01$). Diet ($P < 0.05$) and age ($P < 0.05$) affected emissions of CO_2 and CH_4. A diet effect ($P < 0.01$) on NO emissions was observed. No diet or age effects ($P > 0.05$) were observed for NO_2 or non-CH_4 total hydrocarbons. Results demonstrated that diet and layer age influence air emissions from poultry operations.

Key words: hen, air emission, diet, ammonia, hydrogen sulfide

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INTRODUCTION

It is documented that gaseous emissions from laying hen feeding operations can have potential negative effects on the environment and on human and bird health. Feeding diets formulated to reduce excess CP reduced N excreted, resulting in lower NH_3 emissions (Elwinger and Svensson, 1996). Acidogenic materials reduce manure pH, resulting in the protonation of NH_3 to NH_4^+, which is less volatile (McCrory and Hobbs, 2001). Gypsum is one of the acidogenic compounds that has been tested and can also serve to partially replace limestone as a Ca source in laying hen diets without reducing laying hen performance (Keshavarz, 1991). Zeolite has been shown to be a beneficial feed additive that exhibits a strong preference for binding nitrogenous cations like NH_4^+, resulting in lower, but inconsistent, NH_3 emission (Nakaue and Koelliker, 1981) when included at 10%. A study conducted by Hale (2005) showed that using a reduced-protein diet in combination with acidogenic materials, such as $CaSO_4$ and nitrogenous binding compounds like zeolite, decreased NH_3 concentration (as measured in vitro) from laying hen excreta. However, the effectiveness of feeding such a diet on all gaseous emissions in vivo has not been reported. The objectives of the current study were to evaluate the effectiveness of feeding a reduced-emissions (**RE**) diet containing 6.9% of a $CaSO_4$-zeolite mixture that replaced 35% of the limestone and slightly reduced protein to laying hens of different ages on short-term hen performance and emissions of NH_3, H_2S, NO, NO_2, CO_2, CH_4, and non-CH_4 total hydrocarbon (**NMTHC**) as compared with feeding a commercial (**CM**) diet.

MATERIALS AND METHODS

Experimental Birds and Design

The study consisted of 3 trials utilizing Hy-Line W-36 hens, starting at 21 (trial 1), 38 (trial 2), and 59 wk (trial 3) of age. During each experimental age, laying hens were fed for a 3-wk period. All hens were obtained at the respective ages from commercial high-rise laying hen houses (Rose Acre Farms, Stuart, IA) within 1 h of

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Table 1. Composition (as-fed basis) of the reduced emission (RE) diet and the commercial (CM) diet fed to 21-, 38- and 59-wk-old laying hens

	Laying hen age (wk)					
	CM diet			RE diet		
Item	21	38	59	21	38	59
Ingredient (% of diet)						
Corn	52.31	54.68	59.93	47.26	49.53	53.52
Soybean meal (48% CP)	30.07	27.09	23.16	29.67	26.65	23.74
Soy oil	5.16	4.90	3.73	7.19	6.97	6.00
Salt	0.41	0.41	0.41	0.41	0.41	0.41
DL-Met	0.20	0.16	0.09	0.22	0.18	0.11
Lys	0.00	0.00	0.00	0.00	0.03	0.00
Limestone	9.72	9.91	10.11	6.32	6.44	6.57
Dicalcium phospate	1.78	1.50	1.22	1.78	1.50	1.22
$CaSO_4$ and zeolite mix	0.00	0.00	0.00	6.80	6.94	7.08
Vitamin and mineral premix[1]	0.35	0.35	0.35	0.35	0.35	0.35
Celite	0.00	1.00	1.00	0.00	1.00	1.00
Nutrient composition (calculated)						
ME (kcal/kg)	2,948	2,948	2,930	2,930	2,904	2,904
Protein (%)	18.30	17.80	17.00	16.50	15.80	15.30
Ca (%)	4.20	4.20	4.20	4.20	4.20	4.20
Nonphytin P (%)	0.46	0.46	0.40	0.40	0.40	0.40
Met (%)	0.48	0.49	0.43	0.44	0.35	0.35
Lys (%)	1.02	0.99	0.93	0.93	0.83	0.83
TSAA (%)	0.69	0.68	0.62	0.61	0.56	0.54
Analyzed composition (%)						
Protein	18.0	17.0	16.2	17.0	15.5	15.6
S	0.25	0.20	0.20	0.99	1.20	1.10
Met	0.45	0.49	0.39	0.43	0.36	0.38
Lys	1.16	1.12	1.06	1.09	1.00	1.03

[1]Vitamin and mineral premix provided the following (per kg of diet): vitamin A, 12.3 KIU; vitamin D, 4.6 KIU; vitamin E, 15.4 KIU; vitamin K, 3.1 mg; riboflavin, 6.2 mg; pantothenic acid, 15.4 mg; niacin, 46.3 mg; menadione sodium bisulfate complex, 1.0 mg; choline chloride, 463.1 mg; folic acid, 0.3 mg; vitamin B_{12}, 23.1 μg; Zn as ZnO, 71.4 mg, Fe as ferrous sulfate, 50.4 mg; Mn as MnO, 89.6 mg; Cu as $CuSO_4{\cdot}5H_2O$, 7 mg; I from ethylene diamine dihydroiodide, 0.7 mg; Se as Na_2SeO_3, 0.42 mg.

the research location. Laying hens were moved to the research location 5 d before the start of each trial.

The experiment was designed with 2 treatments. During each experimental phase, a total of 640 hens (initial BW = 1.36, 1.47, and 1.52 kg in trials 1, 2, and 3, respectively) were allocated randomly to 1 of 8 chambers (indirect calorimeters) that were built to allow for continuous monitoring of emissions from livestock. In each chamber, 80 birds were divided among 4 2-cage units (10 birds/cage, 355 cm^2 of cage space/bird). Diets were assigned randomly to each of the 8 chambers (4 chambers/diet), with the chamber constituting the experimental unit.

Diets and Management

All diets were formulated to meet NRC (1994) nutrient requirements for laying hens. Feed (approximately 95, 97, and 99 g/hen per d in trials 1, 2, and 3, respectively) was offered twice daily (0600 and 1600 h) in a mash form, and feed intake was recorded weekly on a 2-cage unit basis (20 birds/unit). Samples of diets were retained weekly for determination of nutrient content. Composition of experimental diets is shown in Table 1.

Temperatures in all chambers were maintained at 22 ± 2°C. The humidity ranged from 20 to 80%. Light (10 to 20 lx) was provided from 0600 to 1800 h for 21-wk-old birds and from 0600 to 2200 h for the 38-wk and 59-wk-old birds. The light program was managed to mimic that of the commercial farm and the recommendations of the *Hy-Line W-36 Commercial Management Guide* (Hy-Line International, 2003). Hens were provided ad libitum access to water via nipples.

Bird Measures

Hens were weighed at the beginning and end of each age period. Body weight change (**BWC**) within each chamber was calculated by subtracting the average chamber BW at the beginning of each trial from the average chamber BW at the end of each trial. Average daily feed intake (**ADFI**) of each chamber was calculated based on that week's total feed consumption, divided by 7 d and the number of birds present. Eggs were collected daily from each 2-cage unit, and egg weight and number were recorded daily. Excreta production was determined at the end of each age phase, and a subsample was collected for compositional analysis. Average daily egg weights (**ADEW**), average daily egg production (**ADEP**), ADFI, and BWC over the study period were calculated at the end of each trial.

Measurements of Gaseous Concentrations

Eight chambers (2.14 × 3.97 × 2.59 m) were designed to continuously measure incoming and exhaust concen-

Table 2. Egg weight, egg production, feed intake, and BW change data from laying hens fed a commercial (CM) or reduced emission (RE) diet at 21, 38, and 59 wk of age

Item	Diet	Egg weight (g)	Egg production (%)	Feed intake (g/hen per d)	BW change (g/hen)
Age (wk)					
21 to 24	CM	52.0	84.8	87.0	70.6
	RE	51.9	88.4	86.7	60.1
38 to 41	CM	58.7	83.3	95.8	24.9
	RE	59.2	83.4	95.4	9.6
59 to 62	CM	58.2	71.9	93.5	–25.9
	RE	57.9	74.3	95.9	2.0
Main effects					
Diet					
CM		56.3	80.0	92.1	23.2
RE		56.3	82.0	92.7	23.9
Age (wk)					
21 to 24		51.9^{a}	86.6^{a}	86.8^{a}	65.4^{a}
38 to 41		58.9^{b}	83.3^{b}	95.6^{b}	17.3^{b}
59 to 62		58.1^{b}	73.1^{c}	94.7^{c}	-12.0^{c}
SEM		7.696	13.231	2.264	14.977
Probabilities					
Diet		0.483	0.274	0.497	0.065
Age		<0.001	<0.001	<0.001	<0.001
Chamber		0.100	0.863	0.008	<0.001
Diet × age		0.914	0.515	<0.001	<0.001

[a–c]Main effect means within a column with different superscripts differ significantly ($P < 0.05$).

trations of NH_3, H_2S, NO, NO_2, CO_2, CH_4, and NMTHC. Ammonia and NO were measured using a chemiluminescence NH_3 analyzer (model 17C, Thermal Environmental Instruments, Franklin, MA), which is a combination of an NH_3 converter and NO-NO_2-NOx analyzer. Hydrogen sulfide was analyzed using pulsed fluorescence H_2S-SO_2 analyzer (model 450C, Thermal Environmental Instruments). Carbon dioxide was monitored using the BINOS 100 2M dual gas detector (Rosemount Analytical Inc., Orrville, OH). Methane and NMTHC were measured by flame ionization detector (model 200, VIG Industries Inc., Anaheim, CA). During trial 1, NMTHC data were not available due to the absence of calibration gases. Through software control, gaseous concentration monitoring of each chamber occurred in a sequential manner, beginning first with incoming air for 20 min, then through each of the 8 chambers' exhaust airs for 15 min, with all gases measured simultaneously within a sample stream. Airflow rates into and out of each chamber were measured accurately using orifice

Table 3. Average daily NH_3 emissions over a 3-wk period from laying hens of different ages fed the reduced emission (RE) diet and the commercial (CM) diet

Item	Diet	Concentration (ppm)	ER[1] (mg/min)	Total mass (mg)	EF[2] (mg/kg of BW)	EF[2] (mg/bird)
Age (wk)						
21 to 24	CM	2.8^{b}	14.4^{b}	$20{,}384^{b}$	183.0^{b}	255.1^{b}
	RE	2.0^{a}	10.5^{a}	$14{,}721^{a}$	132.7^{a}	185.5^{a}
38 to 41	CM	3.4^{d}	32.3^{d}	$44{,}582^{d}$	379.4^{d}	560.6^{d}
	RE	2.2^{c}	17.8^{c}	$24{,}570^{c}$	210.6^{c}	312.2^{c}
59 to 62	CM	4.1^{f}	35.3^{f}	$49{,}062^{f}$	461.5^{f}	616.3^{f}
	RE	2.5^{e}	19.0^{e}	$26{,}521^{e}$	248.5^{e}	333.5^{e}
Main effect						
Diet						
CM		3.3^{h}	26.9^{h}	$37{,}269^{h}$	334.1^{h}	468.2^{h}
RE		2.3^{g}	16.3^{g}	$22{,}628^{g}$	203.4^{g}	286.2^{g}
Age (wk)						
21 to 24		2.5	15.9^{g}	$22{,}165^{g}$	201.9^{g}	277.0^{g}
38 to 41		2.8	23.1^{h}	$31{,}753^{gh}$	269.9^{gh}	402.1^{h}
59 to 62		3.2	25.6^{h}	$35{,}563^{h}$	333.2^{h}	447.5^{h}
SEM		0.3	2.5	3,507	31.6	43.9
Probabilities						
Diet		<0.01	<0.01	<0.01	<0.01	<0.01
Age		0.08	<0.01	<0.01	0.02	0.03
Diet × age		0.73	<0.01	<0.01	<0.01	<0.01

[a–h]Means within a column lacking common superscripts differ ($P < 0.05$).

[1]ER = emission rate by chamber.

[2]EF = emission factors.

Table 4. Average daily H_2S emissions over a 3-wk period from laying hens of different ages fed the reduced emission (RE) diet and the commercial (CM) diet

Item	Diet	Concentration (ppm)	ER[1] (mg/min)	Total mass (mg)	EF[2] (mg/kg of BW)	EF[2] (mg/bird)
Age (wk)						
21 to 24	CM	0.005^{a}	0.03^{a}	36.1^{a}	0.32^{a}	0.45^{a}
	RE	0.012^{b}	0.09^{b}	127.5^{b}	1.15^{b}	1.61^{b}
38 to 41	CM	0.003^{c}	0.11^{c}	153.5^{c}	1.31^{c}	1.93^{c}
	RE	0.011^{d}	0.41^{d}	560.1^{d}	4.79^{d}	7.09^{d}
59 to 62	CM	0.004^{e}	0.04^{e}	63.9^{e}	0.60^{e}	0.80^{e}
	RE	0.010^{f}	0.21^{f}	296.0^{f}	2.77^{f}	3.72^{f}
Main effect						
Diet						
CM		0.004^{g}	0.08^{g}	104.9^{g}	0.92^{g}	1.32^{g}
RE		0.010^{h}	0.23^{h}	322.8^{h}	2.85^{h}	4.08^{h}
Age (wk)						
21 to 24		0.008	0.06^{g}	80.5^{g}	0.71	1.01
38 to 41		0.007	0.26^{i}	350.9^{i}	3.00	4.44
59 to 62		0.007	0.13^{h}	181.7^{h}	1.70	2.28
SEM		0.001	0.02	27.2	0.24	0.341
Probabilities						
Diet		<0.01	<0.01	<0.01	<0.01	<0.01
Age		0.58	<0.01	<0.01	0.07	0.10
Diet × age		<0.01	<0.01	<0.01	<0.01	<0.01

[a–i]Means within a column lacking common superscripts differ ($P < 0.05$).

[1]ER = emission rate by chamber.

[2]EF = emission factors.

plates, calibrated for each chamber under specific ranges of conditions. Cumulative NH_3, H_2S, NO, NO_2, CO_2, CH_4, and NMTHC emissions from each chamber were calculated daily by averaging all recordings for that day (10 to 11 daily observations per chamber). Based on light periods, daytime and nighttime emissions were determined. The average daily gaseous emissions in each chamber were expressed as emission rate (mg/min), cumulative total mass (mg), daytime mass (mg), nighttime mass (mg), milligrams per kilogram of BW, and milligrams per hen.

Statistical Analyses

Performance data were analyzed using a GLM procedure, and emissions data were analyzed using a MIXED procedure of SAS (SAS Institute, 1990). For ADEW, ADEP, ADFI, and BWC variables, the model included the fixed effects of chamber and diet (CM and RE diets), the interaction between chamber and diet. For emissions data, the model tested the fixed effects of diet, age, and the interaction of diet and age on emission. Date was treated as a random variable. Significant differences among the means were declared at $P \leq 0.05$.

RESULTS AND DISCUSSION

Hen Performance

The effect of feeding an acidified diet combined with zeolite and slightly reduced protein on ADEW, ADEP, and ADFI is presented in Table 2. Across ages, the ADEW (56.3 g), ADEP (81.0%), ADFI (92.4 g/hen per d), and BWC (23.5 g/hen) of hens fed the RE diet were not different from hens fed the CM diet.

Age affected ADEW (51.9, 58.9, and 58.1 g at 21, 38, and 59 wk of age, respectively), ADEP (86.6, 83.4, and 73.1% at 21, 38, and 59 wk of age, respectively), ADFI (86.8, 95.6, and 94.7 g at 21, 38, and 59 wk of age, respectively), and BWC (65.4, 17.3, and −12.0 g at 21, 38, and 59 wk of age, respectively). Egg weights in the 59- and 38-wk-old hens were greater than egg weights from 21-wk-old hens. Egg production of 59-wk-old hens was less as compared with that of the 21- or 38-wk-old hens. The highest feed consumption was in 38-wk-old hens. Body weight increased the most in 21-wk-old hens, followed by the 38-wk-old hens, whereas the 59-wk-old hens lost weight.

Across ages, birds fed both the CM and RE diets performed similarly to the performance outlined for Hy-Line W-36 laying hens (Hy-Line International, 2003). Our findings were similar to work conducted by Keshavarz (2003), who reported ADEW of 51.5, 56.2, and 59.7 g; ADEP of 81.2, 73.9, and 69.3%; and ADFI of 91.1, 91.5, and 96.0 g at 20 to 35, 36 to 51, and 52 to 63 wk of age, respectively.

NH_3 Emissions

Across ages, the RE diet reduced the daily mass of NH_3 emitted (mg/hen) by 39% (Table 3). Daily emissions of NH_3 from hens fed the RE diet (185.5, 312.2, and 333.5 mg/hen) were significantly less than from hens fed the CM diet (255.1, 560.6, and 616.3 mg/hen) in the 21-, 38-, and 59-wk trials, respectively. Feeding the RE diet decreased the daily emission rate of NH_3 emitted from all 3 age groups (16.3 vs. 26.9 mg/min, Table 3). The RE diet also reduced the cumulative NH_3 emission mass (mg) over the 3 ages studied by 39% (22,628 compared with 37,269 mg, Table 3). Daily emission of NH_3 adjusted

Table 5. Average daily CH_4 emissions over a 3-wk period from laying hens of different ages fed the reduced emission (RE) diet and the commercial (CM) diet

Item	Diet	Concentration (ppm)	ER[1] (mg/min)	Total mass (mg)	EF[2] (mg/kg of BW)	EF[2] (mg/bird)
Age (wk)						
21 to 24	CM	7.6^{b}	8.7^{b}	$12{,}243^{b}$	110.1^{b}	153.1^{b}
	RE	7.4^{a}	7.8^{a}	$10{,}997^{a}$	99.1^{a}	138.5^{a}
38 to 41	CM	2.2^{d}	2.5^{d}	$3{,}475^{d}$	29.6^{d}	43.8^{d}
	RE	2.1^{c}	1.6^{c}	$2{,}222^{c}$	19.0^{c}	28.2^{c}
59 to 62	CM	0.9	0.6	877	8.2	11.0
	RE	0.9	0.5	753	7.0	9.4
Main effect						
Diet						
CM		4.0	4.6^{f}	$6{,}393.6^{f}$	57.1^{f}	80.2^{f}
RE		3.9	3.8^{e}	$5{,}271.9^{e}$	47.1^{e}	66.4^{e}
Age (wk)						
21 to 24		7.5^{f}	8.615^{f}	$12{,}128^{f}$	108.9^{f}	152.4^{f}
38 to 41		2.2^{e}	1.980^{e}	$2{,}727^{e}$	23.4^{e}	34.4^{g}
59 to 62		0.8^{e}	0.184^{e}	232^{e}	2.4^{e}	2.6^{g}
SEM		0.6	0.850	1,579	10.8	15.2
Probabilities						
Diet		0.42	<0.01	<0.01	<0.01	<0.01
Age		<0.01	<0.01	<0.01	<0.01	<0.01
Diet × age		<0.01	0.43	0.40	0.38	0.31

[a–g]Means within a column lacking common superscripts differ ($P < 0.05$).

[1]ER = emission rate by chamber.

[2]EF = emission factors.

for total live weight from hens fed the RE diet (203.4 mg/kg of BW) was less than daily emissions of NH_3 from hens fed the CM diet (334.1 mg/kg of BW).

An age effect existed for the emission of NH_3 from laying hens. Emissions of NH_3 from the 21-wk age group (277.0 mg/hen, Table 3) were less than from the 38-wk (402.1 mg/hen) and the 59-wk (447.5 mg/hen) age groups. Age differences may have been caused by environmental factors that reduced the airflow, and, therefore, emission, because the 21-wk-old hens were fed during April and May, whereas the other age groups were fed in warmer months (June through early September). This is supported by the lack of an age effect for NH_3 concentration (Table 3) but is difficult to confirm based on the H_2S data reported (Table 4). A significant interaction between diet and age was observed, because feeding the RE diet to the 21-wk-old hens resulted in less reduction in NH_3 emissions, compared with the CM diet, than was observed in the other 2 age groups.

The large reduction in NH_3 emissions that was observed in the current study is the result of a combined effect of including a diet acidulant ($CaSO_4$), a binding material (zeolite), and offering a slightly reduced protein content in the diet. The diet acidulant was likely the single largest contributor to the reduced emissions, based on studies conducted by others. Hale (2005) reported that using $CaSO_4$ as a substitute for a portion of the limestone in laying hens diets reduced pH of the manure from about 8.3 standard units to a slightly acidic pH (<7 standard units) level with a concurrent 15% reduction in NH_3 emissions from manure. Kim et al. (2004) found that an acidogenic Ca and P source ($CaSO_4$-H_3PO_4) in swine diets could decrease the urinary pH and reduce NH_3 emission by 30% from swine facilities. Nakaue and Koelliker (1981) evaluated zeolites first as a broiler-feed additive and found that incorporation of 10% clinoptilolite (1 type of zeolite) to the feed of the birds throughout their lifetime reduced aerial NH_3 concentration by up to 8% in one study, but the reverse was observed in a second study. These findings are in agreement with several other researchers using zeolites as a feed additive (Airoldi et al., 1993; Cabuk et al., 2004). Kerr et al. (1995) suggested that for every 1 percentage unit decrease in dietary protein offered, a 10% decrease in NH_3 emissions could be expected. In the current study, the decrease in protein content of the RE diets was not exceptionally large (1.5 to 2.5 percentage units) and, alone, would not be expected to produce the magnitude of effect observed.

Heber et al. (2004) measured emissions from a modern high-rise egg laying house using a chemiluminescence method along with multipoint extractive gas sampling and found that the average daily means of NH_3 concentrations were 2.4, 16.1, and 43.3 mg/m^3 for inlet, cage, and exhaust air, respectively, and the net NH_3 emission rate was 387 ± 25 kg/d or 1.57 ± 0.10 g/d per hen. Liang et al. (2005) reported an annual average NH_3 emission rate of 0.87 ± 0.29 g/d per hen for the high-rise houses, 0.094 ± 0.062 g/d per hen for the manure-belt houses with semiweekly manure removal, and 0.054 ± 0.026 g/d per hen for the manure-belt houses with daily manure removal. In the current study, NH_3 emissions were determined in chambers over a 3-wk period with manure accumulation for the duration of the test period. Average NH_3 emission was 0.47 ± 0.03 g/d per hen when fed a CM diet, which was lower than the value reported by Liang et al. (2005) for high-rise houses but greater than reported values for houses employing a manure belt. This suggests that had the experimental period been

Table 6. Average daily CO_2 emissions over a 3-wk period from laying hens of different ages fed the reduced emission (RE) diet and the commercial (CM) diet

Item	Diet	Concentration (ppm)	ER[1] (mg/min)	Total mass (mg)	EF[2] (mg/kg of BW)	EF[2] (mg/bird)
Age (wk)						
21 to 24	CM	961.1	3,724[b]	5,246,253	47,135	65,627
	RE	957.6	3,643[a]	5,130,088	46,241	64,626
38 to 41	CM	595.3	4,923[d]	6,866,608[d]	58,386[d]	86,243[d]
	RE	594.1	4,525[c]	6,299,303[c]	53,900[c]	79,799[c]
59 to 62	CM	611.8	4,752[f]	6,590,608	61,958	82,694
	RE	611.9	4,595[e]	6,398,861	59,894	80,335
Main effect						
Diet						
CM		713.0	4,485[h]	6,250,730[h]	55,900[h]	78,432[h]
RE		712.8	4,239[g]	5,909,277[g]	53,013[g]	74,548[g]
Age (wk)						
21 to 24		944.8[h]	3,825[g]	5,374,780[g]	48,691[g]	67,302[g]
38 to 41		599.8[g]	4,618[h]	6,414,139[h]	54,783[h]	81,065[h]
59 to 62		616.3[g]	4,609[h]	6,408,772[h]	59,880[i]	80,493[h]
SEM		28.6	92	629,584	1,877	2,663
Probabilities						
Diet		0.95	<0.01	<0.01	<0.01	<0.01
Age		<0.01	<0.01	<0.01	<0.01	0.01
Diet × age		<0.01	<0.01	0.02	0.04	0.04

[a–i]Means within a column lacking common superscripts differ ($P < 0.05$).

[1]ER = emission rate by chamber.

[2]EF = emission factors.

longer than 3 wk, average daily NH_3 emissions may have been more similar to emissions reported from high-rise housing.

H_2S Emissions

Daily H_2S emissions from hens fed the RE diet (1.6, 7.1, and 3.7 mg/hen) were greater than from hens fed the CM diet (0.5, 1.9, and 0.8 mg/hen) at 21, 38, and 59 wk of age, respectively (Table 4). Feeding the RE diet also increased the cumulative H_2S emission mass 3-fold across all 3 age groups (322.8 vs. 104.9 mg). Daily H_2S emission adjusted for total live weight from hens fed the RE diet (2.9 mg/kg of BW) was more than that from hens fed the CM diet (0.9 mg/kg of BW). Lim et al. (2003) reported H_2S emissions from high-rise laying hen houses of 0.432 mg/kg of BW, which is about half of the emission observed in the current study when hens were fed the CM diet. Differences are likely due to the amount of time that excreta had been stored. Although

Table 7. Average daily NO emissions over a 3-wk period from laying hens of different ages fed the reduced emission (RE) diet and the commercial (CM) diet

Item	Diet	Concentration (ppm)	ER[1] (mg/min)	Total mass (mg)	EF[2] (mg/kg of BW)	EF[2] (mg/bird)
Age (wk)						
21 to 24	CM	0.1	0.05	74.8	0.7	0.9
	RE	0.1	0.04	56.6	0.5	0.7
38 to 41	CM	0.01[a]	0.01[a]	16.1[a]	0.1[a]	0.2[a]
	RE	0.01[b]	0.01[b]	8.8[b]	0.1[b]	0.1[b]
59 to 62	CM	0.2	0.02	22.4	0.2	0.3
	RE	0.2	0.01	16.6	0.2	0.2
Main effect						
Diet						
CM		0.1	0.03[d]	35.3[e]	0.3[d]	0.4[d]
RE		0.1	0.01[c]	18.3[d]	0.2[c]	0.2[c]
Age (wk)						
21 to 24		0.10[d]	0.04[d]	62.7[d]	0.6[d]	0.785[d]
38 to 41		0.01[c]	0.01[c]	14.9[c]	0.1[c]	0.189[c]
59 to 62		0.20[e]	0.01[c]	18.8[c]	0.2[c]	0.236[c]
SEM		0.01	0.01	11.4	0.1	0.144
Probabilities						
Diet		0.30	0.01	<0.01	<0.01	<0.01
Age		<0.01	0.12	0.15	0.18	0.06
Diet × age		0.45	0.76	0.74	0.77	0.73

[a–e]Means within a column lacking common superscripts differ ($P < 0.05$).

[1]ER = emission rate by chamber.

[2]EF = emission factors.

Table 8. Average daily NO_2 emissions over a 3-wk period from laying hens of different ages fed the reduced emission (RE) diet and the commercial (CM) diet

Item	Diet	Concentration (ppm)	ER[1] (mg/min)	Total mass (mg)	EF[2] (mg/kg of BW)	EF[2] (mg/bird)
Age (wk)						
21 to 24	CM	0.090	0.07	94.8	0.8	1.2
	RE	0.090	0.06	91.4	0.8	1.2
38 to 41	CM	0.004	0.01	19.1	0.2	0.2
	RE	0.004	0.01	20.9	0.2	0.3
59 to 62	CM	0.040	0.03	43.6	0.4	106.4
	RE	0.040	0.02	34.7	0.3	103.8
Main effect						
Diet						
CM		0.04	0.034[b]	44.3	0.4	0.6
RE		0.04	0.029[a]	38.6	0.3	0.5
Age (wk)						
21 to 24		0.087[c]	0.080[b]	114.1[b]	1.0[b]	1.43[b]
38 to 41		0.004[a]	0.012[a]	17.6[a]	0.1[a]	0.22[a]
59 to 62		0.040[b]	0.030[a]	41.0[a]	0.4[a]	0.51[a]
SEM		0.007	0.012	15.1	0.4	0.19
Probabilities						
Diet		0.41	0.03	0.24	0.24	0.25
Age		<0.01	0.28	0.25	0.32	0.25
Diet × age		0.01	0.51	0.57	0.55	0.57

[a–c]Means within column lacking common superscripts differ ($P < 0.05$).

[1]ER = emission rate by chamber.

[2]EF = emission factors.

H_2S emissions increased 3-fold as a result of feeding the RE diet, the increase was not to the extent that most laying hen operations would trigger federal reporting requirements. Over 10 million hens would be needed on a single site for those reporting requirements to be exceeded.

Whitney et al. (1999) found that a mean reduction of 23% in the S concentration of nursery pigs diets during a 5-wk period tended to reduce H_2S emissions from the stored manure, although this tendency was not significant. It was shown by J. Shurson, M. Whitney, and R. Nicolai (Univ. Minnesota, St. Paul, personal communication) that S excretion was reduced by 30%, by selecting low-S feed ingredients, without affecting their growth. In the current study, $CaSO_4$, a S-containing compound, was added to the diet as an acidifying agent. This additional dietary S combined with the acidifying effect of the $CaSO_4$ likely caused the increased H_2S production. Because feed is ultimately the major source of manure S, 1 method of mitigating manure H_2S emissions is to reduce dietary S. This can be done by reducing excess nutrients, selecting low-S ingredients, or including additives that improve digestive efficiency or alter the microflora in the large intestine (Clark et al., 2005). In addition, a reduction in pH from pH 7.0 to 6.0 has been shown to result in a doubling of the proportion of molecular H_2S

Table 9. Average daily non-CH_4 total hydrocarbon emissions over a 3-wk period from laying hens of different ages fed the reduced emission (RE) diet and the commercial (CM) diet

Item	Diet	Concentration (ppm)	ER[1] (mg/min)	Total mass (mg)	EF[2] (mg/kg of BW)	EF[2] (mg/bird)
Age (wk)						
38 to 41	CM	1.5	8.5	4,146	94.3	143.5
	RE	1.4	6.8	2,041	68.6	106.0
59 to 62	CM	1.2	1.7	1,268	23.4	32.5
	RE	1.2	2.2	1,451	28.9	36.2
Main effect						
Diet						
CM		1.3	4.7	2,323	53.2	78.7
RE		1.3	3.4	1,555	40.7	59.8
Age						
38 to 41		1.5	7.0	2,950	39.8	119.8
59 to 62		1.2	2.0	1,310	79.5	34.4
SEM		0.4	1.2	1,343	41.2	41.3
Probabilities						
Diet		0.40	0.15	0.45	0.22	0.19
Age		0.99	0.09	0.54	0.15	0.09
Diet × age		0.52	0.28	0.30	0.35	0.30

[1]ER = emission rate by chamber.

[2]EF = emission factors.

(Xue et al., 1998). Use of a dietary acidulant in the current study contributed to increased S emissions, suggesting that alternative acidulants should be considered to avoid exacerbating sulfurous emissions.

CH_4 Emissions

Across ages, feeding the RE diet reduced daily CH_4 emission (mg/hen) by 17% (Table 5). Daily emissions from hens fed the RE diet (66.4 mg/hen) were less than emissions from hens fed the CM diet (80.2 mg/hen). Across ages, the RE diet decreased the daily emission rate of CH_4 emitted (3.8 and 4.6 mg/min for RE and CM diets, respectively; Table 5). The RE diet also reduced the cumulative CH_4 emission mass (5,272 vs. 6,394 mg/d for RE and CM diets, respectively; Table 5). Daily emission adjusted for total live weight of hens housed in each chamber from hens fed the RE diet (47.1 mg/kg of BW) was less than daily emission from hens fed the CM diet (57.1 mg/kg of BW). Twenty-one-week-old hens produced greater emissions of CH_4 than did 38- and 59-wk-old hens when CH_4 emissions are expressed on a per bird and per kilogram of BW basis. Although the reason for this is not evident, it does follow the same pattern as NH_3 emissions, except that in the case of CH_4, concentration is greater for the 21-wk old hens compared with both the 38- and 59-wk-old hens. No data are available to support differences in cecal fermentation patterns among hens of different ages, but differences, if they did exist, could explain the effect on CH_4 production.

Methane along with N_2O and CO_2 are the primary greenhouse gasses produced by agriculture (Phetteplace et al., 2001). Hilhorst et al. (2001) concluded that CH_4 production has an optimal pH near 7 and proposed manure acidification as 1 mitigation strategy to reduce CH_4 emissions. Misselbrook et al. (1998) demonstrated that slurry from pigs fed a reduced-protein diet had a higher DM content and lower pH and volatile fatty acid (**VFA**) content with a similar total C content compared with slurry from pigs fed a standard CM diet. They also concluded that CH_4 emissions were better related to VFA content than to total C content, with less CH_4 emitted from the slurry from pigs fed the lower CP diet. Kim et al., (2004) found that an acidogenic Ca and P source ($CaSO_4$-H_3PO_4) in swine diets could decrease the urinary pH and reduce CH_4 emission by 14% from swine facilities. In the current study, a reduction in manure pH or perhaps reduced manure VFA could explain the observed 17% reduction in CH_4 emissions from hens fed the RE diet compared with hens fed the control diet. Koerkamp et al. (1998) reported that CH_4 emission was 0.03 kg/year per kilogram of BW from laying hens housed in cages or free-range hens.

CO_2 Emissions

Daily CO_2 emissions from hens fed the RE diet (74,548 mg/hen) were less than from hens fed the CM diet (78,432 mg/hen; Table 6), as was daily emission adjusted for total live weight in the chamber (53,013 mg/kg of BW and 55,900 mg/kg of BW for hens fed the RE diet and the CM diet, respectively; Table 6).

Keshavarz (1991) demonstrated that dietary acid-base balance plays an important role in hen performance by demonstrating that high dietary levels of acidogenic anions such as $CaSO_4$ altered blood acid-base balance and could affect respiration rate, resulting in more CO_2 production to maintain normal pH. In the current study, $CaSO_4$ was added to the diet as an acidifying agent, which may change the cation-anion balance of the diet. However, the reduction in CO_2 emissions from hens fed the RE diet contradicts the idea that feeding $CaSO_4$ would increase respiration rate and therefore result in greater CO_2 production in an attempt to maintain normal pH.

NO and NMTHC

Daily NO emissions from hens fed the RE diet (0.2 mg/hen) were less than NO emissions from hens fed the CM diet (0.4 mg/hen; Table 7). No age effects were observed (Table 7). No diet or age effects on emissions of NO_2 (Table 8) and NMTHC (Table 9) were observed in the current study. No data for these emissions were found in the literature for comparative purposes.

In summary, this study suggests that diet and layer age influence air emissions from laying hen feeding operations. A plausible means of reducing emissions of NH_3 and CH_4 from laying hen houses is through a dietary mitigation strategy of feeding a reduced-CP diet combined with an acidifying feed additive ($CaSO_4$) and an adsorbent additive (zeolite). However, in the current study, because the acidulant fed contributed to additional dietary S, increased H_2S production was observed. Further research is needed to find a better acidifying feed additive or to determine an effective dose that minimizes increases in S emissions.

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