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REVIEW ARTICLE

Ammonia production in poultry houses can affect health of humans, birds, and the environment—techniques for its reduction during poultry production

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Abstract

Due to greater consumption of poultry products and an increase in exports, more poultry houses will be needed. Therefore, it is important to investigate ways that poultry facilities can coexist in close proximity to residential areas without odors and environmental challenges. Ammonia (NH_3) is the greatest concern for environmental pollution from poultry production. When birds consume protein, they produce uric acid, ultimately converted to NH_3 under favorable conditions. Factors that increase production include pH, temperature, moisture content, litter type, bird age, manure age, relative humidity, and ventilation rate (VR). NH_3 concentration and emissions in poultry houses depend on VR; seasons also have effects on NH_3 production. Modern ventilation systems can minimize NH_3 in enclosed production spaces quickly but increase its emissions to the environment. NH_3 adversely affects the ecosystem, environment, and health of birds and people. Less than 10 ppm is the ideal limit for exposure, but up to 25 ppm is also not harmful. NH_3 can be minimized by housing type, aerobic and anaerobic conditions, manure handling practices, litter amendment, and diet manipulation without affecting performance and production. Antibiotics can minimize NH_3, but consumers have concerns about health effects. Administration of probiotics seems to be a useful replacement for antibiotics. More studies have been conducted on broilers, necessitating the need to evaluate the effect of probiotics on NH_3 production in conjunction with laying hen performance and egg quality. This comprehensive review focuses on research from 1950 to 2018.

Keywords Ammonia · Poultry houses · Housing type · Litter amendments · Diet

Introduction

The USA is the second largest egg producer in the world after China. According to data published by the USDA in the World Agricultural Supply and Demand Estimate (June, 2017, WASDE), total egg production in the USA was 104.988 billion (8.749 billion dozen) which was 2.1% more than 2016. According to this report, US egg production is expected to increase by 1.6% to 8.890 billion dozens in 2018. USDA also expects an increase in egg exports in 2017 and 2018. It was predicted that 302.8 million dozen (8.5% more than previous year) and 320.0 million dozen (up 5.7% from 2017) would be exported. If these trends in the US continue, more laying hens will be needed to meet the demand for eggs, prompting the need for more poultry houses. Historically, people living in close proximity to poultry houses have complained about associated foul odors. Gases such as ammonia (NH_3), hydrogen sulfide, and volatile sulfur compounds are responsible for some of these complaints. Odorless methane is often associated with the volatile gases.

Presently, NH_3 produced in poultry houses is a concern for the health of poultry, human, and environment. In this comprehensive review, we discuss major factors leading to formation of NH_3. These factors include determinants of NH_3 in poultry facilities, seasonal and geological effects, NH_3 in the environment, its effects on human and poultry health, and techniques for NH_3 reduction in

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poultry production including housing type, aerobic and anaerobic conditions, litter amendments, and diet manipulation. We conclude by discussing the most important strategies to reduce NH_3 in poultry production.

Formation of NH_3 in poultry

Uric acid is the major source of NH_3 formation in poultry, mostly occurring in the ceca. The microbial breakdown of large amounts of uric acid in feces and urine results in urea in the presence of an enzyme, uricase, and eventually into NH_3 (Almuhanna et al., 2011; Schefferle 1965; O'Dell et al. 1960; Mahimairaja et al. 1994; Whyte 1993; Kim and Patterson 2003a,b; Bachrach 1957; Moore 1998; Anderson et al. 1964; Li et al. 2013; Santoso et al. 1999; David et al. 2015; Creek and Vasaitis 1961).

The hydrolysis of urea to NH_3 and carbon dioxide (CO_2) by urease activity is shown in the following reaction (Figs. 1 and 2).

Bachrach (1957) showed the following schematic representation of degradation of uric acid into NH_3.

The following is the overall reaction suggested by Bachrach (1957).

$$C_5H_4N_4O_3 + 3[O] + 4H_2O \rightarrow 5CO_2 + 4NH_3$$

Bacillus pasteurii (a ureolytic bacteria that facilitates NH_3 production) has no growth in acidic conditions. Thus, NH_3 formation from uric acid is more favorable at a pH higher than 7 (Li et al. 2013; Elliott and Collins 1982).

Several studies have shown that NH_3 formation depends on the amount of urea, urease activity, pH, temperature, relative humidity (RH) air velocity/ventilation rate (VR), manure handling practice, litter, bird age, and moisture content (MC).

Determinants of NH_3 formation in poultry facilities

Table 1 is a compilation of results for effects of various determinants of NH_3 production.

Results of all studies in Table 1 are in agreement with findings of Almuhanna et al. (2011), Schefferle (1965), O'Dell et al. (1960), Mahimairaja et al. (1994), Whyte (1993), Kim and Patterson (2003a), Bachrach (1957), Moore (1998), Anderson et al. (1964), Li et al. (2013), Santoso et al. (1999), David et al. (2015), and Creek and Vasaitis (1961).

$$CO(NH_2)_2 \rightleftharpoons NH_4^+ + OCN^- \qquad OCN^- + H_3O^+ \rightarrow NH_3 + CO_2$$

$$NH_3 + H_2O \leftrightarrow NH_4^+ + OH$$

Fig. 1 Formation of NH_3

For instance, a 2-year study was conducted to find the relationship between pH and NH_3 volatilization. Three different diets [a control, EcoCal (natural mixture of zeolite and gypsum) and DDGS (corn-dried distiller grain with solubles)] were fed to laying hens. Results showed a direct relationship between pH and NH_3 emissions. EcoCal, DDGS and the control had a pH of 8.0, 8.9, and 9.3, respectively. The acidifier (gypsum) content of EcoCal decreased the pH and ultimately less N to convert into aerial NH_3. MC also had an important role in NH_3 production. Based on the results of this study, it was illustrated that EcoCal had a higher MC (50.2%) than the control (46.1%) and DDGS (43.5%). As shown in Table 2, no significance difference in organic nitrogen (Org-N) and total Kjeldahl nitrogen (TKN) was recorded for all three diets while on a dry matter (DM) basis, 68% more NH_3-N was measured in the EcoCal diet than in the control (Li et al. 2012).

Generally, they show the direct relationship between pH and NH_3 production. pH at more than 7 is responsible for NH_3 production and its volatilization from poultry manure while nitrogen (N) stays in the form of ammonium (NH_4^+) when pH is less than 7.

The relationship between NH_3 and hydrogen ion concentration ($[H^+]$) was elucidated by Xue et al. (1998) who trapped NH_3 from manure storage facilities. Calculations showed that less $[H^+]$ produced more free NH_3 as shown in the following equation. pH is the negative log of $[H^+]$; therefore, a higher pH indicates higher free NH_3 (Xue et al. 1998).

$$\frac{[NH_3]}{[NH_3] + [NH_4^+]} = \frac{1}{1 + \frac{K_{NH_3}[H^+]}{K_w}}$$

Bird age is also important in NH_3 production. As the chicken's age increase, they produce more NH_3; this is clearly shown in Table 1.

Results of another study revealed the relationship between bird age and NH_3 production. Laying hens of three different age groups (21-, 38-, and 59-week-old) were housed to observe the effect of bird age on NH_3 volatilization. Manure from the youngest hens volatilized less NH_3 as compared to other two groups (Wu-Haan et al. 2007).

VR also affects NH_3 concentration and emissions. Various studies reported a positive relationship between VR and emissions while an inverse relationship was reported for concentration and VR. This means that NH_3 emissions increases with the increase of VR in summer and vice versa in winter. Ultimately, greater water content is associated with more NH_3 production.

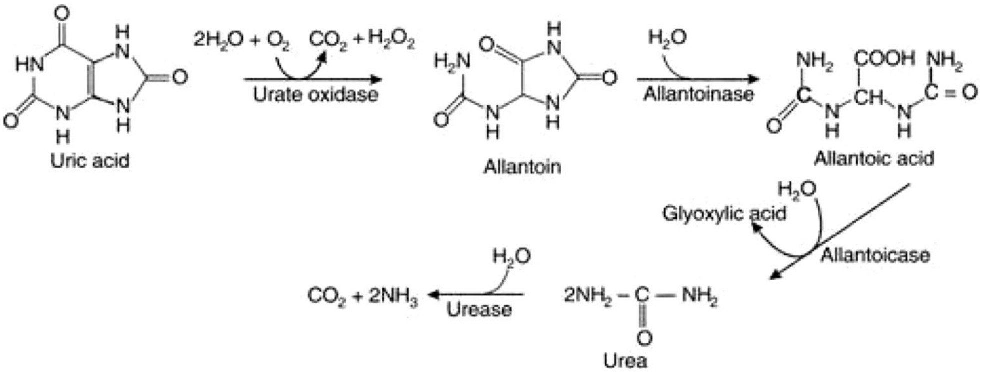

Fig. 2 Probable pathway of aerobic breakdown of uric acid by the pseudomonads used (Bachrach 1957)

Seasonal and geological effects

It has been reported that NH_3 production also depends on seasons and geological sites. Weather and temperature cause various seasons and seasonality affects volatilization. Eighteen consecutive flocks of broilers were studied for seasonal effects. These birds were observed until 40–42 days of age and consumed a commercial diet. Significant difference in volatilization for winter and summer were observed as shown in Table 3 (Coufal et al. 2006).

The dependence of NH_3 reduction on seasons was observed in a 2-year study. NH_3 volatilization by the EcoCal diet varied from −7.1% in September 2008 to 72.2% in February 2009 while it varied from 16.3% in September 2008 to 51.0% in October 2009 with the DDGS diet. More ($p < 0.01$) NH_3 concentration was found in winter than in summer (Li et al. 2012).

NH_3 in the environment

Adverse effects of NH_3 on environment; ecosystem; and health of humans, animals, and birds were revealed in many studies. Environmental groups/agencies have also pressured producers to lower NH_3 emissions (Li et al. 2013; Liang et al. 2005).

NH_3 is a precursor of secondary particulate matter ($PM_{2.5}$) and contributes to the production of $PM_{2.5}$ (Xin et al. 2011; Baek and Aneja 2004). It produces these particles when combined with oxides of N and sulfur. These very small particles affect human health as discussed below (NH_3 effects on human health). As well as producing $PM_{2.5}$, atmospheric NH_3 can alter oxidation rates in clouds and can also elevate acid rain production (Xin et al. 2011; Baek and Aneja 2004; Baek et al. 2004; van Breemen et al. 1982; ApSimon et al. 1987; Sharma et al. 2007).

NH_3 contributes to acidification in soil and N deposition in ecosystem (Li et al. 2013; Liang et al. 2005; Jones et al. 2013). Moreover, nitrifying bacteria in the soil convert it into nitrates which lower pH of ground water and increase concentrations of nitrates in drinking water (Santoso et al. 1999; Adams et al. 1994). Van Breemen, 1988 and Angus et al. (2003) reported N contribution in eutrophication, acidification, and nitrification of groundwater and leaching.

NH_3 effects on human health

NH_3 is a known irritant of the mucous membranes in the upper respiratory tract, nose, and eyes (Santoso et al. 1999; Ihrig et al. 2006; Almuhanna et al. 2011; Pratt et al., 1998); thus, it can damage the respiratory system of workers (Fig. 3) at all levels (Nararaja et al. 1983; Whyte 1993; Charles and Payne 1966). This was confirmed in an epidemiological study by Hartung (2005).

As mentioned above, NH_3 is responsible for the production of $PM_{2.5}$ which can penetrate deeper into the respiratory system of humans and animals where they damage tissues. Birds (feather and skin dander), feed particles, litter, and feces can also be responsible for production of different sizes of inhalable $PM_{2.5}$. Higher concentrations of NH_3 in air affect the respiratory system of humans while cough, nose, and throat irritation can also be caused by lower concentrations. Sundblad et al. (2004) also found increased symptoms of irritation and central nervous system effects upon NH_3 exposure. Poultry workers are adversely affected by NH_3 as compared to non-poultry workers; this is supported by many epidemiological studies. Workers exposed to NH_3 in poultry confinements experienced burning and watery eyes, sneezing, stuffy and running noses, and also coughs (Sanderson et al. 1995; Rees et al. 1998).

Respiratory symptoms during and after work in poultry houses has increased in recent years. All studies showed acute and chronic effects on poultry workers' health (Kirychuk et al. 2003; Zuskin et al. 1995; Reynolds et al. 1993; Santoso et al. 1999; Close et al. 1980; Morris et al. 1991). It was also reported that respiratory symptoms were greater in winter months and

Table 1 Role of pH, moisture content, ventilations rate, litter age, and bird age in NH_3 production

Determinants discussed	Poultry type	Effect on NH_3 concentration/emissions	Source	Year
pH	Broilers	Increased	Moore et al.	1996
	Laying hens	Increased	Mahimairaja et al.	1994
	Laying hens	Increased	Li et al.	2012
	Poultry litter	Increased	Moore	1998
	Poultry litter	Increased	Oliveira et al.	2003
	Storage of manure	Increased	Xue et al.	1998
Moisture content	Broilers	Increased	Liu et al.	2007
	Laying hens	Increased	Koerkamp et al.	1996
	Laying hens	Increased	Pratt et al.	1998
	Laying hens	Increased	Koerkamp et al.	1999
	Laying hens	Increased	Yang et al.	2000
Bird age	Broilers	Increased	Almuhanna et al.	2011
	Broilers	Increased	Elwinger and Svensson	1996
	Broilers	Increased	Redwine et al.	2002
	Broilers	Increased	Madelin and Wathes	1989
	Broilers	Increased	Vučemilo et al.	2007
	Broilers	Increased	Gates et al.	2008
	Broilers	Increased	Hayes et al.	2006
	Broilers	Increased	Knížatová et al.	2010b
	Laying hens	Increased	Wu-Haan et al.	2007
Ventilation rate	Broilers	Decreased/increased	Carr and Nicholson	1980
	Broilers	Decreased/increased	Casey et al.	2004
	Broilers	Decreased/increased	Burns et al.	2007
	Broilers	Decreased/increased	Valentine	1964
	Broilers	Decreased/increased	Demmers et al.	1999
	Broilers	Decreased/increased	Miles et al.	2012
	Broilers	Decreased/increased	Nadier	2013
	Laying hens	Decreased/increased	Zhao et al.	2015
	Type not mentioned	Decreased	Becker and Graves	2004
Manure age	Laying hens	Increased	McQuitty et al.	1985
pH, temperature, water activity	Laying hens	Increased	Koerkamp	1994
pH, moisture content	Laying hens	Increased	Li and Xin	2010
pH, ventilation rate	Broilers	Increased	Carr et al.	1990
Ventilation rate, bird age	Broilers	Decreased/increased, increased	Leonard et al.	1984
Temperature, bird age	Broilers	Increased	Calvet et al.	2011
Temperature, relative humidity	Broilers	Increased	Nimmermark and Gustafsson	2005
pH>>temperature>moisture content	Broilers	Increased	Elliott and Collins	1982
Manure age, pH, moisture content	Broilers	Increased	Maliselo and Nkonde	2015
	Chicken excreta	Increased	Maliselo and Mwaanga	2016
Temperature, moisture content	Laying hens	Increased	Shepherd et al.	2015
Ventilation rate, temperature	Broilers	Increased/decreased	Jiang and Sands	2000
Ventilation rate, manure age	Laying hens	Decreased/increased, increased	Gustafsson and Wachenfelt	2005
Moisture content, ventilation rate	Laying hens	Increased	Ni et al.	2017b
Relative humidity, bird age	Laying hens	Increased	Golbabaei and Islami	2000
Litter age, litter temperature, ventilation rate	Broilers	Increased	Knížatová et al.	2010a, c

pulmonary function also decreased the number of work days (Reynolds et al. 1993). Extensiveness of chronic cough, chronic phlegm, chronic bronchitis, and chest tightness were higher in poultry workers and chicken catchers than the control and non-exposed blue-collar workers (Zuskin et al. 1995; Morris et al. 1991). A

Table 2 Manure properties of high-rise hen houses fed three diets of control, DDGS (10% inclusion rate), or EcoCal (7% inclusion rate) (Li et al. 2012)

Measurements		Mean			SE		
		Control	DDGS	EcoCal	Control	DDGS	EcoCal
NH3-N, %	As-is	0.76b	0.89b	1.21a	0.06	0.05	0.03
	Dry	1.46b	1.62b	2.44a	0.19	0.17	0.10
Org-N, %	As-is	1.40	1.36	0.84	0.23	0.49	0.15
	Dry	2.53	2.31	1.66	0.32	0.71	0.25
TKN, %	As-is	2.16	2.25	2.05	0.19	0.46	0.14
	Dry	4.00	3.93	4.09	0.23	0.65	0.19
pH		9.3a	8.9b	8.0c	0.1	0.2	0.2
Moisture content, %		46.1	43.5	50.2	2.57	3.24	1.69

Row means followed by different letters are significantly different ($p < 0.05$)

NH_3-N ammonia nitrogen, *Org-N* organic nitrogen, *TKN* total Kjeldahl nitrogen, *As-is* as-sampled basis, *Dry* dry matter basis

recent study revealed that a water-based sprinkler cooling system did not reduce NH_3 concentration nor did it improve worker health (Ischer et al. 2017).

NH_3 effects on the health of poultry

Almuhanna et al. (2011) reported that NH_3 is the most abundant toxic gas in poultry houses (Fig. 4).

NH_3 is a colorless gas with a characteristic pungent smell. It is the most common, noxious, and highly water-soluble gas. NH_3 is alkaline and corrosive, adversely affecting the chicken's nasal cavity and eyes. It reacts with nasal moisture to produce the corrosive effect shown below.

$$NH_{3(g)} + H_2O_{(l)} \rightarrow NH_4{}^{+}{}_{(aq)} + OH^{-}{}_{(aq)}$$

As shown in the equation, the NH_4^+ solution formed corrodes the respiratory system of chicken and consequently

Table 3 Seasonal effects on NH_3 concentration and emissions

Poultry type	Effect on NH_3 concentration/ emissions	Source	Year
Broilers	Yes	Wathes et al.	1997
	Yes	Coufal et al.	2006
	Yes	Ritz et al.	2006
	Yes	Wheeler et al.	2006
	Yes	Casey et al.	2004
	Yes	Redwine et al.	2002
	Yes	Carey et al.	2005
	No	Mihina et al.	2010
	No	Knížatová et al.	2010b
Laying hens	Yes	David et al.	2015
	Yes	Burley et al.	2013
	Yes	Kocaman et al.	2006
	Yes	Lim et al.	2003
	Yes	Golbabaei and Islami	2000
	Yes	Kilic and Yaslioglu	2014
	Yes	Li et al.	2012
	Yes	Liang et al.	2005
	Yes	Ni et al.	2017ab
	Yes	Zhao et al.	2013
	Yes	Green et al.	2009
Turkeys	Yes	Whyte	1993
	Yes	Mulhausen et al.	1987
	Yes	Slobodzian-Ksenicz and Kuczyński	2002
Broilers, laying hens	Yes	Nicholson et al.	2004
Broilers, laying hens, turkeys	Yes	Hayes et al.	2006

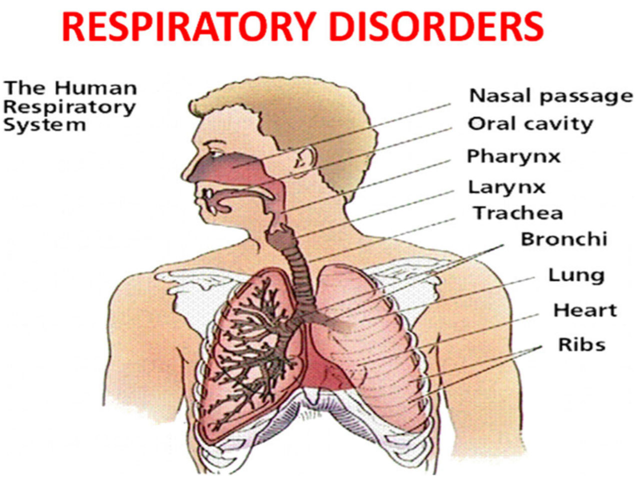

Fig. 3 Effects on respiratory system (http://hotnewsnaija.ng/wp-content/uploads/2016/10/Respiratory.png)

results in paralyzed or lost cilia. Mucus on the mucosal surface of the trachea becomes unclear due to corrosion of cilia which leads trapped bacteria to air sacs and lungs and ultimately causes infection (Aziz and Barnes 2010; Maliselo and Nkonde, 2015; Quarles and Kling 1974; Anderson et al. 1964; Oyetunde et al. 1978; David et al. 2015; Nararaja et al. 1983). Contradictory results were reported by Al-Mashhandani and Beck (1985) who noted no observable effects of NH_3 on the appearance of lungs and trachea. As shown in Fig. 5, production of NH_3 also affects both the performance and health of birds by preventing mobility.

Different levels of NH_3 affect birds' health and performance as shown in Table 4.

Beker et al. (2004) mentioned that no significant differences were recorded in final body weight, body weight gain, and feed consumption when 1-day-old broiler chicks were exposed to 0, 30, and 60 ppm NH_3 concentrations. In addition, or perhaps related to health, Yi et al. (2016b) found insignificant differences in average daily gain, average daily feed intake, and feed conversion ratio when chicken were exposed to 3 and 25 ppm NH_3. No significant differences in feed conversion and mortality with 25 and 50 ppm NH_3 exposure were reported by Reece et al. (1981). Average body weight, air sac scores, lung weights, and Bursa of Fabricius did not differ significantly in ammoniated birds when compared to the control (Caveny et al. 1981).

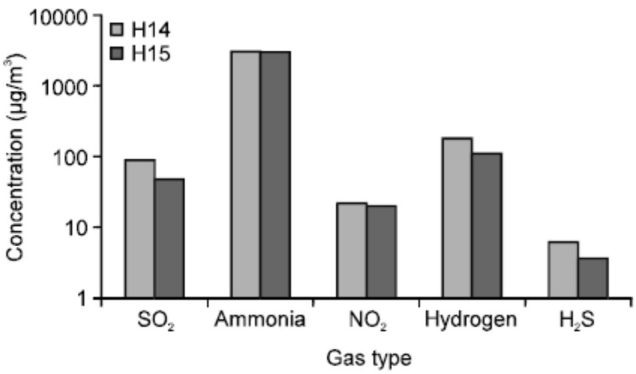

Fig. 4 Measured concentration of toxic gases (NH_3, SO_2, NO_2, H_2S) (Almuhanna et al. 2011)

Fig. 5 Burns on hen's foot (https://chickenrescueandrehabilitation.com/2011/11/08/letter-post-removal-of-3-unhappy-broilers/)

Many experiments on the effects of NH_3 on birds' health were conducted in the middle of twentieth century and continue. While reviewing the literature, it was difficult to discern the meaning of low, medium, and high because actual quantities in ppm were not provided.

Generally, recommendation of NH_3 concentration in poultry houses is less than 25 ppm. Ideally, NH_3 exposure should be less than 10 ppm but temporarily exceeding the limit to 25 ppm is not harmful (NOISH, 2016; Animal Husbandry Guidelines for US Egg Laying Flocks, 2010; Miles et al. 2006; Kristensen et al. 2000). According to the Occupational Safety and Health Administration (Aziz and Barnes 2010), 50 ppm for 8-h exposure is the recommended concentration of NH_3 in a poultry house or OSHA has recommended no more than 35 mg/m^3 for 8-h daily exposure (EPA 2016). It is the lowest concentration which can irritate eyes, nose, and throat.

Techniques for NH_3 reduction in poultry production

Modern ventilation systems in the poultry houses can reduce NH_3 concentration quickly but also increase its emissions in the atmosphere simultaneously. Poultry health is improved by exhausting NH_3 to the outside; however, exhausted NH_3 affects the surrounding environment and, ultimately, the ecosystem. Therefore, actions are necessary to control both concentration and emissions of this toxic gas. A review of the literature discusses many techniques to reduce N production and consequently, NH_3.

Mitigation, without affecting birds' production performance, includes housing type (Fig. 6a–j), bird age, manure age or handling practices, building VR, and diets [low crude protein (CP), synthetic amino acids, addition of fiber, and use of probiotics]. These strategies are discussed below.

Table 4 NH_3 effects on poultry health

NH_3 level (ppm) discussed	Effects on birds health	Source	Year
25	Respiratory system damage	Olanrewaju et al.	2007
	Low ocular abnormalities	Miles et al	2006
	Negative effect on productive performance and immune response	Almuhanna et al.	2011
	Low breast muscle percentage and decline in slaughter rate of broilers	Yi et al.	2016b
30	Immune depression, inflammatory reaction	Wu et al.	2017
	Stress and immunity suppression	Chen et al.	2017
50	Ocular changes Body weight loss	Aziz and Barnes	2010
	Depression in body weight	Miles et al.	2004
52	Effect on growth performance and immunological response	Wang et al.	2010
70	Reduction in growth performance, antioxidative capacities, and meat quality	Wei et al.	2014
75	Body weight loss	Aziz and Barnes	2010
	Depression in body weight and increase in mortality	Miles et al.	2004
78	Reduction in feed consumption, low feed intake, and weight lost	Charles and Payne	1966
100	Negative effect on growth rate	Charles and Payne	1966
	Reduction in egg production, egg weight, egg mass, feed intake, and body weight gain	Amer et al.	2004
200	Loss in egg production, body weight, and feed intake	Deaton et al.	1982
	Reduction in feed intake and growth rate, effect on egg production and mortality	Deaton et al.	1984
2000 (0.2%)	Develop keratoconjunctivitis	Faddoul and Ringrose	1950
20, 50	Increase in infection rate	Anderson et al.	1964
25, 45	Effect on behavior (foraging, resting, and preening)	Kristensen et al.	2000
25, 50	Reduction in body weight and feed efficiency, larger bursae of Fabricius, large lungs, and higher air sac scores	Kling and Quarles	1974
	Reduction in body weight and feed efficiency, severe airsacculitis, higher airborne bacteria	Quarles and Kling	1974
	Reduction in body weight	Reece et al.	1981
	Decrease in feed efficiency	Caveny et al.	1981
30, 60	Lower the performance and increase disease susceptibility	Beker et al.	2004
50, 75	Severe ocular abnormalities, lymphocytes, and heterophils in iris	Miles et al	2006
60–70	Irritate mucous membrane which causes ulceration of eyes and tracheitis, respiratory diseases	Valentine	1964
25, 50, 75	Reduction in body weight	Miles et al.	2002
50, 100, 200	Adverse effects on feed conversion, weight gain, and mortality	Reece et al.	1980
High	Severe chronic hepatic injury through oxidative stress	Zhang et al.	2015
	Negative effect on growth rate	Maliselo and Nkonde	2015
	Effect on fat content in breast muscle, meat quality, and palatability	Yi et al.	2016a
	Production performance, lesions in respiratory tract, and keratoconjunctivitis	David et al	2015
	Suppress immune response	Wei et al.	2015
Very high	Albumen liquefaction	Benton and Brake	2000
Values not available	Decrease in Haugh unit	Cotterill and Nordsog	1954
	Cause keratoconjunctivitis	Bullis et al.	1950
	Irritation to mucous membrane in the eyes and respiratory system, increase susceptibility to respiratory diseases, effect on feed intake, feed conversion efficiency, and growth rate	Kristensen and Wathes	2000
	Loss in body weight	Olanrewaju et al.	2008
	Painful burns on legs and feet	Pratt et al.; Beker et al.; Weaver and Meijerhof; Haslam et al.	1998, 2004, 1991, 2006, respectively

Housing type

There are two common house styles - [high-rise (HR) (Fig. 6a) and manure-belt (MB) (Fig. 6b, c)] in the US egg industry. Manure is removed once a year in HR while in MB, it is removed two to seven times per week. A study was conducted to measure the concentration and emissions rate in both house styles. Commercial layer houses in Iowa and Pennsylvania were used in this study. After 1 year, it was concluded that MB significantly lowered both NH_3 concentration and its emission rate as compared to HR. In addition, a comparison between daily and semi-weekly removal was made. Daily removal showed 74% less NH_3 emission rate in comparison to semi-weekly (Liang et al. 2005). Findings from Green et al. (2009), Koerkamp (1994), Li and Xin (2010), Ni et al. (2012, 2017a), Keener et al. (2002), Roumeliotis and Van Heyst (2008), and Mendes (2010) also support these results. Appropriate temperature and NH_3 levels were found both in

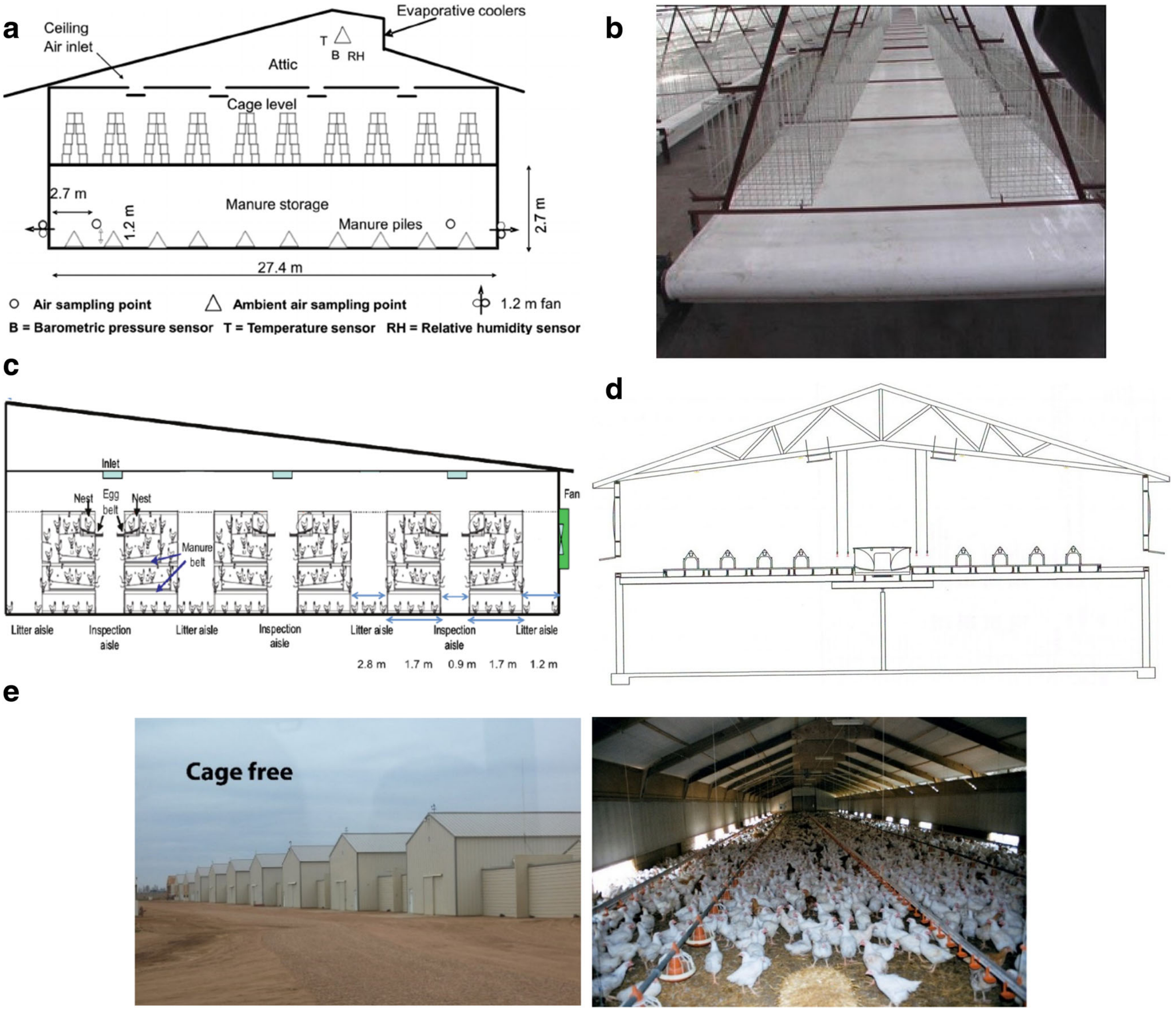

Fig. 6 **a** Cross section of high-rise (https://www.researchgate.net/figure/221971812_fig2_Figure-2-Cross-section-view-of-the-monitored-high-rise-laying-hen-houses-and-sampling). **b** Manure-belt (https://www.alibaba.com/product-detail/poutry-Manure-belt-conveyor-belt-for_60499340942.html). **c** Cross section of manure-belt (https://www.researchgate.net/figure/274345115_fig1_Figure-1-Cross-section-of-the-aviary-hen-house-one-side-of-the-double-house-monitored). **d** Deep-pit (http://www.thepoultrysite.com/poultrynews/37795/midwest-deep-pit-layer-house/). **e** Cage free (https://lpelc.exposure.co/layer-chicken-housing-and-manure-management, http://www.onegreenplanet.org/animalsandnature/think-you-know-free-range-and-cage-free-chicken-think-again/). **f** Stilt house (https://www.pinterest.com/pin/368521181983914852/). **g** Conventional cage (http://www.thepoultrysite.com/articles/3543/the-laying-hen-housing-research-project/). **h** Enriched colony (http://www.thepoultrysite.com/articles/3543/the-laying-hen-housing-research-project/). **i** Aviary house (http://www.thepoultrysite.com/articles/3543/the-laying-hen-housing-research-project/). **j** Broiler house (https://www.wright.ie/case-study/modern-poultry-house-facility-broiler-house-co-monaghan/)

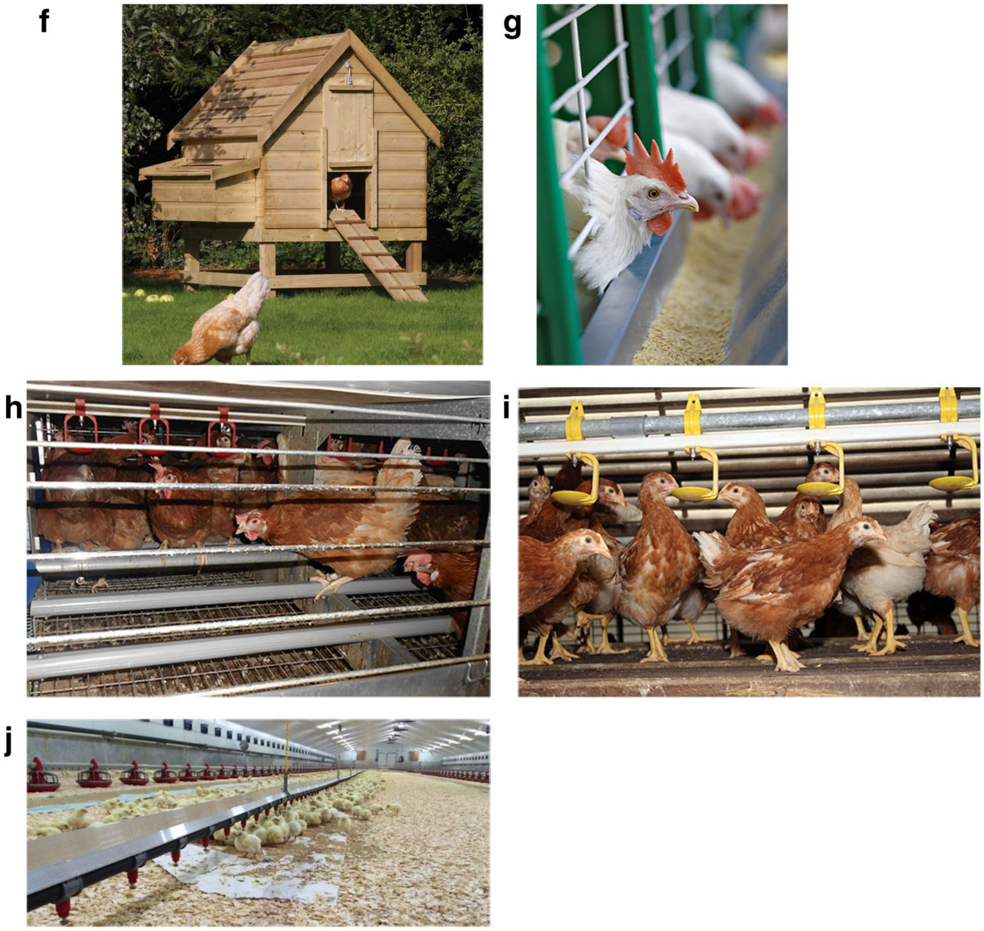

Fig. 6 continued.

HR and MB in winter while in summer, no difference was observed in NH_3 level in all house types. House temperature was slightly, though not significantly, higher than the ambient temperature (Liang et al. 2005).

A review conducted by Xin et al. (2011) also reported less NH_3 release from MB houses due to less surface area and less MC.

Green et al. (2009) conducted a field study to determine the best housing type for reduction of NH_3. Cage-free floor-raised (FR) (Fig. 6e), HR (Fig. 6a), and MB (Fig. 6b, c) were used in this study. Results illustrated that NH_3 emissions was higher in FR (46 ppm) than HR (14 ppm) and MB (7 ppm). Similar findings were noted by Nimmermark et al. (2009), Koerkamp and Bleijenberg (1998), and Costa et al. (2012).

Three houses were used to accommodate laying hens by Nicholson et al. (2004). One of three houses had a belt-scraped design (Fig. 6b, c). Deep-pit (Fig. 6d) and stilt designs (Fig. 6f) were used for the second and third houses, respectively. Daily removal of manure for the belt-scraped design reduced NH_3 more than 2× when compared to weekly removal; these results were confirmed by Koerkamp et al. (1996). In the deep-pit house, more NH_3 was volatilized than in the belt-scraped and stilt houses. Koerkamp et al. (1996) and Keener et al. (2002) also reported comparable findings. Additionally, Fournel et al. (2012) reported lower NH_3 concentration and emissions from manure for the belt-scraped design than for the HR house (Nicholson et al. 2004; Zhao et al. 2013; Fabbri et al. 2007).

The effect of housing type on NH_3 emission rate (ER) was observed in the study of Shepherd et al. (2015). Three different houses [conventional cage (CC) (Fig. 6g), enriched colony (EC) (Fig. 6h), and aviary house (AV) (Fig. 6i)] were used to monitor gas volatilization. The results indicated that NH_3 in CC and EC was significantly less compared to AV.

Housing type with other factors

Nicholson et al. (2004) conducted a study to find the relationship between manure handling practices and NH_3 volatilization in both broiler and laying hen houses. It was reported that NH_3 emissions was greatly influenced by housing type, manure removal, drinker (Fig. 7a, b), and litter type. Housing type and land spreading are the most important factors in NH_3 losses. In broiler houses, two different types of litter (straw and wood shaving) were used. There was no difference

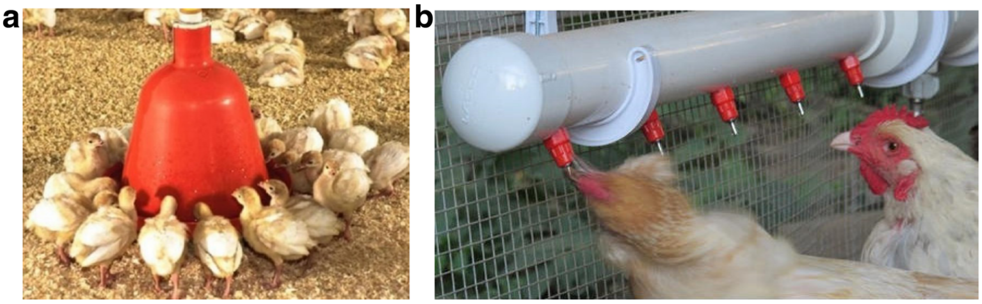

Fig. 7 **a** Bell drinker (http://www.wesstron.pl/drob.php?lang=en&id_strony=82). **b** Nipple drinker (https://www.indiamart.com/proddetail/poultry-nipple-drinker-system-)

in NH_3 losses in summer from both types of litter, and similar findings were also discussed by Elwinger and Svensson (1996) and Tasistro et al. (2007). Moreover, it was mentioned that houses with bell drinkers emitted more NH_3 (numerically) than houses having nipple drinkers, and these results were also similar to that of Elwinger and Svensson (1996) and Da Borso and Chiumenti (1999). It was reported that most of the gas lost occurred during transportation, but no differences were recorded during storage and land spreading.

Aerobic and anaerobic conditions

Mahimairaja et al. (1994) performed an experiment to investigate the effect of four carbon-rich bedding materials, one acidifying material, and two adsorbents on N transformation and its loss in poultry manure under aerobic and anaerobic conditions. Anaerobic conditions showed a significant reduction in NH_3 volatilization in comparison to the aerobic environment after 12-week incubation period of poultry manure (Table 5). Bachrach (1957) also discussed the similar results.

Findings for NH_3 production in aerobic and anaerobic environments were also supported by Kirchmann and Witter (1989). A study was conducted on fresh chicken manure combined with oat straw for both aerobic and anaerobic conditions. Less NH_3 was volatized in an anaerobic condition due to low pH; possibly NH_3 losses to some extent, were dependent on quantity of straw present in aerobic condition but no effect was observed in an anaerobic environment. Significantly higher NH_3 volatilization in aerobic versus anaerobic decomposition was also reported by Kirchmann and Lundvall (1998).

Litter amendments

A review of several studies reported that NH_3 emissions can be minimized by litter amendment. It was helpful in all poultry houses, especially in laying hen facilities (Roumeliotis and Van Heyst 2008). As shown in Table 6, significant effects of litter amendments on NH_3 reduction were observed.

In addition to the negative effect of acidic electrolyzed water, several studies showed that litter amendment was the best way to control NH_3 concentration and emissions. Different types of adsorbents, inhibitors, and bedding materials were applied in poultry houses. Alum and zeolite were used most commonly. When these materials were added to the litter, they lowered pH and produced more NH_4^+ rather than NH_3. Some inhibitors reduced urease activity, responsible for NH_3 production.

Uricase-specific antibody (IgY) from hens immunized with uricase by triplicate injections suppressed microbial uricase activity (Kim and Patterson, 2003b). The investigators suggested that more work was needed to ascertain the effect of the uricase-specific IgY on microbial uricase, possibly reducing NH_3 volatilization from poultry manure. In contrast to results of Nakaue et al. (1981), no effect of clinoptilolite (zeolite) on ammonia reduction was observed when laying hens were fed in a 28-day study (Nakaue and Koelliker 1981). Litter amendment does not commonly affect birds' performance and

Table 5 Amounts of total N (mg/jar) remaining and NH_3 (mg/jar) after 12-week incubation of poultry manure with different amendments (Mahimairaja et al. 1994)

	Treatment	NH_3 volatilization (mg per jar)	
		Aerobic	Anaerobic
	Manure (m) alone	347	20
(a)	Bedding materials		
2	m + woodchip (wc)	276	17
3	m + paper waste (pw)	300	16
4	m + straw	238	16
5	m + peat	258	14
(b)	Acidifying material		
6	m + elemental (S°)	198	15
7	m + wc + S°	152	15
8	m + pw + S°	105	14
(c)	Asorbents		
9	m + zeolite	139	15
10	m + wc + zeolite	136	14
11	m + pw + zeolite	156	14
12	m + wc + soil	210	15
13	m + pw + soil	190	14

Table 6 Litter amendments and their role in NH_3 reduction

Litter amendments	Effect on NH_3 reduction	Source	Year
Alum	*	Moore et al.	1996
	*	Shreve et al.	1995
	*	Moore et al.	2000a
	*	Moore et al.	2000b
	*	Ali et al.	2000
	*	Moore et al.	2008
	*	Moore and Edwards	2005
	*	Moore et al.	1995
	*	Moore et al.	1999
	*	Moore and Edwards	2007
	*	Worley et al.	2000
	*	Eugene et al.	2015
	*	Sims and Luka-McCafferty	2002
	*	Worley et al.	1999
	Reduction in ureolytic bacteria	Cook et al.	2008
	*	Burgess et al.	1998
	*	Moore et al.	1997
	*	Bloomington et al.	2011
	*	Oliveira et al.	2004
	*	Choi and Moore	2008a
Liquid alum	*	Armstrong et al.	2003
Sodium bisulfate	*	Li et al.	2013
	*	Tasistro et al.	2007
	*	Johnson and Murphy	2008
	*	Hunolt et al.	2015
	*	Nagaraj et al.	2007
	*	Li et al.	2006
	*	Wheeler et al.	2008
Liquid aluminum chloride	*	Choi and Moore	2008b
$AlCl_3\cdot$ Aluminum chloride hexahydrate	*	Choi	2004
Superphosphate	*	Cotterill and Winter	1953
Phosphoric acid	*	Moore et al.	1996
Poultry litter treatment	*	Weiss	2015
Granular Al^+ clear (aluminum sulfate)	*	Li et al.	2006
Liquid Al^+ clear (aluminum sulfate)	*	Li et al.	2006
Granular ferix-3 (ferric sulfate)	*	Li et al.	2006
Ferrous sulfate	*	Moore et al.	1996
$ZnSO_4$	*	Kim and Patterson	2003a
Agricultural gypsum	*	Sampaio et al.	1999
Zeolite	*	Li et al.	2006
Clinoptilolite (zeolite)	*	Nakaue et al.	1981
Natural zeolite	*	Eleroğlu and Yalçın	2005

Table 6 (continued)

Litter amendments	Effect on NH_3 reduction	Source	Year
Natural zeolite	*	Schneider et al.	2016
N-(n-butyl) thiophosphoric triamide	*	Singh et al.	2009
Urease inhibitors	*	Manunza et al.	1999
Sand	*	Ali et al.	2000
Biochar	*	Steiner et al.	2010
Refused tea	*	Atapattu et al.	2008
Silage maize	*	van Harn et al.	2012
Alum and superphosphate	*	Ali et al.	2000
Alum and phosphoric acid	*	DeLane et al.	2004
Alum and aluminum chloride	*	Do et al.	2005
Superphosphate and phosphoric acid	*	Reece et al.	1979
Mixture of sodium bisulfate and sodium sulfate	*	Pope and Cherry	2000
Zeolite and coir	*	Kithome et al.	1999
Alum, acidified clay and sodium bisulfate	*	McWard and Taylor	2000
Dry acids (Al^+ clear, poultry litter treatment, poultry guard)	*	Rothrock et al.	2010
Acidifying material (elemental sulfur) and zeolite	*	Mahimairaja et al	1994
Acidified chars (pine chip and coconut husk)	*	Ritz et al.	2011
Acidifying additives (sodium perborate, TiO_2 photocatalyst, and TiO_2 + paraformaldehyde granules)	*	Kaoud	2013
Natural materials (expandable perlite and vermiculite, pumice, zeolite)	*	Turan	2009
Acidic electrolyzed water	N	Chai et al.	2017

N negative effect

*Significant effect

production. Ali et al. (2000) reported contradictory results indicating that alum affected broilers performance.

Figure 8a–c shows the different types of litter amendments in poultry houses.

Diet manipulation

Several studies showed that NH_3 production can be decreased by diet manipulation (Hale 2005; Roberts et al. 2015). Positive results without affecting birds' performance and production were obtained in most of them.

Low crude protein

High protein in the diet of layers is mainly responsible for elevated production of NH_3. Poultry cannot store excess amino acids, resulting in released N, mostly in the form of uric acid (Kristjan and Roberts 2006).

Liang et al. (2005) explained the influence of reduced CP on NH_3 emissions. Birds were fed a diet containing 1% low CP and essential amino acid supplements. There was significantly lower NH_3 concentration and its emissions was low in houses with low CP. Liang et al. (2003), Gates (2000), Ji et al. (2014), Meluzzi et al. (2001), and Nahm (2007) found similar results. Contradictory findings were shown in the study of Burley (2009).

Results of another study revealed that by adding low CP (and lysine), NH_3 gas concentration decreased by 31% and litter N by 16.5% (DM basis) as shown in Table 7. Broilers were fed with three different diets: high CP (High), low CP with additional synthetic amino acids (Low), and an equal blend (1:1) of High and Low CP treatments (Medium). Low CP reduced NH_3 and litter N by lowing pH and MC (Ferguson et al. 1998). Similar results were obtained in studies by Blair et al. (1999), Gates et al. (2000), and Namroud et al. (2008).

Direct relationships between dietary protein and NH_3 emissions, litter N, or total N were found in several other studies. Results showed that these factors increased with the increase of CP (Elwinger and Svensson 1996; Summers 1993; Keshavarz and Austic 2004; Robertson et al. 2002; Aletor et al. 2000; Rezaei et al. 2004).

The effects of dietary protein were also observed in laying hen houses. A 2-year study was conducted using three commercial HR houses (Fig. 6a). Three different diets included a control, 7% EcoCal, and DDGS. Results showed that Ecocal and DDGS significantly lowered NH_3 volatilization compared to a control diet. EcoCal and DDGS had 39.2% and 14.3% less NH_3 emissions, respectively. Manure obtained from the

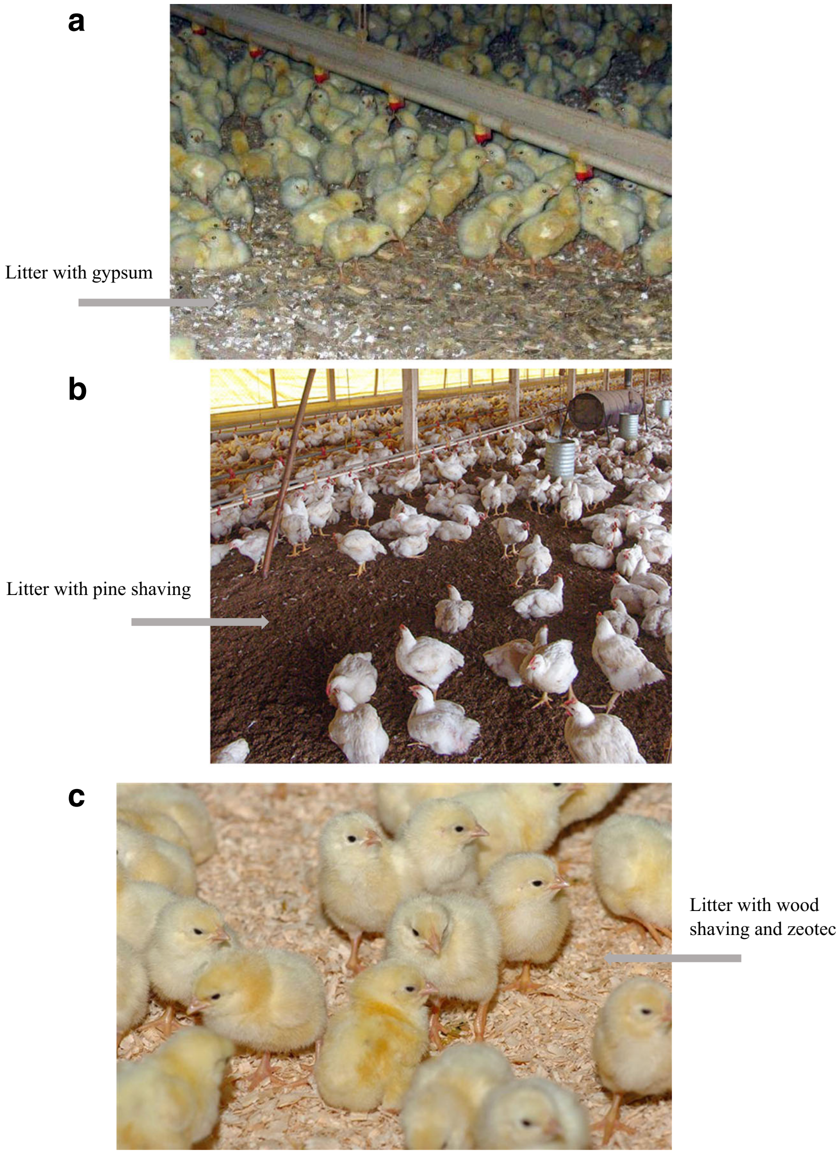

Fig. 8 **a** Litter amendment with gypsum (https://www.usagypsum.com/gypsum-products/gypsum-poultry-litter-amendment). **b** Litter amendment with pine shaving (http://www.thepoultrysite.com/articles/3554/alternatives-to-pine-shavings-for-poultry-bedding/). **c** Litter amendment with wood shaving and poultry additive, zeotec (https://www.bpmnz.co.nz/en/products/zeotec/)

EcoCal diet had higher NH_3-N retention (68%) than the control. NH_3 emission rates are shown in Table 8 (Li et al. 2012). The findings of Roberts (2009) showed contrasting results for DDGS.

Wu-Haan et al. (2007) confirmed findings of others when two different diets were fed to three different age groups of hens. Diets were a reduced-emission (RE) diet, containing a mixture of 6.9% of $CaSO_4$-zeolite and slightly reduced CP

Table 7 The effect of dietary crude protein on the mean ± SEM of equilibrium ammonia gas concentration and litter characteristics (Ferguson et al. 1998)

Treatment	NH_3 (ppm)	pH	Moisture (g/kg)	Nitrogen[a] (g/kg)
Low	53 ± 7.2	5.0 ± 0.20^{b}	560 ± 10.8^{b}	47 ± 2.0^{b}
Medium	58 ± 5.1	$5.1 \pm 0.09^{a,b}$	569 ± 16.2^{b}	49 ± 1.4^{b}
High	83 ± 13.8	5.5 ± 0.34^{a}	603 ± 29.1^{a}	59 ± 0.2^{a}
Significance	**	*	*	***

One pen from the medium and high treatments ($n = 4$) were excluded because of unusually high air flow over the litter, which affected the equilibrium NH_3 gas concentration and litter characteristics (low treatment $n = 5$). Means in a column with no common letters differ significantly ($p < 0.05$)

*$p < 0.05$; **$p < 0.10$; ***$p < 0.001$

[a] Nitrogen values expressed on a dry matter basis

Table 8 Monthly mean NH_3 emission rates of high-rise hen houses fed three diets of control, DDGS (10% inclusion rate), or EcoCal (7% inclusion rate) (Li et al. 2012)

Month, year	Mean T_{out}, °C	NH_3 ER, g/hen/day (SD)		
		Control	DDGS	EcoCal
Dec, 2007	− 0.2	1.11 (0.04)	0.60 (0.05)	0.48 (0.04)
Jan, 2008	− 6.4	1.29 (0.06)	0.92 (0.03)	0.40 (0.02)
Feb, 2008	− 6.2	0.99 (0.04)	0.72 (0.02)	0.35 (0.01)
Mar, 2008	3.0	1.02 (0.05)	0.76 (0.04)	0.39 (0.02)
Apr, 2008	8.6	1.32 (0.04)	1.19 (0.07)	0.62 (0.02)
May, 2008	15.8	1.15 (0.05)	1.05 (0.05)	0.71 (0.04)
Jun, 2008	22.4	1.25 (0.07)	1.07 (0.05)	0.92 (0.04)[a]
July, 2008	24.4	1.38 (0.07)	1.18 (0.04)	0.90 (0.05)[a]
Aug, 2008	21.8	1.12 (0.04)	1.16 (0.04)	1.06 (0.03)
Sep, 2008	18.1	0.94 (0.06)[a]	1.09 (0.05)	1.00 (0.04)
Oct, 2008	11.8	0.81 (0.04)[a]	0.85 (0.04)	0.69 (0.04)
Nov, 2008	5.1	0.88 (0.04)	0.66 (0.55)	0.58 (0.03)
Dec, 2008	− 5.7	0.91 (0.02)	0.73 (0.04)[a]	0.58 (0.04)
Jan, 2009	− 6.9	0.6 (0.05)	0.80 (0.06)[a]	0.36 (0.01)
Feb, 2009	− 1.5	0.78 (0.04)	0.96 (0.03)	0.22 (0.01)
Mar, 2009	4.5	0.91 (0.03)	0.80 (0.02)	0.26 (0.01)
Apr, 2009	9.1	0.58 (0.04)	0.60 (0.04)	0.46 (0.02)
May, 2009	16.6	0.70 (0.03)	0.76 (0.02)	0.68 (0.06)[b]
Jun, 2009	21.0	1.01 (0.06)	0.94 (0.06)	–
July, 2009	21.1	1.01 (0.14)[b]	0.61 (0.03)	–
Aug, 2009	21.0	0.53 (0.03)[c]	0.72 (0.03)	–
Sep, 2009	18.0	0.73 (0.08)[c]	0.58 (0.02)	0.67 (0.05)
Oct, 2009	7.8	–	0.47 (0.02)	0.47 (0.02)
Nov, 2009	7.6	–	0.56 (0.02)[b]	0.40 (0.01)
Overall mean	9.5 (2.14)	0.96 (0.05)	0.82 (0.05)	0.58 (0.05)

– no meaningful comparison due to flock changing

[a] Molting diet was used. [b] Flock was depopulated. [c] The new flock was considered as control before the EcoCal diet was fed

and a commercial diet (CM). Laying hens (21-, 38-, and 59-week-old) were used in this study. Significant reduction ($p < 0.01$) in NH_3 emissions was observed when hens were fed the RE diet. Other investigators reported similar findings (Romero et al. 2012; Xin et al. 2005; Cabuk et al. 2004, Wu-Haan 2006). Lon-Wo (2010) also reported less NH_3 volatilization when hens were fed a diet containing 3% natural zeolite (Clinoptilolite) instead of a control diet. After 10 days, NH_3 emissions from manure of hens fed zeolite was only 30.6 ppm while 937 ppm NH_3 emissions was reported for the control (Nakaue et al. 1981; Hale 2005).

Findings of Nakaue and Koelliker (1981) and Karamanlis et al. (2008) were not in agreement with the results discussed above. Ferguson et al. (1998) also reported an insignificant effect of dietary protein on NH_3 gas emissions, MC, and pH; but, litter N was lowered significantly by adding low CP and P in a broiler diet. Results also showed that gaseous NH_3 production was inversely proportional to dietary P, and this relationship was previously explained by Taraba et al. (1980) as well. Based on the results, it was suggested that NH_3 concentration depended on pH and litter surface moisture which were not sensitive response variables as compared to chemical analyses (Ferguson et al. 1998; Taraba et al. 1980). Analysis by Burley et al. (2013) showed no significant difference in NH_3 emissions when laying hens were fed diets containing different levels [low, intermediate, and high (control)] of CP.

Fiber

According to Roberts et al. (2007b), NH_3 emissions can be diminished by feeding a fibrous diet because (1) amino acids in ingredients of a highly fibrous diet are less digestible as compared to that of those in a low fibrous diet and (2) amino acids in a fibrous diet are not available to degrade to urea and consequently to NH_3. Additionally, investigators stated that fermentable fiber can change the form of N excretion from urea (urine) to microbial protein (feces). Microbial protein is more stable and less degradable to NH_3. Fiber also helps in minimizing pH of the manure by production of volatile fatty acids. This is important because low pH retards production of NH_3 and produces more NH_4^+ ions which are not volatile (Roberts et al. 2006, 2015).

Roberts et al. (2006) also reported that hens digest less fiber, so diets with high fiber decrease protein digestibility and increase excretion of N (Fig. 9). In this study, three types of fiber (soy hulls, wheat middlings, and DDGS) were added to the diet. Inclusion rate for DDGS was 10% and wheat middlings were also included to obtain the same neutral detergent fiber. Researchers found no difference in N excretion both in the control and the diet with fiber. Wheat middlings caused a significant reduction in uric acid excretion which is the main source of NH_3 production in birds. pH is also important in NH_3 production, and addition of fiber decreased pH of the manure without affecting hen production performance. Reduced uric acid and decreased pH were factors in minimizing NH_3 volatilization (Pineda et al. 2008).

Roberts et al. (2007a) also supported findings in Fig. 10. This study was conducted with 17-week-old laying hens. Hens were fed eight different diets [normal crude protein = corn and soybean meal control diet, control with 10% DDGS, 7.3% wheat middlings (WM), and 4.8% soybean hulls (SH); reduced CP = corn and soybean meal control diet, control with 10% DDGS, 7.3% wheat middlings (WM), and 4.8% soybean hulls (SH)] . Addition of higher fibers lowered NH_3 emissions from manure over 7 days in comparison to the control. Reduced CP by 1% did not lower NH_3 emissions as supported by results from previous studies with reduced CP (Bregendahl et al. 2002; Roberts et al. 2007b; Bregendahl and Roberts 2007).

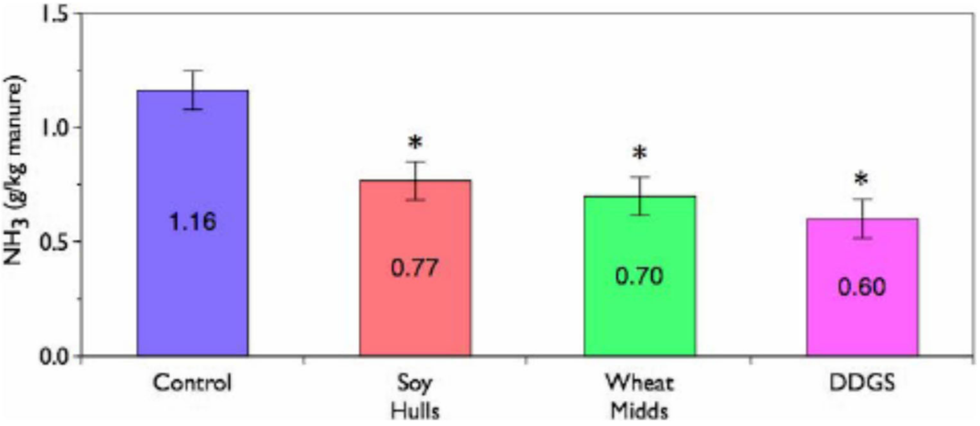

Fig. 9 Total ammonia emission from manure over 7 days. Data are means ± pooled SEM, $n = 6$. *Different from control ($p < 0.05$) (Roberts et al. 2006)

One possible high fiber dietary addition for reduction of NH_3 is meal made from sunflower seed, a globally grown oil crop having high fiber and fat. Meal is the by-product of seed processing (with or with part of the hull) left after oil extraction and could be an important protein source in animal diets (Kalmendal et al. 2011; Laudadio et al. 2014; Selvaraj and Purushothaman 2004, Ditta and King, 2017). Although it provides very low utilizable carbohydrate and low lysine, 25% sunflower seed meal (SFM) could be used in a balanced diet without affecting weight gain or feed efficiency of growing chicks (Rodriguez et al. 1998). It contains linoleic acid which is a fat source for laying hens (San Juan and Villamide 2001). Abdelrahman and Saleh 2007 reported that SFM can be effectively used rather than soybean meal. It contains about the same average CP (30–32%), a higher quantity of methionine, and less lysine as compared to soybean meal. SFM (10%) could be used to improve average body weight and lessen feed cost for production. Another advantage of SFM is that it is free of most antinutritional factors (Senkoylu and Dale 1999; Deaton et al. 1979; Rose et al. 1972; Walter et al. 1959; Villamide and San Juan 1998).

Bamboo charcoal

Maliselo and Nkonde (2015) recommended the use of bamboo charcoal particles in diet manipulation to minimize NH_3 emissions. These results indicated that bamboo charcoal had adsorption properties to bind NH_3.

Probiotics

Along with decreasing CP, feeding essential synthetic amino acids, and adding fiber to reduce N excretion, use of antibiotics also created positive results; but, consumers have concerns as antibiotics are deposited in eggs and thereby, may cause antibiotic resistance in humans. Odors may be decreased by administration of live microorganisms (probiotics), which are non-pathogenic and non-toxic. They help hosts maintain health by (1) fortifying the digestive system and (2) lowering NH_3 concentration by competitive exclusion of other bacteria.

Several studies have been conducted to analyze the effect of probiotics on humans. Along with humans, many

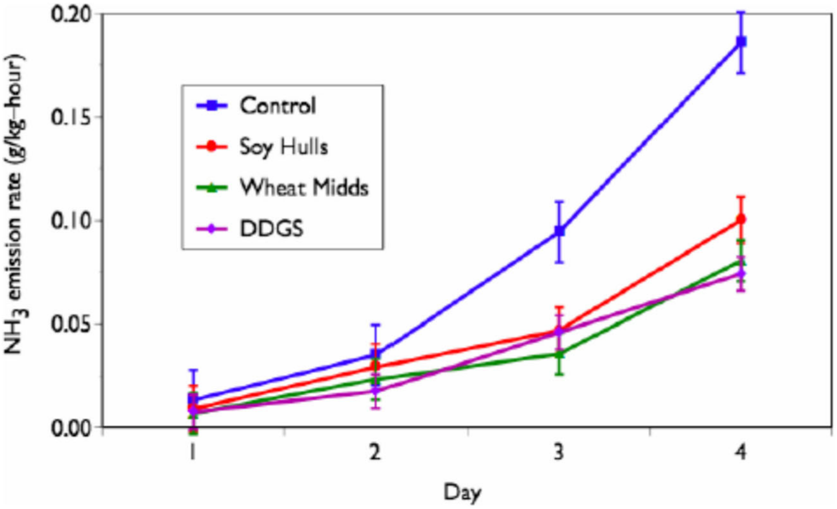

Fig. 10 Ammonia emission rate from manure. Data are means ± pooled SEM, $n = 6$ (Roberts et al. 2006)

investigations were conducted to reduce NH_3 production without affecting birds' health and performance.

Probiotic (*Lactobacillus casei*) suppressed NH_3 production in the GI tract of broiler chicken in a 6-week study. *Lactobacillus casei* at 0.1%, chloroxytetracycline (antibiotic) at 0.1%, and yucca extract at 0.2% were added in the diet. Two-day-old broiler chicks were randomly assigned to a control and treated diets. Diets containing probiotic showed significant effects on feed intake and weight gain. Urease activity also decreased in the GI tract of broilers which were fed the diet containing probiotic. These findings concluded that dietary probiotic restrained bacterial growth which was responsible for urease activity and, ultimately, NH_3 production (Yeo and Kim 1997). Isshiki (1979) also found positive effects of dietary *Lactobacillus casei* on reduction of non-protein N and urea N which resulted in decreased uric acid and NH_3 level (Isshiki 1979).

Environmental NH_3 levels in the broiler house were decreased by feeding a *lactobacilli* probiotic (*ecozyme*). Two experiments were conducted on 56-day-old-male broilers. Probiotic contained *Lactobacilli ecozyme* with a minimum of 6.0 CFU per gram of the product in experiment 1 while 3.0 CFU per gram of the product was added in experiment 2. Birds in one treatment were fed a control diet without any probiotic while birds in the other treatment were fed a control diet containing 5% *ecozyme*. There was a significant difference in NH_3 concentration between two treatments after week 3 (Fig. 11).

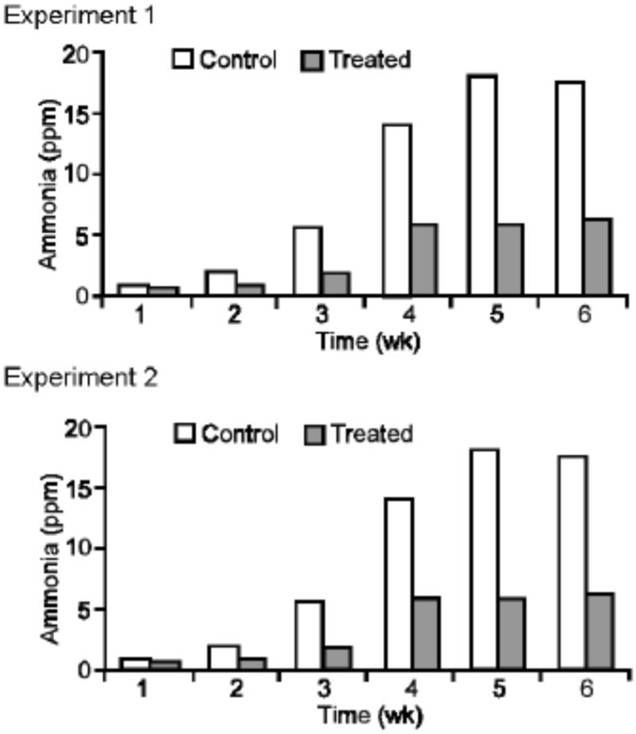

Fig. 11 Environment ammonia concentration of broiler room as affected by *ecozyme* diet supplementation. Exp. 1: log 6 *Lactobacilli* cfu/g feed; exp. 2: log 3 *Bactobacilli* cfu/g feed (Chang and Chen 2003)

Statistically similar results were obtained by feeding *ecozyme* with 3.0 CFU/g. Earlier studies illustrated that NH_3 production depended on pH and MC, so lower pH and lower MC in both experiments were observed in the fecal matter of treated birds (Chang and Chen 2003).

Ahmed et al. (2014) also conducted a study to analyze the effect of dietary probiotics (*Bacillus amyloliquefaciens*, BAP) on NH_3 production. Four hundred 1-day-old male broiler chicks were fed with commercial broiler feed containing five different levels of BAP (0, 1, 5, 10, and 20 g/kg of BAP). Table 9 shows the relationship between different levels of BAP and NH_3 volatilization. Higher NH_3 emissions from the control at all the incubation times were recorded. It was also observed that NH_3 volatilization reduced as the probiotic level (20 g/kg of BAP) was increased. BAP lowered the pH and ultimately NH_3 volatilization (Ahmed et al. 2014).

Santoso et al. (1999) conducted two experiments on 65-week-old Hyline W36 and 2-week-old broiler chicks to determine the effect of dried *Bacillus subtilis* culture (DBSC) on body weight, feed intake, protein intake, feed conversion ratio, NH_3 gas, total N, urate N, NH_3-N, N utilization, and serum urea-N. It was reported that DBSC significantly decreased NH_3 gas without affecting chicken body weight, feed intake, and egg production. It was also observed that DBSC did not decrease total N in feces. Possibly, DBSC produced subtilin which helped to inhibit urease producing microflora in the gastrointestinal lumen and eventually NH_3. DBSC also produced a substance which helped to reduce NH_3 gas by binding N present in the feces.

The above findings were also supported by the results of Tanaka and Santoso (2000) in a 3-week study. Seven-day-old female broiler chicks were fed different levels of fermented product from *Bacillus subtilis*. A significant decrease in NH_3 production was recorded in treated chicks when compared to the control; but, there was no difference in total N, urate N, NH_3-N in fecal matter, pH, and NH_3-N of cecum in both groups of chicks.

Dried *Bacillus subtilis natto* reduced NH_3 level in chicken blood when it was fed at different levels in two experiments. Diets having 0, 0.5, 1, and 3% levels of *Bacillus subtilis natto* were fed to White Leghorn chickens for 3 days in experiment 1 and 0, 0.2, 0.5, and 1% levels were fed for 28 days in experiment 2. It was reported that 0.5% dietary *Bacillus subtilis natto* depressed the NH_3 concentration in chicken blood in experiment 1 and in all levels in experiment 2. It was concluded that *Bacillus subtilis natto* restrained the growth of urease-producing bacteria and consequently NH_3 concentration (Samanya and Yamauchi 2002).

Hmani et al. (2017) reported less NH_3 production when *Bacillus subtilis* HB2 was fed to chicken. *Bacillus subtilis* UBT-MO_2 was found to be effective in decreasing NH_3 emissions in broiler fecal matter. Mixed sex broilers were fed two

Table 9 Effect of *Bacillus amyloliquefaciens* probiotics (BAP) supplementation on ammonia emissions (mg/kg) from broiler excreta (Ahmed et al. 2014)

Length of incubation (h)	BAP (g/kg)					SEM	Contrast, p value	
	0	1	5	10	20		Linear	Quadratic
0	15.8	12.5	8.33	5.83	4.67	1.898	0.0009	0.43
3	28.7	13.8	8.90	6.50	4.83	2.735	0.0006	0.05
6	39.7	21.3	9.33	7.17	4.83	2.474	< 0.0001	0.006
12	62.3	37.3	12.4	7.93	5.33	1.981	< 0.0001	< 0.0001
24	98.3	65.5	15.7	8.43	5.60	4.587	< 0.0001	0.002
48	283	97.8	18.7	9.20	6.31	10.98	< 0.0001	< 0.0001
Average	87.9	41.5	12.2	7.51	5.26	2.762	< 0.0001	< 0.0001

Values represent means of three replicates (front, middle, and back of the house)

levels of enramycin (0 or 5 ppm) and *Bacillus subtilis* (0 or 10^5 cfu/kg). The NH_3 gas was significantly ($p = 0.03$) lowered in broilers fed diets containing *Bacillus subtilis* in contrast to that for bird sans *Bacillus subtilis*. Enramycin or *Bacillus subtilis* did not impact *Escherichia coli* and *Lactobacillus* in ceca and small intestine. *Bacillus subtilis* showed more effective results when added alone as shown in Table 10 (Zhang et al. 2013).

Zhang and Kim (2013) reported less NH_3 emissions when 40-week-old laying hens were fed a diet supplemented with 0.01% probiotic (*Enterococcus faecium* DSM 7134). It was reported that probiotic improved intestinal microbial balance of treated hens and ultimately less NH_3 volatilization. Excreta of probiotic treated hens had more *lactobacillus* counts and less *Escherichia coli* counts in comparison to that of hens fed no probiotics.

According to the literature, multistrain probiotics provided better results and improved functionality when compared to monostrain (Timmerman et al. 2004; Chapman et al. 2011). Yoon et al. (2004) reported the effect of multiple probiotics on NH_3 gas emissions in broiler chicks. One-day-old male broiler chicks were fed with two levels of diets containing probiotics (0 and 0.2%) and three levels of drinking water containing probiotics (0, 0.01, and 0.1%). Drinking water with a 0.1% level significantly decreased NH_3 gas volatilization from broiler fecal matter in contrast to the 0% level. Overall, it was noticed that dietary probiotics reduced this noxious gas emissions from fecal matter. In a similar manner, Hassan and Ryu (2012) illustrated the effect of multiprobiotics [*Lactobacillus plantarum* (5×10^7 cfu/g), *Saccharomyces cerevisiae* (6×10^7 cfu/g), and *Bacillus subtillis* (2×10^7 cfu/g)] on NH_3 gas emissions. The work of Chiang and Hsieh (1995) supported these findings. There was no indication in reduction of malodor by their results, but NH_3 level in fecal matter was lowered by feeding probiotics containing *Lactobacillus acidophilus*, *Streptococcus faecium*, and *Bacillus subtilits*. The effect of dietary probiotics on NH_3 emissions was also observed when

Table 10 Effects of *Bacillus subtilis* probiotic on gas concentration in excreta and intestinal microbial shedding in broiler chicken (Zhang et al. 2013)

Items	− *Bacillus subtilis*		+ *Bacillus subtilis*		p value			
	− Ant	+ Ant	− Ant	+ Ant	SEM[a]	*Bacillus subtilis*	Ant	*Bacillus subtilis* × Ant
NH_3 (ppm) 0.69	78.3	60.9	42.9	58.9	6.2	0.03		0.42
Small intestine								
Lactobacillus 0.11	7.43	7.53	7.51	7.62	0.15	0.14		0.13
E. coli 0.14	6.45	6.28	6.37	6.22	0.21	0.28		0.19
Cecum								
Lactobacillus 0.11	7.95	8.06	8.04	8.16	0.15	0.14		0.13
E. coli 0.14	6.97	6.86	6.79	6.82	0.21	0.28		0.19

Bacillus subtilis and antibiotic (Ant, enramycin) were supplemented at 10^5 cfu/kg and 5 ppm, respectively, or combined at 10^5 cfu *Bacillus subtilis*/kg and 5 ppm enramycin

[a] Standard error of the means; six replicate pens of 20 chicks/pen per treatment for gas concentration in excreta and six replicate pens of 3 chicks/pen per treatment for intestinal microbial shedding

broilers were fed *Bacillus subtilis* and *Lactobacillus acidophilus* versus the control and antibiotics. NH_3 emissions was measured after feeding probiotics and antibiotics for 15 and 35 days. The results showed significant difference in NH_3 reduction in fecal matter of broilers fed probiotics after 15 and 35 days as compared to the control plus antibiotics. Malodor in probiotic fecal matter was detected as lighter than the control and antibiotics. The findings of this study proved the importance of probiotics' use in NH_3 reduction (Chen et al. 2012).

Zhang and Kim (2014) conducted a study to examine the effects of multistrain probiotics on excreta odor for broilers. *Lactobacillus acidophilus*, *Bacillus subtilis*, and *Clostridium butyricum* were added in the control diet with different levels [control diet + 1×10^5 cfu of multistrain probiotics/kg of diet (P1) and control diet + 2×10^5 cfu of multistrain probiotics/kg of diet (P2)]. In another treatment, antibiotic avilamycin (5 mg/kg of avilamycin) was added to the control diet. P2 significantly lowered NH_3 concentration in contrast to all other treatments. P1 also decreased NH_3 concentration as compared to the control. At days 3 and 5, both P1 and P2 reduced NH_3 production in broiler fecal matter over that for the control as shown in Table 11.

Results from Hossain et al. (2015) supported the above findings when tri-strain probiotics (TSP, *Bacillus subtilis*, *Clostridium butyricum*, and *Lactobacillus acidophilus*) were fed to chicken. DM and N digestibility were improved by feeding TSP which led to less NH_3 volatilization.

In 1999, probiotic consisting of *Bacillus*, *Lactobacillus*, *Streptococcus*, *Clostridium*, *Saccharomyces*, and *Candida* species were fed to both male and female broilers to analyze their effect on caecal flora and metabolites, lipid metabolism, meat components, productivity, and raising environment. In the probiotic group, NH_3 in the cecum was significantly ($p <$ 0.05) lower than that for the control group. Additionally, it was reported that pH in cecum was decreased significantly in the probiotic group which was responsible for NH_3 production according to earlier studies (Endo and Nakano 1999).

Table 11 The effect of a multistrain probiotic preparation on NH_3 emission in excreta of broiler (Zhang and Kim 2014)

	NH_3 (mg/m^3)					
DAY	CON	ANT	P1	P2	SEM[a]	*p* value
d1	38.3a	35.2ab	32.4bc	31.0c	0.95	< 0.01
d3	56.2a	55.4a	48.3b	50.5b	1.06	0.01
d5	82.5a	78.5ab	76.3b	77.4b	1.55	0.04

Means in the same row with different letters differ ($p < 0.05$)

CON antibiotic-free diet, *ANT* CON + 5 mg/kg of avilamycin, *P1* CON + 1×10^5 cfu of multistrain probiotics/kg of diet, *P2* CON + 2×10^5 cfu of multistrain probiotics/kg of diet

[a] Each mean represents 15 observations per treatment

Conclusion

The following are the most important strategies used to reduce NH_3 production in poultry houses (Table 12).

NH_3 is the most noxious gas in poultry houses needing control. pH, moisture content, litter, bird age, manure age, relative humidity, ventilation rate, and temperature play important roles in NH_3 production. Seasonality and geological sites are also responsible for its production.

Housing type, manure handling practices, aerobic and anaerobic conditions, and litter amendment are postdigestive strategies. Dietary manipulation for reduction of NH_3 uses low crude protein, synthetic amino acids, supplementation of fiber, and probiotics (single and multistrains).

Many studies have been conducted to evaluate the effect of probiotics on broilers and less with laying hens.

Table 12 Strategies to reduce NH_3 in poultry houses

Determinants	Type
Housing	Manure-belt
	High-rise
	Deep-pit
	Cage-free
	Stilt house
	Conventional cage
	Enriched colony
	Aviary house
Manure handling practice	Once a year
	After every flock
	Once a week
	Twice a week
	Daily
Environment	Anaerobic
Litter amendments	Alum
	Natural zeolite
	Agricultural gypsum
	Dry acids (Al^+ clear, poultry litter treatment, poultry guard)
	Acidified chars (pine chip and coconut husk)
	Urease inhibitors
Diet manipulation	Low crude protein
	Fiber
	Probiotics (single or multiple strains)

More laying hens are needed to fulfill the demand for eggs; therefore, there will be more malodor and environmental pollution produced by NH_3. One possibility includes use of a combination of strategies for reducing NH_3 in layer house. Researchers need to conduct studies on laying hens to minimize the NH_3 production and emissions in poultry houses to protect animal and human health and also to protect the environment from its harmful effects.

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