Research Progress on the Impact of Indoor Air Quality on Broiler Health (Postprint)

Authors: Sun Yong, Wang Ya, Sarenna, Zhang Hongfu(1

Date: 2018-12-24T00:00:00+00:00

Abstract

With the development of large-scale livestock and poultry production, the impact of environmental factors on animal health has become increasingly prominent. High-density, intensive rearing leads to elevated concentrations of microorganisms, dust, and harmful gases within livestock facilities, resulting in continuously deteriorating air quality. Long-term exposure to low-quality air environments contributes to frequent occurrences of respiratory diseases such as broiler tracheitis and broiler respiratory syndrome, indirectly compromising growth performance and immune function. Strengthening research on the hazards of air pollutants in livestock housing to animal health and exploring effective measures to improve air quality in livestock facilities is of great significance to the healthy development of China’ s animal husbandry industry. This paper primarily provides a theoretical basis for in-depth research on the mechanisms of action of air pollutants on broiler health and rational regulation of air quality in housing by reviewing pollutants such as microorganisms, dust, and ammonia, as well as their hazards and countermeasures.

Full Text

Research Progress on the Effects of Air Quality in Poultry Houses on Broiler Health

SUN Yongbo, WANG Ya, SA Renna*, ZHANG Hongfu
State Key Laboratory of Animal Nutrition, Institute of Animal Sciences, Chinese Academy of Agricultural Sciences, Beijing 100193, China
*Corresponding author, E-mail: sa6289@126.com

Abstract

With the development of large-scale livestock and poultry production, environmental impacts on animal health have become increasingly prominent. High-density, intensive farming leads to elevated concentrations of microorganisms, dust, and harmful gases, resulting in continuously deteriorating air quality. Long-term exposure to poor air quality environments causes frequent respiratory diseases such as bronchitis and broiler respiratory syndrome, indirectly reducing growth performance and immune function. Strengthening research on the hazards of air pollutants to livestock health and exploring effective measures to improve air quality in animal housing are of great significance for the healthy development of China' s animal husbandry. This paper primarily reviews pollutants such as airborne microorganisms, dust, and ammonia, their harmful effects, and countermeasures, providing a theoretical basis for further investigating the mechanisms by which air pollutants affect broiler health and for rationally regulating air quality in poultry houses.

Keywords: air quality; broiler; health

---

1. Overview of Air Quality

Healthy broiler growth depends on air quality in poultry houses, which directly affects growth performance, immune function, and product quality [3]. Poor air quality compromises broiler immune function and triggers respiratory diseases. In particular, harmful gases such as ammonia and hydrogen sulfide, as well as microorganisms and their metabolites like endotoxins, can cause airborne infectious diseases that seriously endanger animal health and productivity [4-5]. Respiratory diseases that frequently occur in broilers during winter and spring have become a thorny problem for large-scale farms, with high morbidity and difficulty in control, primarily due to poor air quality in poultry houses [6]. Air quality in livestock facilities has received increasing attention. The Ministry of Agriculture' s "Environmental Quality Standards for Livestock and Poultry Farms" (NY/T 388-1999) 明确规定 that ammonia concentration should not exceed 10 mg/m^3 and hydrogen sulfide should not exceed 2 mg/m^3 in chick houses, while in adult poultry houses ammonia should not exceed 15 mg/m^3 and hydrogen sulfide should not exceed 10 mg/m^3. Additionally, carbon dioxide concentration should not exceed 1,500 mg/m^3, inhalable particulate matter (PM10) should not exceed 4 mg/m^3, and total suspended particulates (TSP) should not exceed 8 mg/m^3. In 2006, the United States launched the "National Air Emissions Monitoring Study" to systematically investigate air pollutants and their hazards at livestock operations. Researching the relationship between air quality in poultry houses and animal health, and exploring effective and practical approaches to control air quality, reduce harmful gases, dust, and pathogenic microorganisms, and improve environmental air quality in chicken houses are of great significance for healthy livestock growth in China.

2.1 Airborne Microorganisms

Poultry houses contain large quantities of microorganisms, mainly including *Staphylococcus*, *Enterococcus*, *Campylobacter*, *Salmonella*, *Clostridium perfringens*, and *Escherichia coli* [7]. Monitoring the concentration of airborne microorganisms or the composition and concentration of certain pathogenic bacteria serves as an effective indicator for evaluating air quality. Vučemilo et al. [8] reported that airborne bacterial concentrations in poultry houses increase with broiler age, with significant increases in microbial contamination during the later growth stages, reaching 6.40×10 CFU/m^3 at 5 weeks of age. Agranovski et al. [9] found that airborne bacterial concentrations in broiler houses ranged from (0.11-6.38)×10 CFU/m^3, with Gram-positive bacteria accounting for 85%; fungal concentrations ranged from (4–620)×10^3 CFU/m^3, primarily including *Cladosporium*, *Aspergillus*, *Penicillium*, and *Fusarium.* Although Gram-negative bacteria accounted for a smaller proportion, they included numerous opportunistic pathogens such as *E. coli*, *Pseudomonas*, *Pasteurella*, and *Neisseria.* Microorganisms attach to dust particles and aerosols to form microbial aerosols, which can spread and transmit through air media, invading the body via respiratory mucosa and causing excessive immune loading, reduced vaccine response, decreased disease resistance, and enhanced susceptibility [10-11]. Zhang et al. [12] reported that elevated bacterial and fungal concentrations in chicken house air significantly reduced Newcastle disease antibody titers and compromised vaccine response capacity in broilers. Xue et al. [13] used an Anderson-6 microbial sampler to study microorganisms in broiler houses and found that bacterial aerosols were primarily collected in stages I, II, and III of the sampler, indicating that bacteria mainly affect the upper respiratory tract of broilers, though some microorganisms were also present in stages IV, V, and VI, capable of entering the lower respiratory tract and damaging lungs. Furthermore, many pathogenic bacteria can produce endotoxins, and long-term exposure to high concentrations of airborne endotoxins can cause poisoning in poultry, growth retardation, immune dysfunction, and various respiratory diseases. Zuker et al. [14] reported that endotoxins can cause respiratory diseases in poultry such as malignant pneumonia and airway obstruction.

2.2 Dust

Dust and particulate matter (PM) in chicken houses primarily originate from feed, feces, droplets produced during respiration, coughing, and vocalization, skin and feather shedding, and airborne microorganisms and fungi [15]. Zhao et al. [16] monitored traditional cage systems and found daily average PM10 and fine particulate matter (PM2.5) concentrations of 0.57-0.61 mg/m^3 and 0.033-0.037 mg/m^3, respectively. Particulate matter in poultry houses has a complex composition, containing heavy metals, ammonia, hydrogen sulfide, volatile organic compounds, endotoxins, bacteria, and viruses [17]. Dust enters the respiratory system through inhalation; particles larger than 10 m are blocked in the nasal cavity and irritate the nasal mucosa, most PM10 adheres to tracheal or lung walls, while PM2.5 can reach deep into alveoli and deposit, entering the bloodstream and potentially causing lung diseases such as emphysema and lung cancer [18-19].

Dust serves as a carrier for harmful gases like ammonia and hydrogen sulfide, as well as microorganisms such as bacteria and viruses, forming microbial aerosols that enter the respiratory system of livestock and poultry, stimulating respiratory mucosa and causing inflammation. Continuous inhalation of dust continuously delivers pathogenic microorganisms to inflamed areas, triggering upper respiratory diseases, chronic bronchitis, and other respiratory infections [20]. Studies have shown that coarse particulate matter primarily causes inflammatory responses through Toll-like receptor-4 (TLR4), while PM2.5 mainly induces macrophage expression of tumor necrosis factor- (TNF-) and interleukin-6 (IL-6) through Toll-like receptor-2 (TLR2) [21]. Particulate matter can also directly affect the respiratory mucosal barrier, reducing expression of antimicrobial peptides defensin-2 and defensin-3, locally lifting inhibition of pathogenic microbial growth [22]. Qu [23] reported that PM2.5 can cause cellular and biomembrane damage in rat lung tissue, induce humoral immune responses and local mucosal immunity changes, and suppress non-specific immune function through various pathways. Shi et al. [24] reported that fine particulate matter causes oxidative stress and inflammatory responses in the trachea and lungs of rats and other animals, destroys mitochondrial and cellular structures, and causes cellular damage. Additionally, dust can adsorb ammonia and odor mixtures, exacerbating hazards to broilers [17].

2.3.1 Ammonia

Under high-density, enclosed housing conditions, broiler houses produce large amounts of toxic and harmful gases, with ammonia being the most hazardous [25]. Amino acids degrade in the body to produce uric acid and urea that are excreted into the gastrointestinal tract, where microbial urease generates ammonia. Meanwhile, litter and other nitrogen-containing materials also produce ammonia under urease action [26]. Zhang et al. [27] found that from 1 to 42 days of age, white-feathered broilers emitted an average of 2,778 mg of ammonia per bird, with an average emission rate of 66 mg/(bird · d). High ammonia concentrations affect cerebral nerve and muscle cell metabolism, cause ammonia poisoning, increase energy consumption for detoxification in organs such as the liver, and consequently reduce broiler growth performance [28]. Reports indicate that excessive ammonia concentrations affect broiler welfare and human health, reduce production performance [29-31], damage the respiratory tract [32], and increase the incidence of airsacculitis and keratoconjunctivitis [33]. Charles et al. [34] reported that exposing chicken houses to high ammonia concentrations of 102 mg/m^3 for one week significantly reduced average daily feed intake and daily weight gain in broilers. Zhang et al. [35] found that 75 mg/m^3 ammonia upregulated 21 proteins related to lipid synthesis, amino acid decomposition, oxidative stress, and liver injury, while downregulating 17 proteins related to energy metabolism, cytoskeletal structure, immune and inflammatory responses, and detoxification functions. Meng et al. [36] reported that ammonia significantly affected footpad scores, hock joint scores, and gait scores in broilers, with increasing ammonia concentrations raising the incidence and severity of feather soiling, footpad infections, and lameness. The broiler respiratory system is particularly sensitive to ammonia stimulation, and long-term exposure causes pathological changes and even necrosis in tracheal and lung tissues. Li [37] found that as ammonia concentration in chicken houses increased, mRNA expression of tight junction protein 1 (claudin1) and mucin 2 (MUC2) in broiler tracheal tissue decreased significantly, while mRNA expression of cysteine protease 3 (caspase-3) increased significantly, indicating that ammonia stress destroyed the mucosal barrier function of tracheal tissue and induced apoptosis in tracheal cells. Prolonged ammonia stimulation causes pathological changes and even necrosis in tracheal and lung tissues, potentially leading to blockage of bronchiole epithelium, edema, atelectasis, hemorrhage, and alveolar emphysema, resulting in respiratory dysfunction [38]. Zhang et al. [39] reported that 0.77 g/m^3 ammonia caused necrosis, shedding, and hemorrhage of tracheal epithelial cells and obvious lung hemorrhage and congestion in broilers. Xiong et al. [40] reported that ammonia stimulation caused oxidative stress damage and histopathological injury in broiler trachea, leading to disorders in immune response and muscle contraction processes, increasing mucus secretion, and causing respiratory obstruction. These studies demonstrate that ammonia seriously endangers broiler health, making it imperative to reduce ammonia concentration and improve air quality in poultry houses.

2.3.2 Hydrogen Sulfide

In anaerobic environments, microorganisms reduce sulfates and decompose sulfur-containing organic matter in livestock feces to produce large amounts of colorless, corrosive, toxic hydrogen sulfide gas with a strong rotten egg odor. Hydrogen sulfide strongly stimulates animal mucosa, causing conjunctivitis, rhinitis, tracheitis, and even pulmonary edema [41]. Hydrogen sulfide combines with sodium ions in mucus to form sodium sulfide, which irritates animal mucosa. When hydrogen sulfide enters the respiratory tract, it stimulates the nasal cavity causing rhinitis and damages the trachea; when it enters the lungs, it causes tracheitis and pulmonary edema. Regular inhalation of low concentrations of hydrogen sulfide leads to autonomic nervous system disorders, and when hydrogen sulfide enters the bloodstream, it hinders oxygen transport, causing hypoxia, weakened constitution, and decreased immunity in livestock [42-43]. Meng [44] reported that hydrogen sulfide reduces feed intake and daily weight gain in broilers, increases mucus secretion in tracheal mucosa, increases cilia damage rate and alveolar rupture, and reduces immunity and meat quality.

2.3.3 Odorous Gases

Livestock farm odors refer to gaseous substances harmful to animals and humans that cause olfactory aversion, mainly including volatile fatty acids, indoles and phenols, ammonia and volatile amines, volatile sulfur compounds, and skatole. Intensive farming models with high stocking density, poor ventilation, and delayed manure removal combined with microbial decomposition result in excessively strong odors. Most of these odorous substances are water-soluble gases that easily adsorb onto respiratory mucosa of humans and animals, reducing immune function and causing respiratory diseases [45].

2.3.4 Carbon Dioxide and Others

Carbon dioxide primarily originates from broiler respiration in poultry houses, with microbial decomposition of feces and litter also producing some carbon dioxide. Although carbon dioxide itself is not toxic, excessively high concentrations lead to low oxygen levels in the house. Chronic oxygen deficiency can cause chronic poisoning, reduced immune function, and decreased feed intake [46]. Carbon dioxide release depends mainly on the number of broilers in the house, and high concentrations indicate poor ventilation and air quality, reduced oxygen content, and affected metabolism. Carbon dioxide concentration serves as a reliable indicator for monitoring air pollution levels, as when it increases, concentrations of other harmful gases also rise [47]. Additionally, in enclosed houses, incomplete combustion of coal for heating in winter may produce large amounts of carbon monoxide, which is toxic to the nervous and blood systems. Carbon monoxide entering broilers combines with hemoglobin in the blood, hindering oxygen transport and causing acute hypoxia, leading to dysfunction of the nervous, circulatory, and respiratory systems and even death [48].

3.1 Enhanced Air Quality Monitoring and Environmental Management

Understanding air conditions in poultry houses is essential for timely and reasonable regulation. Modern livestock house environmental monitoring systems combine multiple environmental sensors for continuous multi-point monitoring, enabling real-time tracking of various air quality indicators including carbon dioxide, ammonia, and hydrogen sulfide, which is crucial for timely air quality improvement. Wang et al. [49] designed a remote monitoring system for poultry house environments based on wireless transmission that can monitor carbon dioxide, ammonia, and other indicators in real time, providing scientific management basis for farm managers and improving management efficiency. Zhu and Liang [50] developed a harmful gas monitoring system for poultry houses based on ZigBee and GPRS technology that can monitor the three major harmful gases—carbon dioxide, ammonia, and hydrogen sulfide—conveniently, quickly, and accurately. Through air quality monitoring, managers can promptly understand air conditions and strengthen management to improve air quality when it deteriorates. Ventilation is the most direct and effective way to reduce harmful gases, dust particles, and microorganisms in chicken houses, though house temperature must also be considered. Timely removal of excreta prevents long-term accumulation and fermentation, thereby reducing emissions of ammonia and hydrogen sulfide. Proper disinfection of poultry houses can reduce airborne microorganism counts and dust concentrations, thereby improving air quality. Wang et al. [51] demonstrated that disinfection with birds present significantly reduced airborne bacterial concentrations in chicken houses, with bacterial counts decreasing significantly one hour after disinfection.

3.2 Dietary Structure Adjustment

Incomplete digestion and absorption of nutrients in feed is the main cause of harmful gases and odors in livestock houses. Reasonable adjustment of dietary structure to improve nutrient utilization can reduce production of ammonia and hydrogen sulfide in poultry houses, thereby improving air quality. Ferket et al. [52] showed that using ideal protein patterns and balancing dietary amino acids with synthetic amino acid additives can improve protein utilization and reduce ammonia and hydrogen sulfide production in excreta. Ferguson et al. [53] found that reducing dietary crude protein content could decrease ammonia concentration in chicken houses by 31%. Roberts et al. [54] reported that feeding laying hens high-fiber diets reduced ammonia volatilization from excreta. These studies demonstrate that adjusting dietary structure can effectively improve air quality in poultry houses.

3.3 Use of Feed Additives

Common feed additives include probiotics, prebiotics, and compound microecological preparations, plant extracts, Chinese herbal additives, enzyme preparations, and acidifiers. Probiotics, prebiotics, and compound microecological preparations can improve feed conversion efficiency and modify intestinal microbial structure, thereby reducing emissions of harmful gases such as ammonia. Hossain et al. [55] reported that adding 0.1% compound probiotics (containing *Bacillus subtilis*, *Clostridium butyricum*, and *Lactobacillus acidophilus*) to diets significantly reduced ammonia emissions. Wang et al. [56] showed that adding 0.3% fructooligosaccharides and 0.1% *Bacillus subtilis* to feed significantly reduced ammonia and hydrogen sulfide emissions. Tong et al. [57] reported that spraying compound *Bacillus* solution in houses significantly reduced populations of *E. coli* and *Staphylococcus aureus* in broiler house air. Luan et al. [58] found that spray preparations significantly reduced total aerobic bacteria, *E. coli*, and *S. aureus* counts in chicken house air and excreta, purifying the microbial environment. Using plant extracts to reduce harmful gas concentrations in livestock houses has become a research hotspot, as they can inhibit urease activity and block microbial urease synthesis pathways, reducing urease secretion and thereby inhibiting ammonia production from urea decomposition in excreta. Yu et al. [59] showed that extracts from Lauraceae and *Yucca* plants could reduce ammonia and hydrogen sulfide emissions from livestock excreta. Li et al. [60] reported that dietary supplementation with phytoncide significantly reduced ammonia emissions, with ammonia decreasing linearly as phytoncide concentration increased. Bostami et al. [61] found that adding 0.5% fermented pomegranate byproducts to diets significantly reduced ammonia and hydrogen sulfide concentrations in houses. Enzyme preparations such as protease and phytase can supplement endogenous enzymes, reduce anti-nutritional factors in feed, and promote nutrient digestion and absorption, thereby reducing nitrogen and sulfur content in feces. Zhang [62] showed that adding different levels of enzyme preparations to broiler diets significantly reduced airborne microorganism counts and ammonia concentrations. Acidifiers can reduce gastrointestinal pH in broilers, providing a suitable environment for digestive enzymes and microorganisms, promoting pepsin synthesis, improving protein digestibility, and reducing odor from intestines and excreta [63]. Additionally, many minerals with large specific surface area and pore volume have strong adsorption capacity for ammonia, hydrogen sulfide, carbon dioxide, and water, thereby improving air quality. Currently, many minerals are used to improve air environment in livestock houses, such as zeolite, bentonite, attapulgite, and montmorillonite, which can adsorb ammonia, hydrogen sulfide, carbon dioxide, and water molecules, inhibiting production and volatilization of harmful gases [64].

3.4 Application of Air Electro-Purification Technology

High-voltage electrodes in space electric fields discharge to produce high-energy charged particles and trace ozone that can oxidize and decompose harmful gases, while the electric field and high-energy charged particles can also inhibit harmful gas production. High-energy charged particles and trace ozone produced by discharge from high-voltage electrodes can effectively kill or inactivate pathogenic microorganisms attached to dust particles and droplets [65]. Ritz et al. [66] reported that using an electrostatic space charge system (ESCS) significantly reduced dust and ammonia concentrations in chicken houses. Yang et al. [67] found that high-energy photoelectric deodorization equipment and photoelectric deodorizers significantly reduced ammonia concentration, particle counts, and microbial concentrations, improving air quality. Negative air ions carry negative charges and easily attract, collide with, and combine with positively charged pollutants in the air to form larger molecules that settle, providing bactericidal, dust-reducing, and air-purifying effects. Jiao et al. [68] installed artificial negative ion generators in houses, significantly reducing total aerobic bacteria counts and dust concentrations, demonstrating that artificial negative ions can improve air quality and promote healthy livestock growth. These studies show that electro-purification technology has become an effective measure for air purification in poultry houses and warrants further research and promotion.

4. Conclusion

Air quality in broiler farms not only affects broiler disease prevention, health, and product quality, but is also closely related to human health. Strengthening research on the relationship between air quality in broiler houses and health, and improving air quality are of great significance for promoting healthy development of the broiler industry. Future research should combine advanced technologies such as high-throughput sequencing, proteomics, transcriptomics, and metabolomics to deeply investigate the hazards and mechanisms of airborne microorganisms, dust, and harmful gases on livestock and poultry. Meanwhile, meta-analysis methods should be employed to integrate and analyze the effects of microorganisms, dust, and harmful gases, providing references for establishing air quality evaluation models and standards for broiler houses.

References

[1] 袁建敏, 张开臣, 胡骁飞. 环境因素影响肉鸡生长的研究进展 [J]. 家畜生态学报,2007,28(6):135-138.

[2] URBAIN B, PROUVOST J F, BEERENS D, et al. Chronic exposure of pigs to airborne dust endotoxins environmental chamber: technical note[J]. Veterinary Research,1996,27(6):569-578.

[3] HOMIDAN A A, ROBERTSON J F, PETCHEY A M. Review of the effect of ammonia and concentrations broiler performance[J]. World' s Poultry Science Journal,2003,59(3):340-349.

[4] URBAIN B, PROUVOST J F, BEERENS D, et al. Acute effects of endotoxin inhalation on respiratory tract pigs: interaction ammonia[J]. Inhalation Toxicology,1996,8(9):947-968.

[5] WHYTE R, WILLIAMSON P, LACEY J. Air pollutant burdens and respiratory impairment of poultry house stockmen[J]. Livestock Environment,1993,4:709-717.

[6] 伍清林, 金兰梅, 周玲玲, 等. 规模化猪场舍内外空气质量变化的研究 [J]. 中国畜牧兽医,2012,39(11):220-225.

[7] 高敏, 贾瑞志, 仇天雷, 等. 畜禽养殖中逸散生物气溶胶特征的研究进展 [J]. 生态与农村环境学报,2015,31(1):12-21.

[8] VUČEMILO M, VINKOVIĆ B, MATKOVIĆ K. Influence of broilers age on airborne pollutants content in poultry house[J]. Krmiva,2006,48(1):3-6.

[9] AGRANOVSKI V, REPONEN T, RISTOVSKI Z. Survey of bioaerosol emissions from australian poultry buildings[C]//European Aerosol Conference 2007. Salzburg: Abstract,2007.

[10] HO J, DUNCAN S. Estimating aerosol hazards from an anthrax letter[J]. Journal of Aerosol Science,2005,36(5/6):701-719.

[11] 仝永娟. 复合芽孢杆菌制剂对鸡舍空气微生物及肉鸡免疫功能的影响 [D]. 硕士学位论文. 北京: 中国农业科学院,2013.

[12] 张红双, 秦梅, 柴同杰, 等. 不同养殖环境对商品肉鸡免疫功能的影响 [J]. 华中农业大学学报,2011,30(1):34-38.

[13] 薛俊龙, 刘源, 王志宇, 等. 智能化密闭商品肉鸡舍冬季生物气溶胶分布研究 [J]. 中国家禽,2017,39(5):39-44.

[14] ZUCKER B A, TROJAN S, MÜLLER W. Airborne gram-negative bacterial flora in animal houses[J]. Journal of Veterinary Medicine, Series B,2000,47(1):37-46.

[15] 刘会娟. 鸡舍内粉尘控制方法初探 [J]. 畜牧与兽医,2013,45(10):58-60.

[16] ZHAO Y, SHEPHERD T A, LI H, et al. Environmental assessment of three egg production systems-Part I: Monitoring system indoor quality[J]. Poultry Science,2015,94(3):518-533.

[17] CAMBRA-LÓPEZ M, AARNINK A J A, ZHAO Y, et al. Airborne particulate matter from livestock production systems: A review of an air pollution problem[J]. Environmental Pollution,2010,158(1):1-17.

[18] 汪开英, 代小蓉. 畜禽场空气污染对人畜健康的影响 [J]. 中国畜牧杂志,2008,44(10):32-35.

[19] XING Y F, XU Y H, SHI M H, et al. The impact of PM2.5 on the human respiratory system[J]. Journal of Thoracic Disease,2016,8(1):E69-E74.

[20] DAVID B, MEJDELL C, MICHEL V, et al. Air quality in alternative housing systems may impact laying welfare. Part —Ammonia[J]. Animals,2015,5(3):886-896.

[21] 张宏福. 环境生理在畜禽健康养殖中的研究与应用 [J]. 中国家禽,2015,37(24):1-4.

[22] RIVAS-SANTIAGO C E, SARKAR S, CANTARELLA P, et al. Air pollution particulate matter alters antimycobacterial respiratory epithelium innate immunity[J]. Infection and Immunity,2015,83(6):2507-2517.

[23] 曲红梅. PM2.5 对大鼠的肺损伤及其机制的研究 [D]. 硕士学位论文. 兰州: 兰州大学,2006.

[24] 史云洁, 王沛, 马姗婕, 等. 大气细颗粒物对实验动物氧化应激及炎症反应研究进展 [J]. 中国公共卫生,2017,33(1):35-38.

[25] CARLILE F S. Ammonia in poultry houses: a literature review[J]. Worlds Poultry Science Journal,1986,40(2):99-113.

[26] 彭焕伟, 沈亚欧. 畜禽生产中氨的危害及防治措施 [J]. 饲料工业,2005,26(13):54-59.

[27] 张晓迪, 卢庆萍, 张宏福, 等. 利用呼吸舱测定肉鸡氨气排放的研究 [J]. 畜牧兽医学报,2014,45(2):249-254.

[28] 魏凤仙, 胡骁飞, 张敏红, 等. 相对湿度和氨气应激对肉仔鸡血氨水平及细胞因子含量的影响[J]. 动物营养学报,2013,25(10):2246-2253.

[29] 李聪, 卢庆萍, 唐湘方, 等. 不同氨气浓度对肉鸡生长性能及肉质性状的影响 [J]. 中国农业科学,2014,47(22):4516-4523.

[30] BEKER A, VANHOOSER S L, SWARTZLANDER J H, et al. Atmospheric ammonia concentration effects on broiler growth and performance[J]. The Journal of Applied Poultry Research,2004,13(1):5-9.

[31] MILES D M, BRANTON S L, LOTT B D. Atmospheric ammonia is detrimental to the performance of modern commercial broilers[J]. Poultry Science,2004,83(10):1650-1654.

[32] AZIZ T, BARNES H J, 郭传凤. 氨气对家禽的危害 [J]. 国外畜牧学 (猪与禽),2010,30(5):33-35.

[33] KRISTENSEN H H, WATHES C M. Ammonia and poultry welfare: a review[J]. World' s Poultry Science Journal,2000,56(3):235-245.

[34] CHARLES D R, PAYNE C G. The influence of graded levels of atmospheric ammonia on chickens. . Effects performance laying hens[J]. British Poultry Science,1966,7(3):177-187.

[35] ZHANG J Z, LI C, TANG X F, et al. High Concentrations of atmospheric ammonia induce alterations in the hepatic proteome of broilers (Gallus gallus): an iTRAQ-based quantitative proteomic analysis[J]. PLoS One,2015,10(4):e0123596.

[36] 孟丽辉, 李聪, 卢庆萍, 等. 不同氨气浓度对肉鸡福利的影响 [J]. 畜牧兽医学报,2016,47(8):1574-1580.

[37] 李聪. 不同浓度氨气对肉鸡生长性能及呼吸道黏膜屏障的影响 [D]. 硕士学位论文. 北京: 中国农业科学院,2014.

[38] BOYD E M, MACLACHLAN M L, PERRY W F. Experimental ammonia gas poisoning in rabbits and cats[J]. Journal of Industrial Hygiene and Toxicology,1944,26(1):29-34.

[39] 张西雷, 张莉平, 王春民, 等. 试验性肉鸡氨气急性中毒的病理学研究 [J]. 家畜生态学报,2006,27(1):63-65.

[40] 熊嫣, 唐湘方, 孟庆石, 等. 高氨刺激下参与免疫应答和肌肉收缩过程的肉鸡气管蛋白差异表达——基于 iTRAQ 标记技术的差异蛋白质组学研究 [J]. 中国科学: 生命科学,2016,46(11):1267-1276.

[41] GUARRASI J, TRASK C, KIRYCHUK S. A systematic review of occupational exposure hydrogen sulfide livestock operations[J]. Journal Agromedicine,2015,20(2):225-236.

[42] 孙建忠. 畜禽圈舍有害气体对畜禽及环境的危害 [J]. 畜禽业,2015(1):36-37.

[43] 张莹莹, 刘春青, 刘晓辉, 等. 畜禽舍有害气体的来源及其常用消毒方法 [J]. 饲料博览,2014(3):11-13.

[44] 孟庆平. 不同硫化氢浓度对肉仔鸡生长性能、免疫功能和肉质的影响 [D]. 硕士学位论文. 杭州: 浙江大学,2009.

[45] 张鸿郭, 周少奇, 石永. 恶臭气体微生物处理技术研究进展 [J]. 四川环境,2006,25(3):95-100.

[46] 魏凤仙, 胡骁飞, 李绍钰, 等. 肉鸡舍内有害气体控制技术研究进展 [J]. 中国畜牧兽医,2011,38(11):231-234.

[47] 黄华, 牛智有. 基于 PIC18F2580 的畜禽舍有害气体环境控制系统 [J]. 测控技术,2009,28(4):49-52,57.

[48] 刘希颖, 赵越. 畜舍中有毒有害气体对畜禽的危害及防治 [J]. 饲料工业,2004,25(10):58-60.

[49] 王欢, 李骅, 尹文庆, 等. 基于无线传输的鸡舍环境远程监测系统 [J]. 南京农业大学学报,2016,39(1):175-182.

[50] 朱凤舞, 梁天航. 基于 ZigBee 和 GPRS 鸡舍有害气体监控系统的设计 [J]. 农业与技术,2016,36(7):63-65.

[51] 王静, 谷巍, 代惠洁. 规模化养鸡场鸡舍内空气和饮水细菌含量检测 [J]. 家畜生态学报,2011,32(3):71-74.

[52] FERKET P R, VAN HEUGTEN E, VAN KEMPEN T A T G, et al. Nutritional strategies to reduce environmental emissions from nonruminants[J]. Journal of Animal Science,2002,80(2S):168-182.

[53] FERGUSON N S, GATES R S, TARABA J L, et al. The effect of dietary crude protein on growth, ammonia concentration, and litter composition broilers[J]. 1998,77(10):1481-1487.

[54] ROBERTS S A, XIN H, KERR B J, et al. Effects of dietary fiber and reduced crude protein on ammonia emission from laying-hen manure[J]. Poultry Science,2007,86(8):1625-1632.

[55] HOSSAIN M M, BEGUM M, KIM I H. Effect of Bacillus subtilis, Clostridium butyricum Lactobacillus acidophilus endospores growth performance, nutrient digestibility, meat quality, relative organ weight, microbial shedding and excreta noxious gas emission in broilers[J]. Veterinarni Medicina,2015,60(2):77-86.

[56] 王晓霞, 易中华, 计成, 等. 果寡糖和枯草芽孢杆菌对肉鸡肠道菌群数量、发酵粪中氨气和硫化氢散发量及营养素利用率的影响 [J]. 畜牧兽医学报,2006,37(4):337-341.

[57] 仝永娟, 萨仁娜, 张宏福, 等. 三株芽孢杆菌抑菌活性分析及对肉鸡舍空气微生物的影响 [J]. 中国农业科学,2013,46(20):4344-4353.

[58] 栾素军, 孙永波, 萨仁娜, 等. 芽孢杆菌喷雾制剂对鸡舍环境微生物的影响 [J]. 西北农林科技大学学报（自然科学版）,2017,45(10):21-29.

[59] 喻洋, 李晓燕, 王旭平, 等. 樟科提取物、腐植酸及其复合添加对仔猪粪尿中氨排放的影响 [J]. 中国畜牧杂志,2011,47(9):61-64.

[60] LI H, ZHAO P Y, LEI Y, et al. Phytoncide, phytogenic feed additive as an alternative to conventional antibiotics, improved growth performance and decreased excreta gas emission without adverse effect on meat quality in broiler chickens[J]. Livestock Science,2015,181:1-6.

[61] BOSTAMI A B M R, AHMED S T, ISLAM M M, et al. Growth performance, fecal noxious gas emission and economic efficacy in broilers fed fermented pomegranate byproducts as residue of fruit industry[J]. International Journal,2015,3(3):102-114.

[62] 张莉平. 微生态酶制剂对鸡舍空气净化的研究 [J]. 中国畜牧兽医,2010,37(7):227-229.

[63] 张土保, 许英梅, 安立龙, 等. 养殖场中的恶臭及其营养控制措施 [J]. 饲料工业,2009,30(7):48-52.

[64] 史明雷, 郑兰, 郭孝烨, 等. 载铜硅酸盐纳米微粒对黄羽肉鸡肠道菌群、氮代谢和排泄物氨逸失的影响 [J]. 动物营养学报,2013,25(8):1843-1850.

[65] 张义俊, 王万章, 李保谦, 等. 畜禽舍环境控制技术 [J]. 中国家禽,2007,29(5):24-26.

[66] RITZ C W, MITCHELL B W, FAIRCHILD B D, et al. Improving in-house air quality in broiler production facilities using an electrostatic space charge system[J]. The Journal of Applied Poultry Research,2006,15(2):333-340.

[67] 杨立强, 施正香, 赵芙蓉, 等. 不同空气净化设备对鸡舍空气净化效果的比较研究 [J]. 中国畜牧杂志,2017,53(5):127-131.

[68] 焦洪超, 孙利, 崔灿, 等. 人工负离子对鸡舍空气环境净化作用研究 [J]. 畜牧兽医学报,2017,48(8):1543-1550.

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv —Machine translation. Verify with original.