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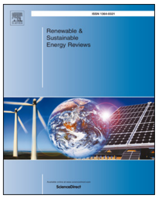

Tackling ammonia inhibition for efficient biogas production from chicken manure: Status and technical trends in Europe and China

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ABSTRACT

The increased global consumption of chicken products has resulted in the generation of huge amounts of manure. Numerous studies emphasized the large potential of this waste as an untapped source of renewable energy through anaerobic digestion (AD). However, intrinsic difficulties, in particular the high N content, induce instable process conditions, including the accumulation of intermediates, and foaming, which reduces methane yields. Such issues limit the widespread application of this energy-rich substrate for biogas production. The process inhibition by ammonia is usually prevented by reducing the concentration of chicken manure through dilution or by operating the plant considerably below its theoretical reactor capacity. However, this process compromises process efficiency, thereby increasing capital investments and operational costs. Another option to achieve optimal process performance is co-digestion with less N-rich materials. However, co-digestion also has its limitations due to the frequent unavailability of sufficient amounts of C-rich substrates. A series of promising technical solutions have been developed to overcome the aforementioned bottlenecks. Examples include stripping or membrane extraction as means to reduce ammonia concentration in the fermenter. Several full-scale plants employing ammonia removal techniques have been installed recently. Latest research also investigated the use of additives, such as zeolites and trace elements, as well as bioaugmentation, to mitigate ammonia inhibition. The current study reviews the state of technology as well as recent achievements and perspectives. It provides an overview of the different approaches to remove ammonia from AD-process and presents practical examples from China and Europe.

1. Introduction

World food economy is driven by the shift in consumption pattern towards livestock products, as reflected by the extraordinary performance of the global poultry meat production. Chicken meat consumption increased by almost 50% (from 14.8 kg to 22 kg per capita) from 2000 to 2014. In the same period, global egg production increased by 36.5% or an average of 2.8% per year [1]. According to statistics of the Food and Agriculture Organization of the United Nations, China and the European Union produced 26.8 and 7.2 million tons of egg and 13.3 and 11.9 million tons of chicken meat in 2016, respectively [2]. Growing demands lead to a massive intensification of the poultry industry with increased stocking densities. Clustering of poultry production in certain preferred locations occurs in Europe and in China. As a result, large volumes of excreta are accumulated in concentrated areas, thereby contributing to regional-level nutrient overload [3]. The excessive use of chicken manure as organic fertilizer may cause eutrophication in soil and water bodies, pathogen spread, air pollution, and greenhouse gas emission [4]. The sustainable operation of such large production units is only feasible when chicken manure is adequately reutilized. Composting is a possible treatment for stabilization. However, a distinct disadvantage is the strong loss of N. This phenomenon reduces the fertilizer value and may cause odor nuisance and pose a considerable threat to the environment [5]. An ecofriendly treatment alternative is anaerobic digestion (AD), which offers additional benefit to allow the recovery of the caloric value through biogas

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Abbreviations: AD, Anaerobic digestion; Anammox, Anaerobic ammonium oxidation; BMP, Bio-methane potential; CHP, Combined heat and power plant; CSTR, Continuous stirred-tank reactor; DQY, Deqingyuan (location of large chicken farm in China); MWel, Installed electrical capacity in megawatts; MWh, Megawatt hours (amount of electric energy over a period of time); NH_3, (Free) Ammonia; NH_4^+, Ammonium ion; OLR, Organic loading rate; TAN, Total ammoniacal nitrogen; TN, Total nitrogen; TKN, Total kjeldahl nitrogen; TS, Total solids; UASB, Up-flow anaerobic sludge blanket (reactor); VFAs, Volatile fatty acid(s); VS, Volatile solids

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generation. Unfortunately, the high N content of chicken manure is prohibitive to efficient AD. During microbial degradation, organic N is converted to ammonia. At high concentrations, ammonia exerts a strong inhibitory effect on microbiological conversion. The toxicity is caused by the nondissociated free ammonia [6,7]. This compound diffuses into cells and causes proton imbalance or interferes with the metabolic enzymes of microorganisms [8]. The key to successful chicken manure AD is to overcome ammonia inhibition.

Numerous studies have pointed out that chicken manure is a potential source of renewable energy through AD [9–14]. However, the number of successful full-scale applications has been limited. Rewarding prospects have triggered considerable research effort to tackle the encountered difficulties. A huge variety of options, including dilution, change in process parameters (i.e., pH or temperature), biomass adaptation, bioaugmentation, and use of additives (e.g., zeolites or trace elements), have been under investigation. More recently, technical options for N removal have been under intensive investigation. In this context, significant technological progress has been achieved to overcome restrictions associated with the use of chicken manure as a substrate for biogas production. The current paper reviews the latest trends and innovations with a particular view of the situation in Europe and China. It presents different options used to enhance the AD of chicken manure, with focus on the latest technical solutions that have not been fully acknowledged in previous reviews. It provides an overview of research trends and compares it with a brief compiled information on established full-scale AD plants to provide an overview of the current state of technological development.

2. AD of chicken manure

2.1. Composition of chicken manure and biomethane potential (BMP)

Chicken reared in intensive production systems consume large amounts of protein and other N-containing substances in their diets. The conversion of dietary N to animal products is relatively inefficient, where 50–80% of N is excreted [15]. Consequently, chicken manure is rich in N-compounds and other nutrients, such as P and K. The main N compounds occurring in fresh waste are uric acid and undigested protein, which represent approximately 70% and 30%, respectively, of the N content [16]. Uric acid is rapidly converted to ammonia by aerobic and anaerobic microorganisms [17,18]. Depending on storage time and conditions, ammonia constitutes 50–90% of the total N [19]. In general, chicken manures may vary in physical and chemical compositions. Factors affecting composition include types of chicken raised, number of chickens per area, feed nutrient density, and other management factors. As mentioned before, environmental factors during production and storage as well as post-handling methods significantly influence the composition of poultry manure [20]. One major difference is related to the type of chicken industry, that is, egg or meat production. Broiler breeding involves the use of bedding materials, such as sawdust, wood shavings, wheat straw, peanut, or rice husks. During broiler production, these materials are mixed with accumulating manure. The mixture of poultry excreta, spilled feed, feathers and bedding material, and manure [4,5] is commonly also denoted as poultry litter. By contrast, poultry manure consists only of fecal droppings and is associated with caged laying hens. Shen at al. [21] conducted a comprehensive survey on different types of animal manure in China. In the study, 162 layer manures and 111 broiler manures were sampled. The typical composition of the chicken manure in their study is presented in Table 1.

Table 1
Typical composition of chicken manure [21].

Parameter	*Unit*	*Layer manure*	*Broiler manure*
Moisture content	(%)	72.26 ± 9.95	63.88 ± 8.79
Volatile solids (VS)	(% of TS)	62.56 ± 7.09	62.47 ± 11.02
Ash	(% of TS)	32.44 ± 9.80	27.76 ± 13.56
Total nitrogen (TN)	g/kg	33.9 ± 12.5	37.0 ± 12.6
Total phosphorus (TP)	g/kg	12.83 ± 5.27	11.07 ± 5.47
Potassium (K)	g/kg	23.86 ± 7.63	15.96 ± 9.93

With respect to renewable energy generation, chicken manure is particularly suitable due to its high BMP which is among the highest of all livestock manures [22,23]. On average, each kilogram of organic matter yields approximately 0.5 m^3 of biogas with approximately 58% methane content. A frequently used biogas handbook indicates a methane yield range of 200–360 mL/gVS for chicken manure [24]. BMP also changes with the increase in the age of chicken; it is high in young chicks and gradually decreases parallel to the maturation of the digestive tract.

2.2. Difficulties related to the AD of chicken manure

Certain limitations in using chicken manure for biogas generation need to be addressed. Chicken manure is viscous in nature with high Ca content and sand/grit. Careful sand removal is an important prerequisite, and measures need to be implemented to avoid sediments in the digesters and guarantee long-term process stability. Feathers also pose a problem and require pretreatment [16,25–33]. In addition to the aforementioned factors that may affect AD performance, ammonia concentration is also crucial. Ammonia is a final product of the anaerobic conversion of N-containing compounds, such as proteins, nucleic acid, and urea or uric acid. In general, N is an essential nutrient for microbial growth. However, N, as a major excretory constituent, is abundant in different types of animal manure. In addition to its role as nutrient, ammonia can act as a counter ion for bicarbonate, thereby allowing its enhanced dissolution in the aqueous phase. Therefore, optimal ammonia concentration ensures sufficient buffer capacity of methanogenic medium in AD, thereby increasing process stability [34]. On the other hand, a high amount of ammonia is regularly reported as the primary cause of digester failure because of its direct inhibitory effect on microbial activity [35]. Several mechanisms for ammonia inhibition have been proposed, such as change in intracellular pH, increase in maintenance energy requirement, and inhibition of specific enzyme reactions [36]. Methanogens are generally less tolerant than the other microbial groups involved in AD. Thus, methanogens are likely to cease methane production [37]. Acetoclastic methanogens are also more sensitive than hydrogenotrophic species to ammonia inhibition [38–40]. More details on the mechanisms underlying inhibition and its effects on the anaerobic microbial flora are provided in the study by Rajagopal et al. [35]. Previous studies associated inhibition to total ammonia nitrogen (TAN) concentration, which is the sum of free ammonia (NH_3) and its ionized form ammonium (NH_4^+) [7,41,42]. According to different studies, the inhibitory TAN concentration ranges widely from 1.5 g/L to 7.0 g/L, which is attributed to differences in the nature of substrates, inoculum, environmental conditions, and acclimation periods [36,43]. It has been suggested that, for an undisturbed AD, TAN concentration should remain below 3.0 g/L, which is supposed not to cause toxicity [44]. However, successful acclimation of the microbial flora to TAN concentrations as high as 4.0 g/L to 5.0 g/L has been reported [35,45,46]. According to the authors' experience, based on numerous samples from biogas plants in Austria and Central Europe, typical TAN concentrations in plants applied with chicken manure range from 4.0–5.0 g/L. A few exceptions operate at TAN levels of up to 6.5 g/L. This concentration range fits also the scarce data that have been obtained from full-scale chicken manure biogas plants in China.

3. Strategies to overcome ammonia inhibition

Both at lab and full scale it has been demonstrated that a well-managed system can tolerate TAN concentration of up to 7.500 g/L [47,48]. It is generally acknowledged that free ammonia is the main cause of anaerobic microflora inhibition [35,46,49], although TAN