Waste Management 69 (2017) 508–517

Contents lists available at ScienceDirect

Waste Management

journal homepage: www.elsevier.com/locate/wasman

Cost-effective treatment of swine wastes through recovery of energy and nutrients

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ARTICLE INFO

Article history:
Received 6 February 2017
Revised 4 August 2017
Accepted 22 August 2017
Available online 31 August 2017

Keywords:
Swine waste
Anaerobic digestion
Struvite
Ion exchange
Nutrient recovery
Life cycle cost analysis

ABSTRACT

Wastes from concentrated animal feeding operations (CAFOs) are challenging to treat because they are high in organic matter and nutrients. Conventional swine waste treatment options in the U.S., such as uncovered anaerobic lagoons, result in poor effluent quality and greenhouse gas emissions, and implementation of advanced treatment introduces high costs. Therefore, the purpose of this paper is to evaluate the performance and life cycle costs of an alternative system for treating swine CAFO waste, which recovers valuable energy (as biogas) and nutrients (N, P, K^+) as saleable fertilizers. The system uses in-vessel anaerobic digestion (AD) for methane production and solids stabilization, followed by struvite precipitation and ion exchange (IX) onto natural zeolites (chabazite or clinoptilolite) for nutrient recovery. An alternative approach that integrated struvite recovery and IX into a single reactor, termed STRIEX, was also investigated. Pilot- and bench-scale reactor experiments were used to evaluate the performance of each stage in the treatment train. Data from these studies were integrated into a life cycle cost analysis (LCCA) to assess the cost-effectiveness of various process alternatives. Significant improvement in water quality, high methane production, and high nutrient recovery (generally over 90%) were observed with both the AD-struvite-IX process and the AD-STRIEX process. The LCCA showed that the STRIEX system can provide considerable financial savings compared to conventional systems. AD, however, incurs high capital costs compared to conventional anaerobic lagoons and may require larger scales to become financially attractive.

1. Introduction

The treatment of animal manure represents a significant environmental problem that has grown in importance as meat demand has increased. From 1961 to 1999, worldwide meat demand grew from 9 to 19 kg/capita/yr and is expected to increase to 30 kg/capita/yr by 2025 (Choi, 2007). In particular, swine production represents nearly 40% of the world's meat production, and waste generated from swine production is a growing international concern (Choi, 2007). Due to this increased demand, large-scale production of swine in concentrated animal feeding operations (CAFOs) has become increasingly common. These CAFOs generate large amounts of waste which contain high levels of organics, solids, pathogens, phosphorus (P), nitrogen (N), and potassium (K^+), resulting in considerable stress on the environment (Bernet and Béline, 2009; Chynoweth et al., 1999).

Conventional treatment of CAFO waste in the U.S. in uncovered anaerobic lagoons has high land requirements and is associated with odors, attraction of insects and rodents, greenhouse gas emissions, poor effluent quality, release of pathogens, contamination of surface and ground water, and catastrophic spills (Moser, 1998; Sakar et al., 2009). These systems also do not allow for removal or recovery of nutrients (N, P, K^+), leading to eutrophication of water bodies (Burke et al., 2004). Because of these issues, USEPA now requires CAFOs to develop nutrient management plans and to eventually eliminate the use of open-air and unlined lagoons for CAFO waste treatment and storage (USEPA, 2008). However, implementation of alternative treatments is often associated with high costs. Technologies that are able to recover valuable resources such as N, P, K, and energy from the waste, such as capture of bioenergy from covered anaerobic lagoons or screening and composting of solids, could potentially avoid the negative environmental effects of conventional treatment while offsetting treatment costs.

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http://dx.doi.org/10.1016/j.wasman.2017.08.041
0956-053X/

An alternative technology for treatment of swine CAFO waste is in-vessel anaerobic digestion (AD). AD allows for energy recovery in the form of methane, which can be used for cooking, heating buildings, vehicle fuel, liquid fuel production, and/or co-generation of electricity, and can be added to natural gas infrastructure or contribute to the energy requirements of operating the AD system (Westerman et al., 2008). When treated waste leaves AD, the solid and liquid portions can be separated to allow for recovery of the stabilized biosolids, which can be applied to land for beneficial reuse. AD also allows for release of nutrients from digested solids into liquid solution (hereafter termed "centrate", even if the liquid-solid separation process is not centrifugation), making the nutrients more accessible for recovery as a valuable fertilizer (Booker et al., 1999).

Struvite ($MgNH_4PO_4{\cdot}6H_2O$) precipitation represents a viable option for recovery of both N and P from AD centrate in the form of a saleable solid fertilizer, reducing the demands for conventional fertilizer production (Tao et al., 2016). Struvite precipitation has been investigated by a number of researchers for municipal wastewater (see review by Corre et al., 2009). However, struvite precipitation in AD centrate from swine waste is less well understood. In particular, high magnesium (Mg^{2+}) concentrations in swine waste may prove particularly beneficial because they decrease the need for Mg^{2+} addition, often the most significant cost component in struvite precipitation (Dockhorn, 2009).

While struvite precipitation is expected to remove a large portion of the P, only a small portion of the dissolved N is typically recovered (Corre et al., 2009). Therefore, additional treatment is required to remove or, preferably, recover N that remains in solution after struvite precipitation. Towards this goal, use of ion exchange (IX) with natural zeolites has the potential to recover both N and K^+ as a solid fertilizer. Natural zeolites are hydrated aluminosilicates that have affinity for ammonium and potassium (Jorgensen et al., 1976) and have been used in agriculture and environmental remediation (Chmielewska, 2003; Mumpton, 1999; Polat et al., 2004; Tian and Wen, 2004). Furthermore, when applied as a soil amendment, zeolites reduce overall fertilizer requirements and decrease eutrophication by increasing the soil ion exchange capacity, which allows for slower release of applied fertilizers (Mumpton, 1999). Therefore, IX using zeolites can be a potentially cost effective method for recovering nutrients. Use of zeolites for nutrient recovery from wastes has been evaluated previously (Ganrot et al., 2007; Liberti et al., 1981; Lind et al., 2000), but typically the zeolite is regenerated with a brine solution which may require disposal. Using the nutrient-rich zeolite as a solid fertilizer, however, avoids the need to use or dispose of brine.

When zeolites are added to water, a hydrolysis reaction occurs, which raises the pH (Perić et al., 1999). This has the potential to allow for struvite recovery and IX in a single reactor (termed here as STRIEX). Advantages of the STRIEX process are a reduced number of unit operations required and elimination of chemicals required to change pH. Prior studies have evaluated STRIEX with synthetic swine and municipal wastes, concluding that the process is feasible and can achieve over 80% recovery of nutrients (Huang et al., 2014; Lin et al., 2014). However, to date, the STRIEX process has not yet been assessed with real swine wastewaters.

Therefore, the purpose of this research was to evaluate the performance and carry out life cycle cost analysis (LCCA) of treatment of swine CAFO wastes by two proposed systems (Fig. 1): either AD followed by struvite precipitation and IX with natural zeolites, or AD followed by STRIEX. We hypothesize that the recovery of bioenergy and nutrients will make both of the proposed technologies more cost-effective than conventional swine CAFO treatment. The specific objectives were to (1) evaluate bioenergy recovery, water quality improvement, and the fate of nutrients for the proposed systems in bench- and pilot-scale reactors and (2) perform a LCCA on the proposed processes individually and together. This research provides increased understanding of the interactions and synergies of utilizing anaerobic digestion and nutrient recovery technologies together, particularly in the context of swine waste treatment. Furthermore, this represents the first assessment of the proposed STRIEX process on real waste as well as the first LCCA of the STRIEX process.

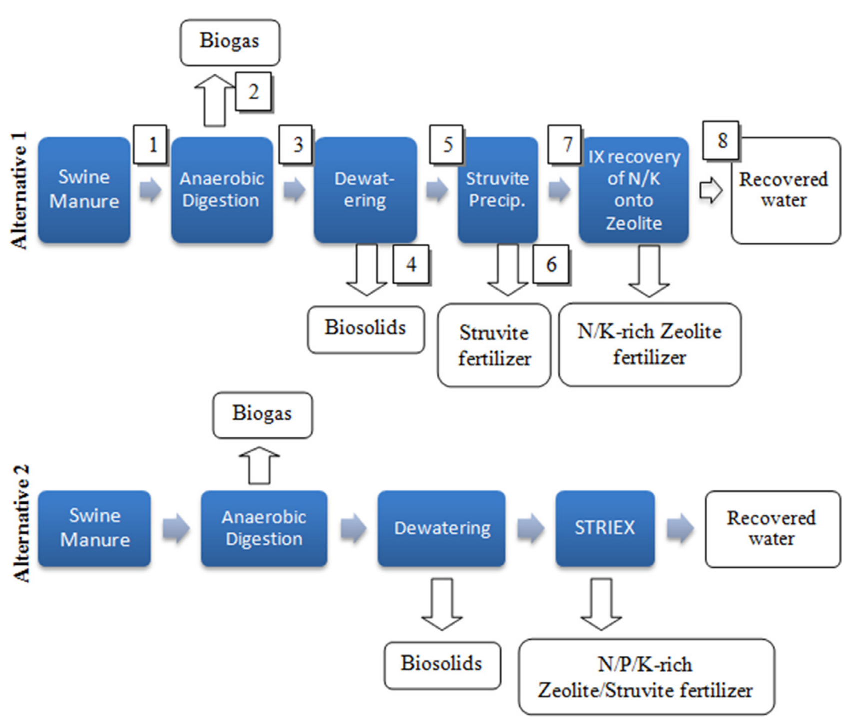

Fig. 1. Proposed scheme for recovery of energy and nutrients from swine CAFO waste, showing resources recovered, sampling locations for laboratory tests, and the alternative process using STRIEX.