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Nitrogen release from mechanically dewatered sewage sludge during thermal drying and potential for recovery

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A B S T R A C T

The increasing demand for food has led to heightened demands for fertilizers containing nitrogen, a vital nutrient for efficient crop yields. In the study, a potential for nitrogen recovery during thermal drying of sewage sludge was examined. The mechanically dewatered sewage sludge from a municipal wastewater treatment plant was batch dried under controlled temperature regimes without pH adjustment. The drying temperatures were set to 100 °C, 130 °C, and 160 °C. Fourier transformed infrared (FTIR) spectroscopy analysis was applied to continuously measure the ammonia concentration in the exhaust fumes generated during the batch drying tests. The results indicated that the mass of ammonia released during the drying process ranged between 4700 and 6850 mg/kg total solids (TS), which corresponded to 78−99% of the 6220 mg/kg TS ionized ammonia nitrogen (NH_4^+−N) content determined in the sewage sludge prior to the drying process. No clear relationship between the drying temperature and the amount of ammonia released was identified. Still, out of the total nitrogen contained in the sewage sludge (53,000 mg/kg TS), 81% was present as organic nitrogen, which is bound in cell structure and, therefore, could not be released.

1. Introduction

Increased food consumption driven by the global population growth has resulted in an unprecedented utilization of nitrogen and phosphorous. Considerably increased human-induced fluxes of nitrogen and phosphorous have led to the transgression of the planetary boundaries through disruptions of their natural cycles (Rockström et al., 2009; Steffen et al., 2015). In the meantime, population growth coupled with expanding urbanization has generated ever-increasing amounts of municipal sewage sludge, a substantial sink of biogenic nitrogen and phosphorous (Grönman et al., 2016). As such, efficient recycling of the organic nutrients embodied in sewage sludge could help to mitigate the negative environmental impact caused by the unrestricted consumption of inorganic fertilizers.

The nitrogen that is present in sewage systems primarily originates from urea, which quickly hydrolyzes into ammonia nitrogen, the largest nitrogen species in the wastewater that enters a wastewater treatment plant (WWTP). The ammonia nitrogen in wastewater is concurrently present in both forms: un-ionized, NH_3, and ionized, NH_4^+ The equilibrium between the two forms of ammonia in a liquid solution is pH and temperature (T) dependent and can be calculated following the study by Körner et al. (2001).

The behavior of nitrogen throughout the WWTP, along with the nitrogen species present in different media, is illustrated in Fig. 1. During the wastewater treatment process, a two-stage nitrification-denitrification process is applied to convert ammonia nitrogen into molecular nitrogen, N_2, which represents the biggest share of nitrogen within the WWTP (Cao, 2011; Wett and Alex, 2003). However, most nitrogen is released into the atmosphere and, therefore, is lost from the system during the operation of the WWTP. However, a part of the nitrogen is present in sewage sludge and can potentially be recovered to avoid an excessive load of man-made nutrients on the environment.

Nutrient recovery has often been a key factor in sewage sludge treatment and utilization; e.g., by direct utilization on land, composting, or anaerobic digestion with consequent utilization of digestate on land (Fytili and Zabaniotou, 2008). Such methods enable the efficient use of nutrients, including nitrogen, for fertilization and soil enhancement. Nevertheless, sludge utilization by the methods described can be constrained by several factors including potential environmental damage due to the high

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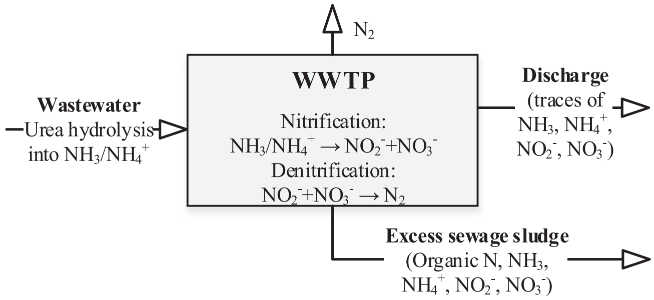

Fig. 1. Nitrogen species in wastewater introduced into treatment, within the treatment process, and in discharge water and sewage sludge leaving the WWTP.

content of heavy metals, lack of social acceptance of sludge use on land, and economic barriers, such as high transportation costs. Under such circumstances, sludge incineration is typically employed.

During incineration, the nitrogen that is present within the sludge transitions into exhaust fumes, which are then released into the environment, which eliminates any further possibilities of nitrogen recovery. While no nitrogen is present in ash, the ash does, however, contain another vital nutrient, phosphorus, which has been successfully recovered in previous research; e.g., in a pilot plant (Havukainen et al., 2016). Therefore, nitrogen recovery should be implemented prior to sludge incineration, which is oftentimes preceded with the thermal drying required to reduce the moisture content of sludge (Bennamoun et al., 2013).

As recently described by Bennamoun et al. (2013) and Tunçal and Uslu (2014), sewage sludge drying can be implemented via various methods, which can be grouped into convective drying, conductive drying, and solar drying approaches. The convective driers, such as belt driers, flash driers, fluidized bed driers, and rotary driers, often utilize hot air or steam within the drying process. The conductive driers, represented by disc driers or paddle driers, conventionally utilize hot oil or saturated steam within the drying process, and no direct contact between the heating media and dried sludge occurs. The uses of waste oil as described, for example, by Peregrina et al. (2008) and Wu et al. (2012), or superheated steam as presented, for example, by Mujumdar (2014), are considered to represent innovative methods of sewage sludge drying. Finally, solar driers are structurally prototyped from greenhouses. Overall, convective driers are perceived to be advantageous because such driers can potentially be integrated into a sludge incineration plant (Li et al., 2014) or a cement plant (Stasta et al., 2006), thereby increasing the energy efficiency of the incineration plant through the consumption of low-grade steam for the drying process.

In spite of the wide application of thermal drying for sewage sludge treatment, the potential of nitrogen recovery during the process was not addressed properly. Meanwhile, only limited research has been published that describes the detection of ammonia in the exhaust fumes generated during the thermal drying process; as such, there is a lack of understanding of the total amount of ammonia released. Lu et al. (2013) studied the release of ammonia (among other constituents of exhaust fumes) during the sewage sludge drying process. Deng et al. (2009) examined the emissions of volatile compounds, including ammonia, during the thermal drying of sewage sludge and determined that the rate of ammonia released increases with the raising drying temperature. However, both research groups were concerned with ammonia from the perspective of a source of air pollution omitting the determination of the total amount of ammonia released and its potential for further recovery.

The objective of the present study was to quantitatively study the release of ammonia during thermal batch drying of sewage sludge while also examining the relationship between the mass of ammonia released during the drying process and the temperature of the process. The results of the present study could be used to assess the recovery potential of nitrogen and may serve as a basis for designing the recovery process, which could be facilitated by acid absorption or adsorption on activated carbon or biochar.

2. Materials and methods

2.1. Sewage sludge sample

Sewage sludge for the study was obtained from Toikansuo WWTP, which is located in Lappeenranta, a Finnish town that has a population of 72,000 inhabitants. The WWTP treats municipal wastewater from the City of Lappeenranta, municipalities of Lemi and Taipalsaari, as well as industrial wastewater, which accounts for approximately 10% of the total volume of wastewater treated. The average treatment capacity of the WWTP is 16,000 m^3/day corresponding to nearly 6,000,000 m^3 annually (Lappeenrannan Energia Oy, 2014; Ritari, 2014).

The WWTP includes preliminary sedimentation, filtration of coarse rejects, and chemical-biological treatment employed with a nitrification-denitrification process for nitrogen removal (Pöyry Finland Oy, 2013). Excess secondary sludge is dewatered in a centrifuge. In 2013, 7700 t of sewage sludge was generated with an average total solids (TS) content of 24% (Ritari, 2014). Samples for the study were collected from the discharge end of the centrifuge in plastic buckets with tightly closing caps. The samples were stored in a refrigerator until tested. The dry matter content of the sewage sludge studied was determined before the tests. The dry matter content was 20.3 ± 0.5% and the ash content 4.12 ± 0.14% (SFS 3008, 1990).

2.2. Experimental setup

The equipment used for the sludge drying tests is shown in Fig. 2. The samples of sewage sludge were placed into a metallic vessel (a) that was kept closed during the tests; the vessel had an inlet (b) and an outlet (c) pipe. The vessel was then placed inside an electric oven (d). The drying temperature was continuously recorded using a thermocouple (e) placed inside the metallic vessel. Hot air for the drying process was supplied through the inlet pipe from inside the electric oven. The outlet pipe was connected to the gas preparation unit (f), which was connected to a gas analyzer (g). The gas preparation unit aspirated exhaust fumes from the vessel at a constant suction rate of 2.5 L/min of hot air.

The sewage sludge samples were dried in the electric oven at three different temperatures to ascertain if there was a relationship between the drying temperature and the amount of ammonia released to a gas phase. The temperatures chosen were 100 °C, 130 °C, and 160 °C because the temperatures were considered to be representative of the industrially applied temperatures employed during sewage sludge drying. It was anticipated that a further increase of the drying temperature would facilitate a greater release of volatile compounds, thus decreasing the heating value of sewage sludge (Vesilind and Ramney, 1996). Despite the well-known effect that pH has on ammonia release, no addition of alkaline materials was considered in the study so as to imitate an ordinary sludge drying process without significant technological alterations. The drying tests were run in duplicate for each temperature, and the weight of the samples was set to 50 g.

After passing through the gas analyzer, all exhaust fumes progressed through a pipe in which water vapor and a part of volatile