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Utilization of digestate in a convective hot air dryer with integrated nitrogen recovery

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NH_3 emissions from agricultural production and from digestate represent a significant part of total nitrogen emissions and can be significantly reduced by adapting the respective process technology. A recovery rate of more than 90 % of the released NH_3 could be detected in a two-belt dryer with an exhaust air scrubber, which was operated to investigate the drying parameters of dewatered digestate. The specific thermal energy consumption of the dryer ranged between 0.89 and 1.04 kWh kg^{-1} depending on the throughput and the temperature of the digestate. Drying resulted in a loss of about 50 % of total-N in the substrate, which is equivalent to about 80 % of the NH_4-N content. NH_3 concentrations of 10.8 mg m^{-3} were measured in the purified exhaust air. This corresponds to a release into the environment of 25.5 g h^{-1}. The NH_3 release from the digestate was only dependent on the amount of digestate and was not influenced by the drying temperature.

Key words
Digestate drying, nitrogen recovery, ammonia emissions, nutrient recycling

A conventional biogas plant with an electrical output of 500 kW produces digestate with a nitrogen content of about 100 t per year. Applying this amount of digestate can supply an area of approximately 440 ha with nutrients (Fuchs and Drosg 2010) when fertilizing with 227 kg nitrogen (N) per hectare. Digestate from regions with an excessive amount of nutrients must either be transported over long distances to other regions, often under uneconomical conditions, or are processed locally (Döhler and Schliebner 2006). The direct application of liquid and solid digestate fractions without pre-treatment leads to N losses in the form of ammonia emissions (NH_3), nitrate leaching (NO_3) and climate-relevant nitrous oxide emissions (N_2O) (Möller 2009, Möller et al. 2011, Möller et al. 2008). At present, the usual practice of applying digestate does not achieve an optimum nutrient ratio for crop cultivation taking into account the nutrient limit values from the amendment to the German Fertilizer Regulation 2017 (Möller et al. 2008). Possible consequences can be over-fertilisation with phosphorus (P) or an undersupply regarding N.

Alternatively to direct application, nutrients can be extracted after separating of the solid and liquid fractions and subsequent drying of the dewatered digestate. Separation is usually carried out mechanically by centrifuges, chamber filter- and screw presses or sedimentation devices. A successful separation depends mainly on the composition of the feedstock (Moller et al. 2002). The solid fraction is usually composted or dried. Currently, processes based on hot or cold air drying are used for drying, such as belt dryers, drum dryers, tumble dryers or fluidized bed dryers. The main disadvantages are the high energy consumption and the long processing time, impeding the economic use of these procedures. Despite the marketability and the corresponding availability of the technology, it has only rarely been used to date. In a study by Witt et al. (2010), only 6 of 441 biogas plants

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were equipped with digestate dryers in 2009. According to a survey of biogas operators by the DBFZ in 2016, only 17 % of biogas plants with digestate treatment were also equipped with dryers (Daniel-Gromke et al. 2017).

Drying of the freshly separated solid fraction digestate leads to the release of NH_3 into the exhaust air, which can be measured by FTIR spectrometry (Awiszus et al. 2018, Maurer und Müller 2012). Therefore, permits for the drying of digestate are often only granted if the release of NH_3 into the environment is significantly reduced. In order to achieve this goal and to recover nitrogen, the exhaust air can be passed through acid-operated scrubbers and nitrogen can be recovered in the form of ammonium sulphate, for example. However, there are hardly any scientifically published studies on digestate drying, especially in belt dryers or regarding the efficiency of the available scrubber systems. The present study describes the drying of the solid fraction of digestate in a belt dryer in terms of air flow and energy requirements, as well as the effect of drying on the release of NH_3 and the N content in the dried digestate. In addition, the potential to reduce NH_3 emissions by a nitrogen scrubber is estimated.

Materials and Methods

Material

Mechanically dewatered digestate from the Unterer Lindenhof, an experimental station at the University of Hohenheim, was used for the drying tests. An overview of the properties is shown in Table 1. The biogas plant has an output of 200 kW_{el}. At the time of the drying experiments, the plant was fed with a substrate mixture of 19 % maize silage, 21 % grass silage, 7 % cereals and 53 % manure from various livestocks. A detailed description of the biogas plant and the operating scheme can also be found in the literature (Awiszus et al. 2018, Lemmer et al. 2013, Lindner et al. 2015, Naegele et al. 2013).

Table 1: Dry matter (DM), total nitrogen (total N) and ammonium nitrogen (NH_4-N) of dewatered and dried digestate

Variant	DM in %	Total N in mg g^{-1} TM	NH_4-N in mg g^{-1} DM
Dewatered digestate	24.4	26.2 ± 0.53 [a]	14.0 ± 0.18 [a]
Dried 45 °C	90.0	13.9 ± 0.92 [b]	2.7 ± 0.04 [b]
Dried 70 °C	91.3	13.9 ± 0.62 [b]	2.4 ± 0.01 [c]
Dried 80 °C	93.4	13.5 ± 0.14 [b]	1.8 ± 0.02 [d]

Different superscript letters in a column represent significant differences (α = 0.05).

Two belt dryer and ammonia recovery

For drying the solid fraction digestate, the prototype of a two-belt dryer (Huber SE, Berching, Germany), which was originally designed for drying sewage sludge, was used (Figure 1). The pilot plant complies with the technology applied in the study by Awiszus et al. (2018) with a temperature-dependent throughput of up to 45 kg h^{-1} digestate at an initial moisture content of 75 %. The thermal capacity of the dryer was 150 kW supplied by the local heating grid from the directly adjacent biogas plant. Since the grid also supplies the farm and the local laboratories, around 34 kW_{th} could be utilized for drying. Therefore, an additional mobile heating unit with a thermal capacity of 150 kW_{th} was used for the drying tests, which required more energy (drying temperatures above 70 °C).

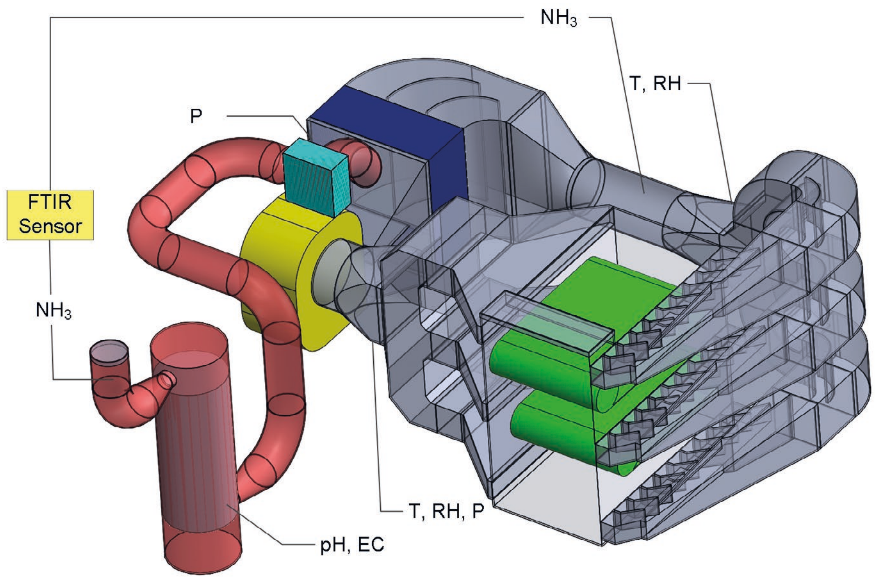

Figure 1: Belt dryer with air channels (grey), drying belts (green), heat exchanger (blue) recirculation fan (yellow), exhaust ventilator (light blue) and nitrogen scrubber (red). Measuring points for NH_3, temperature T, pressure P, relative humidity RH, pH value, electrical conductivity EC

Total drying area of the two belts measures 1.85 m^2. Each belt is 1,150 mm wide and 2,810 mm long. The belts (type 5099, GKD – Gebr. Kufferath AG, Düren, Germany) consist of 2.2 mm thick polyphenylene sulfide (PPS) with a mesh size of 510 µm and an air permeability of 4,500 L m^{-2} s^{-1} (DIN EN 9237, dp = 200 Pa). The speed of each belt can be adjusted separately in a range between 0.56 and 2.81 mm s^{-1}.

After feeding the substrate via a vertical auger (HIMEL Maschinen GmbH & Co. KG, Melchingen, Germany), a material layer of 80 mm is set with a rotating auger and the digestate is homogeneously distributed on the upper belt. The material falls 850 mm deep from the upper drying belt onto the lower belt. After drying, the dry digestate is discharged with a horizontally aligned auger. The main air flow in the dryer is generated by a radial fan (P2MM1B4M-RRV / LG 270, Nicotra Gebhardt GmbH, Waldenburg, Germany) with an output of 7.5 kW, so that an air volume of 18,000 m^3 h^{-1} is established at 970 Pa pressure. The circulating drying air is heated by a finned heat exchanger (water/air) and divided into an upper and lower air flow, which flows vertically through the drying belts in top-down direction. The subsequently combined air flow is returned to the heat exchanger.

The exhaust air (11 % of the total airflow) is extracted by a second centrifugal fan (P2MF3W2C-RRB/RD90, Nicotra Gebhardt GmbH, Waldenburg, Germany) with an output of 0.75 kW and an air flow rate of 2,000 m^3 h^{-1} at 796 Pa pressure. An equivalent amount of fresh air is sucked into the dryer via the material feeder. To assess the drying process, the air flow within the dryer was modelled and analyzed using SolidWorks software (SolidWorks Corp., Waltham, USA) based on the characteristics of the fans used, the drying belts flow through, and the flow-relevant components, such as ventilation blades, heat exchangers and exhaust air scrubbers including fillers.

Measuring of air composition

Temperature and relative humidity (RH) were determined in the air flow before and after the drying area using PT100 sensors (accuracy ± 0.3 °C) and humidity sensors (HMT 330, Vaisala, Helsinki, Finland) with an accuracy of ± 2.5 % RH. The pressure conditions were measured with ± 0.2 % accuracy before and after the air circulation fan (VEGABAR 52, VEGA, Schiltach, Germany), (Figure 1).

Furthermore, the volumetric air flow was determined using a hot-wire anemometer (Testo 435-4, Testo SE & Co. KG, Lenzkirch, Germany), equipped with a 7.5 mm diameter probe, with an accuracy of ± 0.03 m s^{-1} + 5 % of the displayed value. The measured air flows in the dryer and in the exhaust air were used to calculate the energy efficiency and the mass flow of emissions.

The concentration of NH_3 was determined using Fourier Transform Infrared Spectroscopy (FTIR) (GASMET DX4000, Ansyco, Karlsruhe, Germany) inside the dryer in the air circuit and in the purified air leaving the ammonia scrubber. Concentrations were determined in mg m^{-3} and adapted to standardized conditions (TN = 273.15 K; PN = 1013.25 hPa) with the software CALCMET™, with regard to the actual temperature and pressure in the FTIR detector. For a clearer presentation of the results, the measured values of the individual test series were averaged. This also partially compensates for the inhomogeneity of the digestate used for drying.

Experimental design

To keep the initial moisture content of the digestate constant, freshly separated digestate was mixed with accumulated material in the feeding hopper. This was necessary since the moisture content of the material varied considerably due to the composition of the substrate and different weather conditions.

The drying trials were carried out at drying air temperatures of 45, 70 and 80 °C with three repetitions each. The optimal drying time was identified in preliminary experiments to obtain a residual moisture content lower than 10 %, which is necessary to further process the digestate, e. g. pelleting. For this purpose, the dry matter content (DM) was analyzed according standard DIN ISO EN 18134-1 at 105 °C for 24 h in a drying oven (DIN 2015) both, for the initial material and for the dried variants. At 45 °C, a retention time of 50 min on the upper and subsequent 35 min on the lower belt resulted in the desired final moisture content lower than 10 %. 25 min on the upper drying belt followed by 20 min on the lower drying belt were sufficient at temperatures of 70 and 80 °C.

To determine the influence of the drying on the nitrogen content of the digestate and to assess the expected emissions after storing the dried products, the total nitrogen content, according to Kjeldahl (DIN 2012), and the ammonium nitrogen content (NH_4-N) were determined by photometric measurement (DIN 1983).

Results and Discussion

Air Flow

The distribution of the air flow speed of the drying air is shown in Figure 2. During the drying process, an even air flow is formed. The highest air speeds are achieved in those areas with a narrower pipe diameter or in the area of the fans (B). It became obvious that drying occurs mainly on the lower belt of the drying belts (A). This can be explained by the fact that more drying air is blown into the area of the lower belt than to the upper drying belt. The air flow towards the exhaust air scrubber (D) is low compared to the air flow in the dryer, thus ensuring safe operation of the exhaust air scrubber with a high NH_3 separation efficiency.

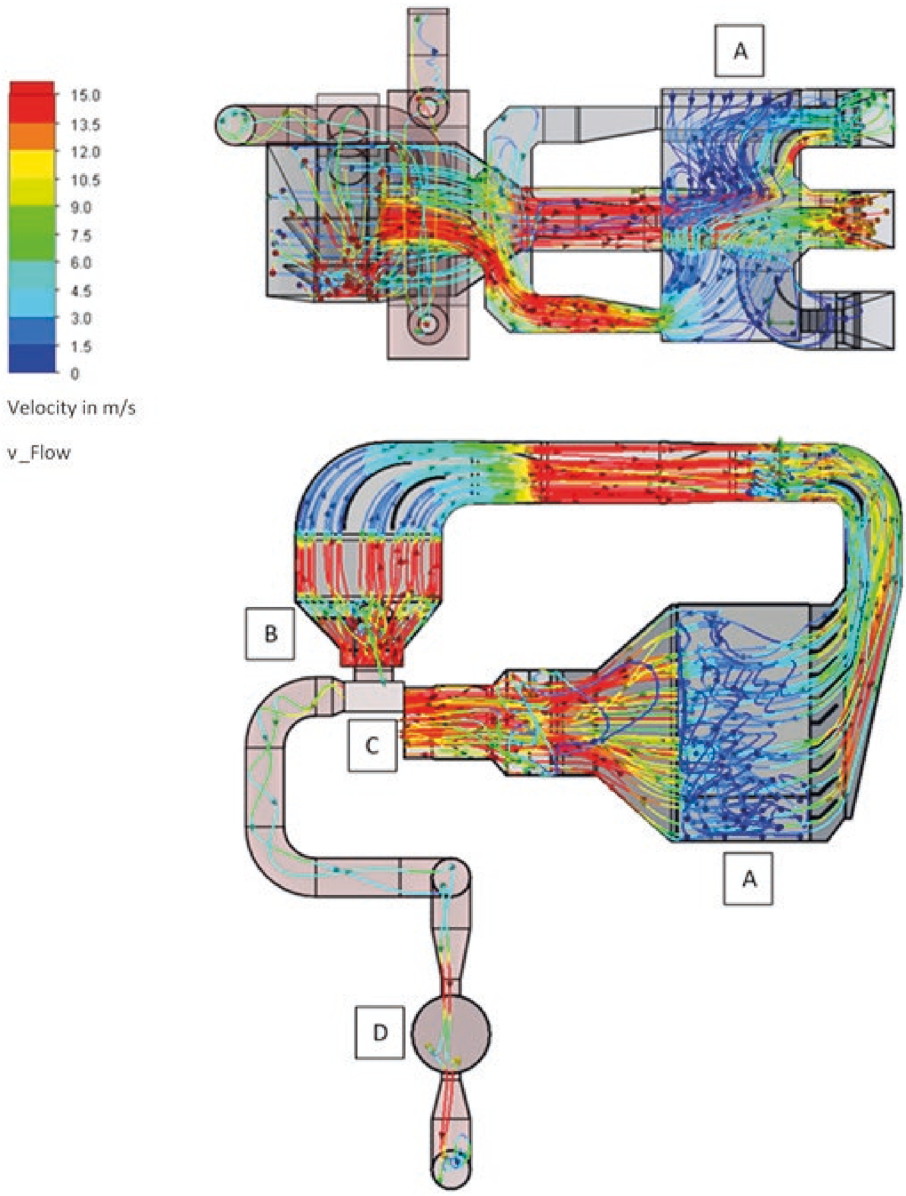

Figure 2: Front and top view of the air flow in the dryer with the zones drying belts (A), circulating air fan (B), exhaust air fan (C) and exhaust air scrubber (D).

Energy consumption

The dryer had an electrical energy demand of 9.7 kW. Table 2 shows the relevant parameters for the drying of digestate in the dryer. The specific thermal energy requirement was calculated as heat energy requirement per kg of evaporated water.

Table 2: Thermal energy input and specific heat requirement of the two-belt dryer at different drying temperatures

Drying temperature	Thermal output in kW	Specific thermal energy demand per evaporated water in kWh kg^{-1}
45 °C	34	0,89
70 °C	85	0,93
80 °C	98	1,04

1) Based on: Bulk density digestate 350 $kg \cdot m^{-3}$; DM content 25 %; η heat exchanger = 80 %.

The specific thermal energy consumption ranged between 0.89 and 1.04 kWh kg^{-1}, depending on the throughput and the temperature of the digestate. These values are similar to those in comparable studies. For example, in the study on the drying of digestate in belt dryers by Döhler et al. (2010), the specific thermal energy requirement ranged between 0.85 and 1.15 kWh kg^{-1}. The results also show increasing heat losses at higher temperatures when substrate is dried at 70 and 80 °C. The main reasons are losses due to insufficient insulation and via the exhaust air, which could be further optimized in the future by improved insulation and heat recovery.

Impact of the drying on the nutrient content of the solid fraction digestate

The dry matter (DM) of the dewatered solid fraction digestate reached 24.4 % and was increased to the target DM of at least 90 % by drying. After drying, the total-N content decreased from 26.2 mg g^{-1} DM to amounts of 13.5 to 13.9 mg g^{-1} DM. The reduction is caused by nitrogen losses from the NH_4 fraction. The initial content was reduced from 14.0 mg g^{-1} DM in the feedstock to amounts of 1.8 to 2.7 mg g^{-1} DM. In this case, higher temperatures led to significantly higher losses. Drying resulted in a loss of about 50 % of the total-N, which is equivalent to about 80 % of the amount of NH_4-N. This confirms the results of Möller and Müller (2012), who also found that the N losses during drying of digestate derive mainly from the NH_4-N fraction.

Ammonia emissions and ammonia scrubbers

The dryer was equipped with an air scrubber to recover NH_3 in the form of $(NH_4)_2SO_4$ from the dryer exhaust air by means of H_2SO_4 and thus minimizes the release of NH_3 into the environment. The measured NH_3 concentrations in the dryer and in the purified exhaust air are exemplarily shown in Figure 3 for a measuring cycle of 10 min.

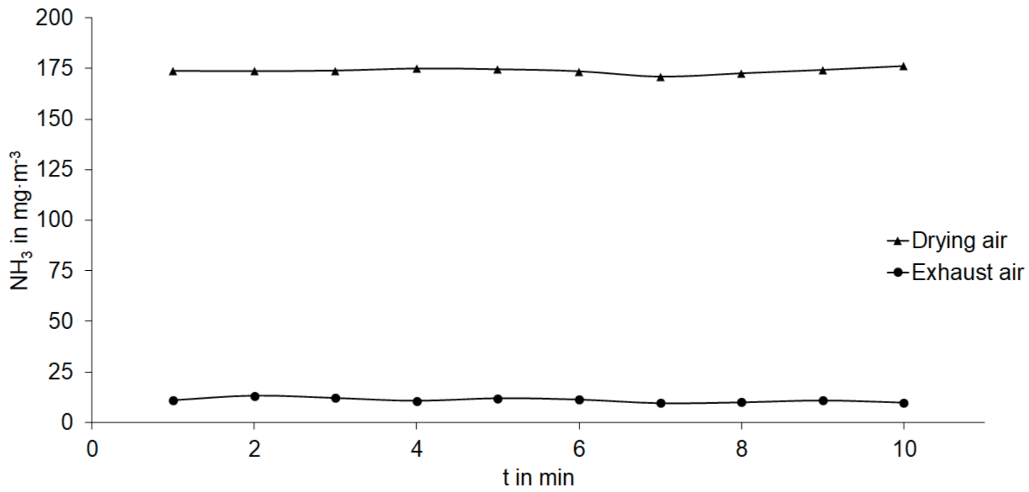

Figure 3: NH_3 concentration in the drying air in relation to the exhaust air of the ammonia scrubber at a drying temperature of 80°C.

NH_3 concentrations of 10.8 mg m^{-3} were found in the purified dryer exhaust air. This corresponds to a calculated mass flow into the environment of 25.5 g h^{-1} NH_3 after cleaning the exhaust air. A 93% NH_3 reduction was observed in relation to the average NH_3 concentration within the dryer of 173.9 mg m^{-3}, or a calculated mass flow of 400.7 g h^{-1} before extraction of the exhaust air. A temperature-dependent NH_3 release from the digestate could not be clearly detected by FTIR, although the results from Table 2 would indicate this. The chemical composition and the examined properties of the scrubber broth (eluate) are shown in Table 3.

Table 3: Chemical properties of the eluate

Parameter	Eluat
pH	2.8
Electrical conductivity EC in mS cm^{-1}	117.6
Total-N in g L^{-1}	21.6
NH_4-N in g L^{-1}	21.4
SO_4 in g L^{-1}	45.1

The eluate contains N almost exclusively in the form of NH_4-N, which is directly available to plants. The NH_4-N content amounted to 21.4 g L^{-1} and the SO_4 content was 45.1 g L^{-1}. This corresponds approximately to an ammonium sulphate solution with an N content of 2%. Due to the low pH value of 2.8, the eluate is unsuitable to be used as foliage fertilizer because of the risk of fertilizer burn. Overall, however, this technology has the potential to partially close the soil-nitrogen cycle. The decoupling of the nutrient fractions in the digestate can also be regarded as an advantage. The nitrogen originating from the digestate is present in the form of an ammonium sulphate solution after the exhaust air purification. This enables an on-demand N-fertilization, decoupled from the P-K content. Thus, the problem of suboptimal nutrient ratios in digestate can be avoided, as described by Möller et al. (2011).

Conclusions

Drying mechanically dewatered digestate in a two-belt dryer leads to nitrogen losses in the substrate in the form of NH_3. A temperature-dependent NH_3 release from the digestate could not be proven clearly during continuous drying. The NH_3 expelled during drying can be recovered as $(NH_4)_2SO_4$ via an air washer using H_2SO_4. This can reduce the input of NH_3 into the environment by 93%. The increasing specific heat requirement to dry digestate at higher temperatures requires thermal insulation of the air ducts to ensure an optimal economic operation. The digestate throughput can be significantly increased via the drying temperature and thus can be flexibly adapted to the amount of digestate produced. Since the composition of the digestate and therefore also the NH_3 emission potential depends on the respective input substrates, the results of this study can only be applied with limitations to substrates from other biogas plants. Therefore, further investigations should clarify the applicability of this technology for digestate from different sources. Due to the low pH value and the low nutrient content, the eluate from the exhaust air washer is currently only conditionally suitable as liquid fertilizer, although it could be optimized for this purpose through additional processing steps. If fields would be fertilized exclusively with the eluate, an oversupply of sulphur to the soil could occur. Therefore, attention has to be paid to the sulphur requirements of the target crops when using the solution as liquid fertilizer.

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