Biogas digestates based on lignin-rich feedstock - Potential as fertilizer and soil amendment

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Abstract

With advances in biogas technology, lignocellulosic material may be increasingly included in feedstock due to the abundance of raw materials. The main goal of this study was to evaluate fertilizing and soil amendment effects of digestates based on lignin-rich feedstock. The digestates originated from reactors fed with manure co-digested with *Salix*, wheat straw or sugarcane bagasse, respectively. In pot experiments with three different soils, Italian ryegrass and reed canary grass were grown with 120 kg ha^{-1} total nitrogen or 150 kg ha^{-1} available nitrogen, respectively, given as either mineral fertilizer or digestate. Soil chemical and physical characteristics were determined after ended experiments. Additionally, an incubation study was carried out to estimate N mineralization from one digestate over time. Digestate addition resulted in similar yields compared to mineral fertilizer, varying from 0.5 (loam) to 1 kg dry matter m^{-2} (silt) for Italian ryegrass and 1.2 (loam) to 2.3 kg m^{-2} (silt) for reed canary grass. Digestates contributed to a favourable pH for plant growth, reduced bulk density in the loam and improved water retention characteristics in the sand. Biogas digestates based on lignin-rich feedstock appear promising as fertilizers and for soil amelioration but results have to be verified in field experiments.

Keywords: lignocellulosic material; biomass production; Italian ryegrass; reed canary grass; soil physical properties

Introduction

Due to the attempt to produce more renewable energy in recent years, the production of biogas from various sources of biomass has increased considerably. Biogas production leaves a digestate that contains organic material but is also rich in plant-available nutrients and should thus be used in new biomass production in order to make the biogas process truly sustainable. In general, the nutrient value of organic fertilizers based on organic waste is highly dependent on the type of organic matter, as well as the processing method (Bungay et al. 2007; Smith et al. 1998). Benefits of organic waste application to soil may include positive effects on, e.g., soil structure and porosity, water retention capacity, trace metal binding, cation exchange capacity, biological activities and thus general soil fertility (Marinari et al. 2000; Shiralipour et al. 1992). Recent reviews suggest that digestate additions have a positive effect on soil fertility aspects compared to mineral fertilizer, which is on a similar level as the effect of farmyard manure despite differences in the quality of the organic matter added (Insam et al. 2015; Möller 2015).

Anaerobic digestion leaves residues with a lower C/N ratio of the organic material compared to the original feedstock (Arthurson 2009). The residues show good fertilizing properties due to their content of nitrogen (N), phosphorus (P) and potassium (K) in a plant-available form (Tambone et al. 2010). Especially the high content of readily available NH_4^+ in biogas digestates is a major advantage for use in plant production is, and digestates could therefore be regarded as mainly a mineral N fertilizer (Svensson et al. 2005). However, the share of NH_4^+-N of total N may vary widely and even an increased NH_4^+-N content in digestates does not necessarily imply an improved N uptake (Möller & Müller 2012).

So far, the majority of studies on recycling nutrients from biogas digestates in plant production have been conducted using digestates based on feedstock with relatively high N contents and thus low C/N ratios. Examples are food and food industry by-products, crop residues from rape, sunflower or maize or also perennials, often in combination with manure or sewage (Müller-Stöver et al. 2016; Alburquerque et al. 2012b; Odlare et al. 2008; Svensson et al. 2005). However, there is an abundance of more lignin-rich materials such as tree residues or cereal straw that may represent a large potential for biogas production in the future. Lignocellulosic material may be hydrolyzed and further digested anaerobically to methane (Sawatdeenarunat et al. 2015; Hendriks & Zeeman 2009). The challenges connected to exploiting the full biogas potential of these materials have recently been the focus of several studies (Risberg et al. 2013; Vivekanand et al. 2013; Horn et al. 2011; Chandra et al. 2012; Estevez et al. 2012). Since it therefore seems likely that more digestates based on lignin-rich feedstock will become available in the future, their value as fertilizer and their effect on soil properties need to be studied. The purpose of the present study was to investigate whether using digestates based on lignin-rich feedstock as fertilizers results in adequate plant growth and/or improves soil quality including physical characteristics.

Materials and methods

Digestate generation

Four different digestates, based partly on lignocellulosic feedstock, were tested as fertilizers in pot experiments. Two digestates were produced from a biogas reactor operating with *Salix viminalis* “Christina” as lignocellulosic substrate. The wood chips were pretreated by steam explosion (210 °C for 10 minutes), and then digested anaerobically with fresh cattle manure in bioreactors with a working volume of 6 L (Dolly - Belach Bioteknik AB, Sweden). Material from a previous experiment with the same feedstock was used as inoculum. After a start-up period, the reactors were fed once a day, 6 days a week, with an organic loading rate (OLR) of 3 g volatile solids (VS) L^{-1} d^{-1} and a hydraulic retention time (HRT) of 30 days. Before feeding the reactors with fresh material, an equivalent volume was removed in order to maintain a constant volume in the reactor. The substrate in the first reactor was produced from feeding a feedstock mixture of *Salix* and manure (40/60 % on a VS basis, C/N ratio 39), diluted to the volume with tap water. For the second digestate product, the feedstock fed to the reactor was diluted with the process liquid after filtering the daily removed volume through a 2.5 mm mesh size sieve (40/60 % on a VS basis). The C/N ratio of this second feedstock mixture diluted with the liquid fraction of the digestate was 34. The experiment was run at 37 °C for 3.3 HRT and ended after 100 days. A detailed description of the biogas experiments can be found in Estevez (2013).

A third digestate was produced from the same type of reactor (6 L) operating with a mixture of steam-exploded straw and cow manure (78/22 % on VS basis, reactor RTcSS) (Risberg et al. 2013). The reactor had been operating for a total of 350 days, under similar operational conditions, i.e. with a HRT, OLR and temperature of 25 days, 2.8 g (VS) L^{-1} d^{-1} and 37 °C, respectively. The C/N ratio of the substrate mixture was 30.

The last digestate used originated from a reactor operating with milled sugarcane bagasse (*Saccharum officinarum*), supplied from Borregaard (Sarpsborg, Norway) and cattle manure. Sewage from a local wastewater treatment plant (Nordre Follo Wastewater Treatment Plant, Vinterbro, Norway) was used as an inoculum during start-up. The OLR of the substrate mixture (C/N ratio 30) was 3.0 g L^{-1} d^{-1} VS, fed 6 days a week and the HRT was 25 days. The experiment was run at 37 °C for 3 HRTs and ended after 86 days.

Digestate and soil analysis

A chemical characterization of the digestates used is shown in Table 1 (pH, macronutrients). Total C was determined in crushed samples by dry combustion (Nelson & Sommers 1982) at 1050 °C using a Leco CHN-1000 instrument (St. Joseph, Michigan, USA). Total N was measured on the same instrument according to the Dumas method (Bremner & Mulvaney 1982). Ammonium and nitrate (NH_4, NO_3) were measured by flow injection analysis (FIA, Tecator FIAstar 5010 Analyzer, Hillerød, Denmark) after extraction with 2M KCl, with measurements based on the fresh material (wet sample). Other nutrients were analyzed by inductively coupled plasma mass spectrometry (ICP-MS, Perkin Elmer SCIEX Elan 6000, Waltham, Massachusetts, USA) or inductively coupled plasma optical emission spectrometry (ICP-OES, Perkin Elmer Optima 5300 DV) after ultraclave digestion in concentrated, double-distilled HNO_3 (0.25 g to 0.3 g sample in 5 mL) and subsequent dilution to 50 mL, with a modification for Hg analysis. Determination of Hg was carried out as quickly as possible after first adding 1 mL H_2O_2 to 0.15-0.2 g sample, followed by 5 mL HNO_3. Digestate pH was measured directly in the liquid sample without addition of water.

((Table 1))

The soils used in the experiments were collected from the top layer (0-20 cm) of agricultural or forest soils at different locations in south-eastern Norway to represent three different soil textures, i.e. sand, silt and loam. Table 2 shows some chemical characteristics of the soils prior to the experiments. Total C and N in soils were measured using the same methods as described above. Plant-available P and K were estimated by extraction with ammonium acetate lactate solution (0.1 M ammonium lactate and 0.4 M acetic acid, pH 3.75) (Egnér et al. 1960), followed by ICP spectrometry. Particle size distribution was determined by the pipette method (Elonen 1971). Soil pH was measured in H_2O with a soil to solution ratio of 1:2.5.

((Table 2))

Ryegrass experiment

In order to study the effect of the different biogas digestates as a fertilizer, a pot experiment was conducted under controlled conditions (20 °C, 18-hour day) with three soils differing in texture and Italian ryegrass (*Lolium multiflorum*, var. Macho) as a test crop. The soils used were classified as a sand, a silt and a loam. All soils were air-dried, and the loam and silt were passed through a 5 mm mesh size prior to being filled into pots. Due to its single grain structure, the sand was not sieved prior to use. The pots (diameter 16 cm) were filled with a soil volume of 3 L. Because of its low original pH, the loam was limed with 8 g $CaCO_3$ per pot, resulting in a pH of approximately 6.

The experiment consisted of the following treatments: fertilization with *Salix* digestate, *Salix* digestate where process water was recycled (*Salix* recycled), and wheat straw digestate, as well as a mineral fertilizer control, all in three replicates, respectively. Amounts of fertilizer on a per hectare basis were calculated estimating a soil volume of 2 000 000 L ha^{-1}, which represents a typical Norwegian plough layer of 20 cm. Digestates and mineral fertilizer were mixed into the whole soil volume. The digestate amounts given were calculated based on estimated available N during the experiment, i.e. NH_4-N and approximately half of the organically bound N. All treatments received approximately 0.18 g available N, i.e. 120 kg N ha^{-1}, which represents a normal amount for the first cut in grass production in southern Norway. Amounts of P and K in the digestate treatments depended on the N concentrations in the digestates used, with P applications varying between 35 (wheat straw) and 45 kg ha^{-1} (*Salix* recycled) and K addition equivalent to approximately 200 kg ha^{-1}. In the mineral fertilizer control, N was given in the form of $Ca(NO_3)_2$ equivalent to 120 kg N ha^{-1}. Phosphorus was added as $Ca(H_2PO_4)_2$ equivalent to 20 kg ha^{-1}. Since ryegrass is known for luxury uptake of K (Øgaard et al. 2001), the amount of K (as K_2SO_4) in the mineral control was divided into a rate equivalent to 100 kg ha^{-1} in the beginning and 50 kg after the first cut to ensure sufficient K later on in the experimental period. Other macro- and micronutrients were added in dissolved form to satisfy plant needs (equivalent to: Mg 1.9, S 10, Fe 1.7, Mn 1, Cu 1.3, Zn 0.8, Mo 0.006, B 0.01 kg ha^{-1}). The micronutrients Fe, Mn, Cu and Zn, which were present in relatively low concentrations in the digestates, were also added to the digestate treatments in a mineral form in order to ensure that they were not growth limiting.

The pots were sown with 0.3 g seeds of Italian ryegrass. Moisture content in the soil was maintained at 60 % of the water holding capacity of the pot by irrigation with deionized water according to weight loss. The grass was cut after 6 and 10 weeks, respectively. Soil samples were taken after 10 weeks and analysed for different N fractions and other available main nutrients, as well as pH (in H_2O, soil : solution ratio 1:2.5).

Mineralization study

In order to estimate the amount of N that would be mineralized from the organic fraction of the digestates during the growth experiments, a simple incubation study was carried out. For this study, digestate originating from a digester operating with *Salix* and manure without recycling of process water was used. Since most of the readily available NH_4-N from the fresh sample was lost upon drying (Table 1) and NO_3-N contents were negligible, the N content of the dried digestate consisted almost exclusively of organically bound N. The digestate was ground and the loam soil dried and sieved (2 mm mesh size) before mixing thoroughly with the digestate (average ratio 0.18 g dried digestate: 20.37 g soil) to ensure as little variation between samples as possible. The samples were incubated in the dark for up to 11 weeks at 15 °C and a soil moisture of 60 % of water holding capacity. A control with the same soil without digestate was included. Three replicates of both control and soil with digestate were removed for analysis every week for the first seven weeks and after weeks 10 and 11. Ammonium and nitrate in the removed replicates were measured by FIA as described above. Nitrogen mineralization from the digestate was calculated as the combined NH_4-N and NO_3-N measured over time in the digestate-amended soil minus the respective values for the control soil. The method is described in more detail in Sogn and Haugen (2011).

Reed canary grass experiment

In a second pot experiment under controlled conditions (20 °C, 18-hour day), reed canary grass (*Phalaris arundinacea*) was grown with either bagasse digestate or mineral fertilizer.

Again, the experiment was conducted with three different soils, i.e. the same loam and silt as in the first experiment, and a sandy soil that differed slightly from the sand used in the first experiment (see Table 2). Reed canary grass was grown in pots (diameter 21 cm) with a soil volume of 6.7 L and three replicates per treatment. In order to increase the pH to approximately 6, 20 g $CaCO_3$ per pot were added to the loam and 10 g $CaCO_3$ per pot to the sandy soil.

The total amount of available N given to both treatments approximated 150 kg N ha^{-1} or 0.5 g N per pot. The amount of digestate added to each pot was calculated by considering both the NH_4-N content in the fresh sample (23.9 g kg^{-1} DM) and the amount that was expected to be mineralized over period of 15 weeks (1.3 g kg^{-1} DM). The latter was estimated based on the results of the incubation study. The P content of the digestate dose was equivalent to approximately 45 kg ha^{-1} and K equivalent to approximately 125 kg ha^{-1}. The mineral fertilizer control received N equivalent to 150 kg N ha^{-1} in the form of $Ca(NO_3)_2$, P equivalent to approximately 20 kg P ha^{-1}, and K equivalent to 200 kg K ha^{-1}. Micronutrients, S and Mg were added to both treatments at the same rate as in the ryegrass experiment to ensure sufficient supply.

The pots were sown with approximately 0.07 g seeds. After germination, the amount of plants per pot was reduced to 20 in all pots in order to increase comparability between replicates and treatments. In the loam, however, germination was poorer than in the other soils, resulting in one pot in both the control and the digestate treatment with only 18 plants, respectively. Moisture content in the soil was maintained at 60 % of the water holding capacity of the pot by irrigation with deionized water according to weight loss.

Soil physical studies

In the reed canary grass experiment, selected soil physical properties were studied in order to investigate possible soil amendment effects of digestate addition. Steel cylinders with a volume of 100 cm^3 were used to sample undisturbed soil cores for determination of water retention capacity, air porosity and bulk density. One sample per pot was taken approximately three cm below the surface after harvest. Water retention characteristics were determined by exposing the soil cores to 0, -20, -50, -100, -1000 and -15000 hPa matric potential and weighing, using a sand box at -20 and -50 hPa matric potential (Eijkelkamp; http://pkd.eijkelkamp.com/Portals/2/Eijkelkamp/Files/Manuals/M1-0801e%20Sandbox.pdf) and ceramic pressure plates at -100, -1000 and -15000 hPa matric potential (Richards 1947; Richards 1948). Air porosity at -100 hPa matric potential was determined with an air pycnometer (Torstensson & Eriksson 1936). Bulk density of the soils was determined after drying the soil cores at 105 °C and weighing.

Statistical analysis

The effect of the different digestates on yield and soil characteristics in the pot experiments was tested statistically by analysis of variance (General Linear Model). The Student-Newman-Keuls test was performed to identify different means. Results with $p < 0.05$ were considered significant. The statistical analysis was carried out using SAS (SAS Institute Inc.).

Results

Ryegrass experiment

In all three soils, the combined yield of both cuts was at least similar in the treatments fertilized with digestates compared to the controls fertilized with mineral fertilizer (Figure 1). In the loam, total yields were significantly higher in the digestate treatments compared to the control.

(Figure 1))

After 10 weeks of growth, pH was significantly higher in both *Salix* digestate treatments in the sand than in the control (Table 3). A similar, though not statistically significant trend was found in the loam, whereas there was no difference in pH between the treatments in the silt.

((Table 3))

Total C in the sand and silt was slightly higher in some of the digestate treatments compared to the control (Table 3). While the amount of total N remained the same in all soils and treatments, there was a trend towards a higher soil NH_4^+ content in treatments with digestate compared to the control. However, the differences were only significant for the straw digestate treatment in the loam and the *Salix* digestate recycled treatment in the silt. The addition of digestates also led to some significantly higher P-AL values of digestate treatments in the loam and K-AL values in the silt compared to the control.

Mineralization study

Nitrogen release from the digestate treated soil was higher than in the control soil for most of the duration of the incubation (Figure 2A). While mineralization in the control occurred at a similar rate for 11 weeks, mineralization rates in the digestate treated soil showed a first peak in weeks 2 and 3 and a second in weeks 6 and 7. Figure 2B shows the net N release from digestate calculated as the difference in N release between the digestate treated soil and the control soil. Overall, after 11 weeks, mineralization from both control and digestate amounted to approximately the same amount of mineral N released.

((Figure 2))

Reed canary grass experiment

((Figure 3))

Reed canary grass yields were similar for plants fertilized with either mineral nutrients or biogas digestate, except for in the silt, where fertilization with digestate resulted in a significantly higher yield (Figure 3). From germination and early growth on, plants in the loam were slower to develop, independent of fertilization. This is reflected in a much lower biomass yield after 15 weeks in this soil than in the sand or silt. At the end of the experiment, however, plants in the sandy soil showed clear signs of nutrient deficiencies, especially N, in both treatments and especially in the control. In the silt, plants also started to get lighter-coloured leaves, whereas in the clay no deficiency symptoms were visible. The soil analysis after the experiment confirms that there was still more available N (both NH_4^+ and NO_3^-), P and K in the loam, and to some extent in the silt compared to the sandy soil, which showed the clearest deficiency symptoms (Table 4). In the reed canary grass experiment, the increase in total C in the soils receiving digestate was stronger than in the ryegrass experiment in all three soils. The bagasse/manure digestate did not have any significant effect on soil pH after the growth experiment.

((Table 4))

Soil physical properties

((Figure 4))

Adding biogas digestate had different effects on the soil physical properties in the three soils (Figure 4). The water retention capacity of the loam was little affected by the digestate treatment except for a lower water content at the permanent wilting point (-15000 hPa). In the sandy soil, adding digestate led to a higher overall pore volume, with more water-filled medium-sized pores at field capacity while air porosity was maintained (-100 hPa). In the silt, effects were not significant. Biogas digestate addition significantly increased air porosity at field capacity in the loam but had no significant effects in the other two soils (Table 4). Bulk density was significantly reduced by digestate addition in the loam, with a similar though not significant trend in the silt, whereas no effects were found in the sand.

Discussion

An advantage of using biogas digestates in plant production is their high content of readily available NH_4^+ (Alburquerque et al. 2012b; Möller & Müller 2012; Svensson et al. 2005). In our experiments, the use of biogas digestates as fertilizer showed good effects on biomass production in both growth experiments. Abubaker et al. (2012) evaluated the effect of four different biogas residues given in three different rates in a pot experiment with spring wheat in a sandy soil. Biomass yields of all digestates were on the same level as equivalent fertilization with mineral fertilizer (NPK). Digestates based on urban wastes resulted in 5 to 30 % higher ryegrass yields compared to similar amounts of inorganic N fertilizer in a pot experiment with a sandy soil (Tampio et al. 2016). In a field study with biogas residues and perennial ryegrass (Sieling et al. 2013), however, reduced yields were reported compared to mineral fertilizer.

In the reed canary grass experiment, digestate was added mainly based on the amount of NH_4-N, and so a similar biomass production as in the control treatment was expected. The results of the incubation study suggested that over the experimental period, organically bound N would be released in similar amounts in both control and digestate treatments. In the ryegrass experiment, however, N in the digestate treatments was added based on total N and the digestates would thus have had to contribute with approximately 50 % of the organically bound N in order to supply the same amount of plant-available N as the mineral control. Still, ryegrass biomass production was similar for both mineral fertilizer and digestate treatments, suggesting a more efficient mineralization than found in the incubation study. Furthermore, NH_4^+-N at the end of the growing period was significantly increased in some of the digestate treatments in the loam and silt, indicating that not all mineralized N was taken up by the plants. In a field situation, this mineralized N might be considered available for the next growing season unless lost by leaching or N_2O emission during winter. These results suggest that microbial activity and thus mineralization in the limited soil volume (3 L), with intensive rooting and favourable growing conditions was higher than both that measured in the incubation study at 15 °C and what might be expected in a field experiment with more variable conditions.

While total C was significantly increased in many of the digestate treatments, total N was not, indicating an effective mineralization as was also found in the mineralization study. There, an initial lag period was seen, most likely due to the necessity to build up microbial biomass in the soil in the beginning. After the most easily degradable organic matter was decomposed, a slight decrease in N mineralization, as seen in week 5, could be accounted for by both changes in substrate and immobilization by microorganisms. However, Alburquerque et al. (2012a) did not find a similar decrease in N mineralization in their incubation study with different digestates. A study including biogas digestate based on pig slurry by Galvez et al. (2012a) showed a fast increase of extractable N over the first week that was sustained over 30 days. An explanation for the pattern observed in our study may lie in the nature of the organic material used in the biogas process. Here, manure was co-digested with lignocellulosic plant material (*Salix*) as opposed to manure co-digested with easier decomposable materials such as agro-industrial wastes in the study by Alburquerque et al. (2012) or pig slurry alone as in the study by Galvez et al. (2012). The decrease in N mineralization after five weeks may represent a shift from the more easily decomposable manure-derived organic matter to the *Salix*-derived organic matter.

The positive effect of digestate addition on biomass production of both ryegrass (loam) and reed canary grass (silt) suggests that mineralization rates in the plant experiments may exceed rates found in the mineralization study without plants, thus rendering more N available for plant growth than calculated. While others have found a certain immobilization of N in soils amended with digestate (de la Fuente et al. 2013), this was not observed in our experiments. Here, mineralization of organic matter did not inhibit plant growth through competition of microorganisms and plant roots for the same nutrients during the mineralization process, possibly because it occurred while enough nutrients were available for both purposes. In general, amounts of organically bound N in the digestates added were too small to detect significant changes in total N in the soils after several months of plant uptake. Repeated additions of digestates over several growing seasons might increase total N content over time by increasing the amount stored as organic N.

The total amount of added P in the soils treated with digestate was higher than in the mineral fertilizer controls. The significant increase in plant-available P in the recycled *Salix* digestate treatment in the loam (Table 3), as well as in the bagasse digestate treatment in the loam and sand in the reed canary grass experiment (Table 4) reflect the rather high amounts of total P added with these digestates (above 40 kg ha^{-1}), which exceeded fertilizer recommendations. Depending on the initial availability of P in soils and the P concentration in the digestates, it might therefore be necessary to add biogas digestate according to P rather than N content in order to avoid excessive P fertilization with its potential effects on the environment.

Soil analysis after the ryegrass experiment showed a clear decrease in available K in the loam and silt in all treatments compared to relatively high values before the growth experiment. This is in accordance with luxury consumption of K in ryegrass as has been found earlier by Øgaard et al. (2001). Also in the reed canary grass experiment, K-AL values decreased in the silt and loam, though to a lesser extent. At the same time, the soil treated with digestate tended to maintain higher amounts of K-AL, despite a similar K fertilization in digestate and control treatments. Since reed canary grass biomass after 15 weeks was considerably higher than ryegrass biomass after 11 weeks, these results suggest that reed canary grass is not taking up excessive K in the same way as ryegrass. Whether K is accumulated in soils amended with digestate will therefore also depend on whether the species growing there is capable of luxury uptake of K. In their field experiment on grassland, Bougnom et al. (2012) observed an increase in K concentrations in plots fertilized with biogas digestate compared with those fertilized with manure.

The main N form added differed between the mineral control and the digestate treatments. This should have had an effect on the pH in the soils as measured after the experiments. Nitrogen in the digestates was predominantly in the form of NH_4^+, which undergoes nitrification in aerated soil, thus releasing H^+-ions. In addition, NH_4^+ uptake by plant roots occurs in exchange for H^+-ions. Both processes decrease the pH in the soil compared to the control that received N as NO_3^-, so a lower pH in the digestate treatments could have been expected. However, the original high pH of the digestates seems to have counteracted this effect in all cases. While there were no significant changes in pH in the soils under reed canary grass, in the ryegrass experiment, addition of digestates tended to contribute to maintaining a higher pH than in the controls.

Due to a relatively low content of both dry and organic matter in the digestates, their soil amendment potential may be expected to be rather low. The total pore volume and water retention characteristics of the three soils are clearly influenced by the fact that the samples were taken in a pot experiment where the soils used were either sieved through a 5 mm sieve prior to use (silt and loam) or had very weak structure (sandy soil) to start with. In a field experiment on a silty clay loam, Beni et al. (2012) found no improvement in soil surface macroporosity upon digestate addition compared to mineral fertilizer addition, but an increased stability of the soil structure as determined by higher resistance to deformation.

Due to more artificial conditions in our experiments with poorly structured soils and regular irrigation, the water retention characteristics cannot be directly related to field conditions. However, bearing in mind these restrictions, they can give some indications of effects in field settings. The sand had the lowest nutrient and organic matter content to start with and was therefore assumed to profit most from the small addition of organic material in the digestate. While no positive effect on yield was observed, soil physical properties were slightly improved in the sand, as shown in the change in water retention capacity. Lack of air is rarely a problem in sandy soils, thus the effect of the digestate on the biggest pores is likely to be of minor importance under field conditions. The amount of plant-available water in the medium-sized pores (-20 to -100 hPa), however, was also significantly increased in the digestate treatment. This could have a positive effect on plant growth on sandy soils if it also occurred under field conditions. Air porosity was significantly increased by digestate addition in the loam but not in the other two soils. In our pot experiments where the soils were sieved prior to the growth experiment, the loam may very likely suffer from a shortage of air-filled pores, and will thus profit from increased air porosity. However, under normal field conditions, the loam with its high organic matter content will show some degree of aggregation and air-filled space in stable macropores.

Conclusions

Biogas digestates based on materials relatively rich in lignin, such as *Salix* stems, wheat straw and sugarcane bagasse, have a good potential as fertilizers at least when co-digested with manure as in this study. Depending on the plant type grown, they may also contribute to keeping the pH of arable soils at a beneficial level for plant growth. The digestates tested in this study resulted in similar or even increased amounts of biomass compared to mineral fertilizer treatments that were equivalent with respect to N amounts. Nitrogen seemed to be well available but soil amelioration effects may also have influenced growing conditions in digestate treatments in a positive way. However, applying digestates according to their content of available N may lead to considerable amounts of P added to the soils that may not be entirely used by the plants during the growing season. For digestates with low N contents and high P contents, such as the digestate based on bagasse in this study, it would therefore be more advisable to apply an amount according to P rather than N requirements and add additional N in a mineral form.

In the artificial conditions of a pot experiment with sieved soils, the latter digestate showed a positive effect on soil physical properties in the sand and the loam tested. In both soils, digestate addition increased soil porosity, leading to higher air porosity in the loam and plant-available water in the sand at field capacity. This effect may be expected to be more pronounced if digestates with a higher dry matter and thus a higher organic matter content could be applied. Whether similar effects can be detected under field conditions, still needs to be investigated.

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Tables

Table 1. Dry matter, pH, and main nutrient content (g kg^{-1} DM) of the biogas digestates used.

Treatment	**pH**	**Dry matter**	**Total C**	**Total N**[a]	**NH_4-N**[a]	**P**	**K**
		%	g kg^{-1}				
Salix + manure	7.3	4.42	442	29.0	9.7	6.6	32
Salix + manure, recycled	7.4	6.47	437	26.8	9.3	6.3	31
Straw + manure	7.7	5.37	377	36.3	17.6	7.8	49
Bagasse + manure	7.3	5.19	380	36.5	23.9	8.1	22

Analyses were conducted in one representative sample per treatment.

[a] Total N and NH_4-N given in Table 1 refer to contents in fresh digestate samples. Because most NH_4-N was volatilized upon drying (NH_4 measured in dried samples equalled approximately 0.07 g kg^{-1}) and NO_3 content in digestates was negligible (<0.1 mg l^{-1}), total N was calculated as the sum of total N determined in a dried sample and NH_4-N in fresh digestate- NH_4-N in dried digestate.

Table 2. Soil texture, pH, organic matter and nitrogen phosphorus and potassium content of the soils used in the ryegrass, reed canary grass and incubation experiments.

Soil texture class	**Sand**	**Silt**	**Clay**	**Organic matter**	**Total N**	**P-AL**[a]	**K-AL**[a]	**pH**
	g 100 g^{-1}				g kg^{-1}	mg kg^{-1}		
Loam	45	38	17	6.1	2.1	58	195	5.2[d]
Sand [b]	96	4	0	0.4	0.0	19	6	6.0
Silt	2	93	5	3.7	1.0	49	200	6.5
Sandy soil [c]	94	3	3	1.3	0.1	16	10	5.1[d]

Analyses were conducted in one representative sample per soil.

[a] AL: Plant-available P and K was estimated as the ammonium-lactate extractable fraction.

[b] Used in the ryegrass experiment

[c] Used in the reed canary grass experiment

[d] Original pH; the soil was limed to approximately pH 6 for the growth experiments.

Table 3. Carbon, nitrogen, phosphorus and potassium content, and pH in the test soils after the second cut in the ryegrass experiment (after 10 weeks of growth).

Soil	**Treatment**	**pH**	**Total C**	**Total N**	**NH_4-N**	**P-AL***	**K-AL***
			g kg^{-1}		mg kg^{-1}		
Loam	Control	5.9 a	21.1 a	1.7 a	5.0 a	57 a	66 a
	Salix/Manure	6.1 a	22.2 a	1.9 a	5.4 a	61 ab	62 a
	Salix/Manure rec.	6.2 a	22.3 a	1.7 a	5.3 a	65 b	67 a
	Straw/Manure	6.0 a	22.2 a	1.6 a	5.6 a	58 a	67 a
Sand	Control	5.9 a	0.1 a	0 a	1.2 a	18 a	9 a
	Salix/Manure	6.2 b	0.3 a	0 a	1.5 a	18 a	12 a
	Salix/Manure rec.	6.3 b	0.3 a	0 a	1.4 a	16 a	14 a
	Straw/Manure	6.1 ab	0.5 b	0 a	1.4 a	16 a	10 a
Silt	Control	6.7 a	14.9 a	0.9 a	2.8 a	51 a	25 a
	Salix/Manure	6.8 a	16.0 b	1.0 a	3.0 a	52 a	27 a
	Salix/Manure rec.	6.6 a	15.9 b	1.0 a	3.4 b	52 a	34 b
	Straw/Manure	6.6 a	15.3 ab	1.0 a	3.1 a	52 a	10 c

All treatments were carried out in triplicates. Figures followed by different letters indicate significantly different results within a soil texture class ($p<0.05$).

* AL: Plant-available P and K was estimated as the ammonium-lactate extractable fraction.

Table 4. Carbon, nitrogen, phosphorus and potassium content, pH, bulk density and air porosity in the test soils after 15 weeks of reed canary grass growth.

Soil	**Treatment**	**pH**	**Total C**	**Total N**	**NH_4-N**	**NO_3-N**	**P-AL**	**K-AL**	**Bulk density**	**Air porosity**
			g kg^{-1}		mg kg^{-1}				g cm^{-3}	%
Loam	Control	6.3 a	23.0 a	1.9 a	7.1 a	21.3 a	51 a	114 a	1.05 a	38.4 a
	Digestate	6.0 a	26.0 b	2.1 a	6.6 a	25.3 a	67 b	164 a	0.88 b	45.9 b
Sandy soil	Control	6.8 a	2.9 a	0.2 a	2.0 a	<0.2 a	19 a	15 a	1.21 a	49.3 a
	Digestate	6.8 a	4.8 b	0.2 a	2.2 a	<0.2 a	24 b	15 a	1.21 a	45.3 a
Silt	Control	6.7 a	15.5 a	1.0 a	3.4 a	0.9 a	54 a	66 a	0.91 a	24.2 a
	Digestate	6.6 a	18.4 b	3.1 a	3.9 a	<0.2 a	66 a	91 a	0.77 a	34.1 a

All treatments were carried out in triplicates. Figures followed by different letters indicate significantly different results within a soil ($p<0.05$).

Figure captions

Figure 1. Italian ryegrass yield (kg DM m^{-2}) in pots fertilized with biogas digestates based on *Salix* or straw co-digested with manure.

All treatments were carried out in triplicates. Statistically significant differences in the first cut are indicated by different letters in the respective bars (per soil), statistically significant differences in total biomass between treatments (only in the loam) are indicated by different letters on top of the figure ($p<0.05$).

Figure 2. N mineralization from biogas digestate produced from a mixed feedstock of *Salix* and manure during 11 weeks of incubation with a loam soil. Part A shows N mineralization over time in control and digestate treatments, Part B the net mineralization due to digestate addition calculated as the difference between N mineralization in control and digestate treatments.

Figure 3. Reed canary grass biomass (kg DM m^{-2}) after 15 weeks of growth.

All treatments were carried out in triplicates. Statistically significant differences in total biomass between treatments in the loam are indicated by different letters ($p<0.05$).

Figure 4. Water retention curve for the three soils fertilized with either mineral N (min N) or bagasse and manure-based digestate after 15 weeks of reed canary grass growth.

All treatments were carried out in triplicates. Differences in water content at -15000 hPa in the loam, and at -20, -50 and -100 hPa in the sand are statistically significant ($p<0.05$).

Figure 1

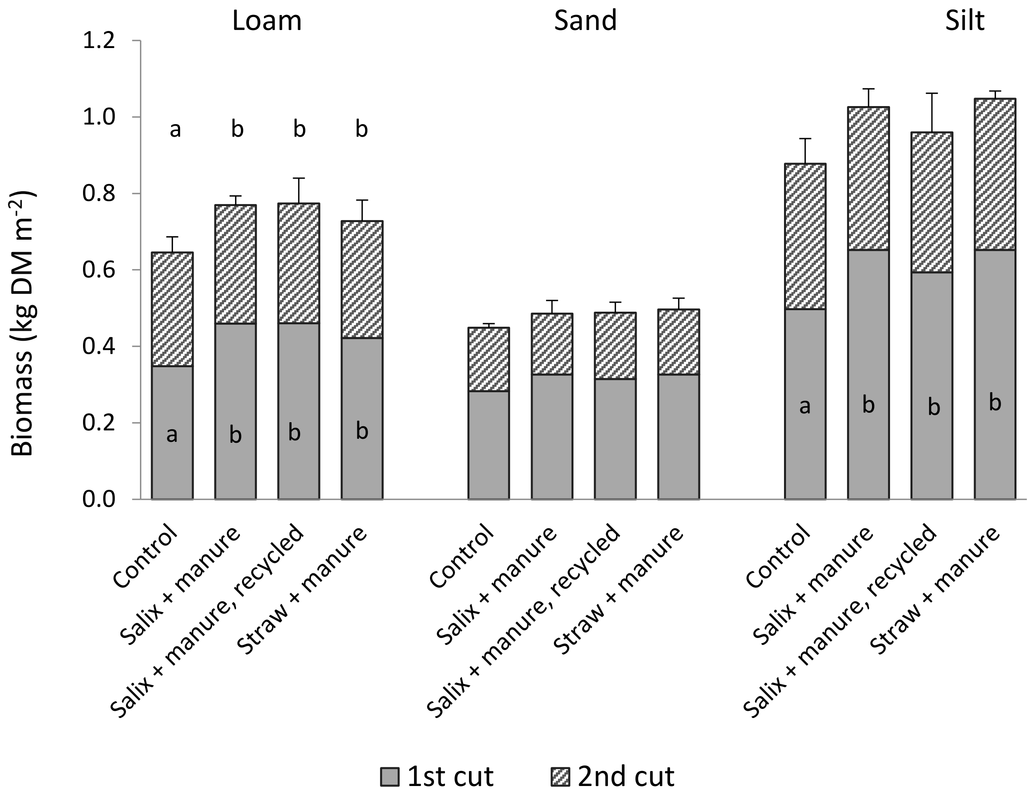

Loam
Sand
Silt
Biomass (kg DM m^{-2})
1.2
1.0
0.8
0.6
0.4
0.2
0.0
a
b
b
b
a
b
b
b
a
b
b
b
Control
Salix + manure
Salix + manure, recycled
Straw + manure
Control
Salix + manure
Salix + manure, recycled
Straw + manure
Control
Salix + manure
Salix + manure, recycled
Straw + manure
■ 1st cut
▨ 2nd cut

Figure 2

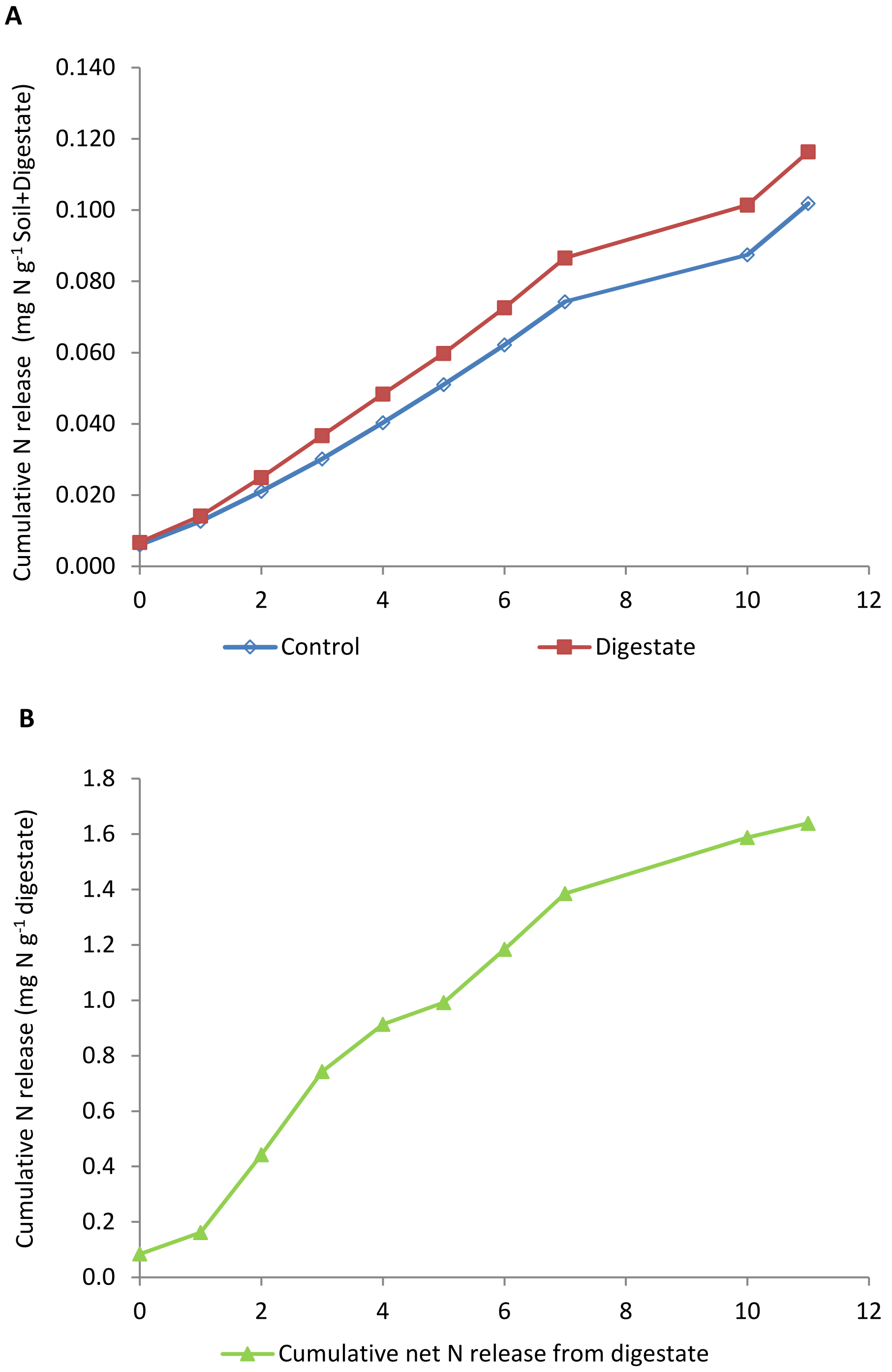

A
Cumulative N release (mg N g-1 Soil+Digestate)
0.140
0.120
0.100
0.080
0.060
0.040
0.020
0.000
0
2
4
6
8
10
12
Control
Digestate
B
Cumulative N release (mg N g-1 digestate)
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
2
4
6
8
10
12
Cumulative net N release from digestate

Figure 3

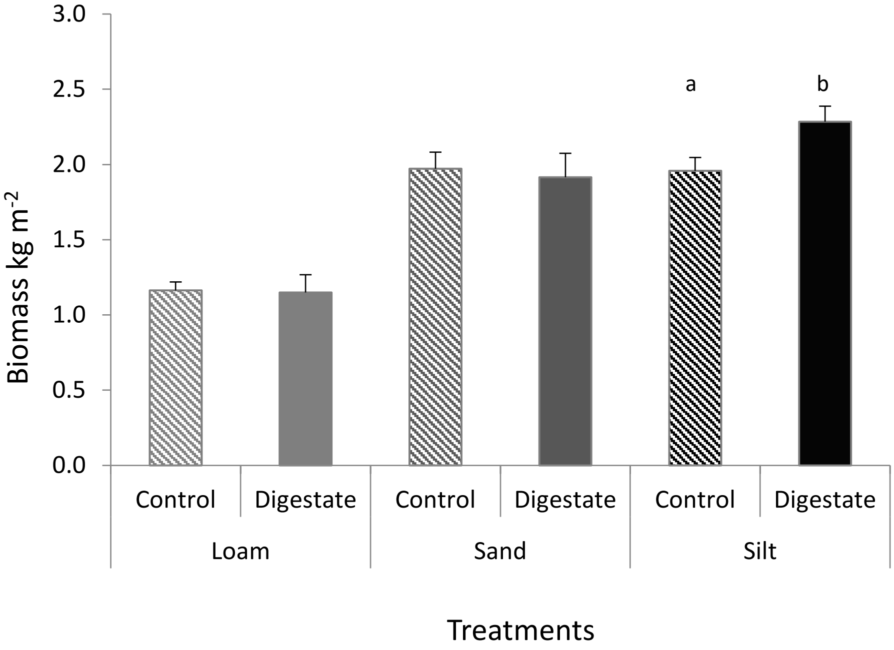
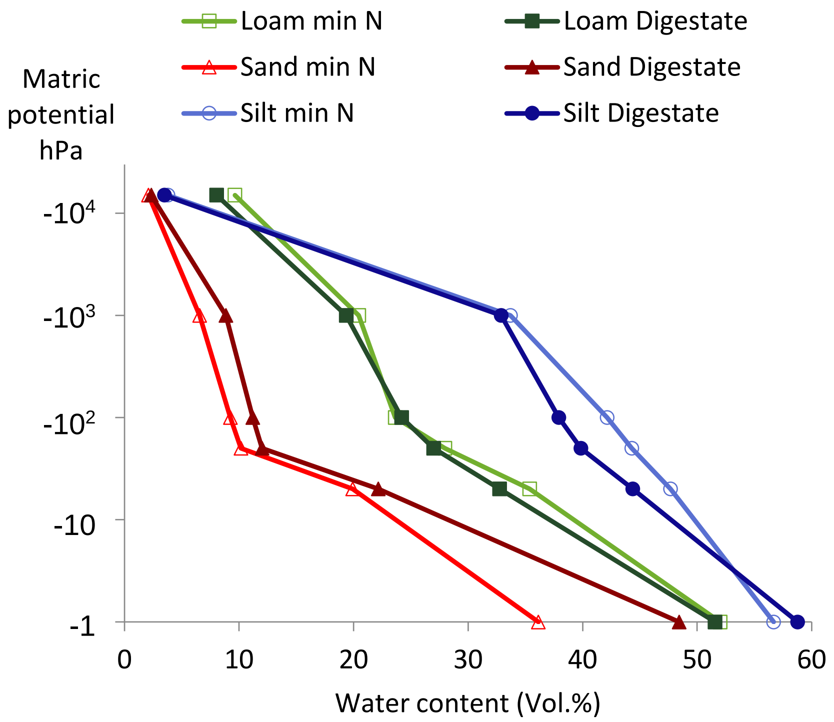

3.0
2.5
2.0
1.5
1.0
0.5
0.0
Biomass kg m^{-2}
a
b
Control
Digestate
Control
Digestate
Control
Digestate
Loam
Sand
Silt
Treatments

Figure 4


Loam min N
Loam Digestate
Sand min N
Sand Digestate
Silt min N
Silt Digestate
Matric potential hPa
-10^4
-10^3
-10^2
-10
-1
0
10
20
30
40
50
60
Water content (Vol.%)