Task 2.11 Study on the behaviour of digestate in agricultural soils

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"Providing support in relation to the implementation of the Nitrates Directive (91/676/EEC)"

Cluster 2: The production of studies concerning the scientific, technical and socio-economic issues related to the Nitrates Directive

Task 2.11

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Summary

Objectives of the study

Required assessment:

• To what extent the **behaviour of digestate in soils**, including its availability to plants and leaching/runoff characteristics can be **compared to that of livestock manure**?

Being aware that digestate composition varies depending on biogas plants, the consultant should review and summarize the existing knowledge considering the main digestate categories existing in Europe. This should include digestate resulting from biogas plants fed with maize and livestock manure.

• What is the **knowledge in terms of efficiency of digestate in agricultural soils**? The review should encompass different categories of digestate and efficiency values should be suggested, to the extent possible, for the different categories of digestate.

Expected results

• A **comprehensive report** that addresses the above mentioned items. The study should include to-the-point **conclusions**, references to the **mentioned case studies** and **numerical examples**.

• The study should include **recommendations relating to the treatment of digestate** in relation to the aspects of the implementation of the Nitrates Directive mentioned above.

List of abbreviations

AD: Anaerobic digestion;
BOD: Biological Oxygen Demand;
MFE: Mineral Fertilizer Equivalent;
NUE: Nitrogen Use Efficiency;
OM: Organic matter.

Short glossary

Nitrogen mineralization is the process by which microbes decompose organic N from manure, organic matter and crop residues to ammonium.

Nitrogen immobilization is the reverse of mineralization and refers to the process in which nitrate and ammonium are taken up by soil organisms and therefore become unavailable to crops.

1. Introduction

The agronomic and environmental effect of the use of digestates for crop fertilization depends upon the three main components of the anaerobic digestion (AD) system: the feedstock, the technology utilized for the digestion process and the digestate management, including field application (Holmes-Nielsen, 2009). More specifically, types and load of feedstock, its pre-treatment and on site preparation, the AD process (i.e. loading rate, temperature, retention time), its post-digestation treatment and management of digestate and its integration in specific farm fertilization plans are sub-components which strongly affect digestate characteristics, fertiliser value and potential losses in the environment, especially with regards to nitrogen (N).

As for all amendments and fertilizers, the dynamics of nutrients after application of digestate to the soil depend on both its characteristics and the biotic and abiotic conditions of the soil . With reference to fertilizer N use, several processes contribute to the overall efficiency of organic material including digestate applied to the soil, such as ammonia (NH_3) volatilization, organic N mineralization, nitrous oxide (N_2O) and N_2 emissions, and nitrate (NO_3^-) leaching. Also agro-ecosystem characteristics (i.e. growing season, crop biomass and nutrient uptake, crop nutrient utilization), strongly influence the short and long-term nitrogen use efficiency (NUE) of digestates.

At the farm scale, NUE is the overall efficiency of N input for the entire farm system to produce N output. It can be very informative to calculate input, output and internal N fluxes in biogas plant systems as well as to estimate digestate N-efficiency using the above-mentioned approach. In this farm system, crops and residues produced in the farm represent a variable fraction of the feedstock (theoretically, from 0 to 100%) and biogas residues a variable fraction of N-fertilizers utilized for crop productions.

2. Digestate types and their characterization

2.1 Characteristics of input materials and anaerobic digestion process

Main feedstocks for anaerobic digestion (AD) both mono-fermented and co-digested, are animal manures, crop residues, wastes from the food industry, municipal wastes, and dedicated energy crops. The composition and fertilization value of digestates can vary greatly, depending on feedstock type and quality and the AD operating parameters (e.g., organic loading rate - OLR, hydraulic retention time – HRT, temperature of digestion). The process of anaerobic digestion induces qualitative and quantitative variations in the input materials, in terms of physical and chemical characteristics and the amounts of organic material and nutrients, respectively.

Such transformations have been investigated in depth (Albuquerque et al., 2012). In summary, during AD about 20–95% of the organic matter (OM) is decomposed, depending on feedstock composition and AD technology. The biological stability of residual OM is in general increased with the increase of more recalcitrant molecules like lignin, cutin, humic acids, steroids, complex proteins (Tambone et al., 2009; Monaco et al., 2010). However, aerobic decomposition rate of biogas residues may still be high with high loading rate and low retention time. While not leading to a reduction of the total N presents in the input materials, the process causes a transformation of the N organic form in ammonium (NH_4^+-N), which is more available for plant, faster active as nutrient but prone to environmental losses, especially NH_3 volatilization.

Under the digesting process, pH is increased. The range of such an increase depends on the quality of feedstock characteristics and the digestion process (Makádi et al., 2012). The final pH of the digested slurry can vary depending on the balance between NH_4^+ and NH_3, CO_2, HCO_3^- and CO_3^{2-}, CH_3COOH and CH_3COO^-. The presence of cations (K^+ and Ca_2^+) may increase the pH, while the formation of struvite by the precipitation of NH_4^+, Mg^+ and PO_4^{3-}, causes a release of H^+ ions and hence a decrease in pH.

2.2 Digestate processing

Digestates could be either directly spread as manures, or processed prior to field application e.g. by solid–liquid separation, drying, dilution or filtration. The application of different processing technologies strongly affects digestate composition, leading to different behaviour after field application. The development of the biogas sector has encouraged the spreading of technologies for digestate's treatment (Fuchs & Drosg, 2013).

Main aims of digestate processing are the following:

- increase of the concentration of nutrients through separating the excess water from the solid fraction;
- change the chemical composition of the material in order to increase the amount of nutritive elements in mineral form (easily assimilated by the crops) rather than in organic form;
- improve the management (i.e. storage, transport, field application) of the material;
- decrease the N nutrient load, preferably through technologies able to recover rather than disperse N i.e. by the production of N mineral fertilizers.

Digestate processing usually produce one or more types of residue which in some cases can be directly applied as fertilizer(e.g. solid and liquid fraction from separation, digestate remaining after ammonia stripping). The properties of these "treated digestates" will depend on the processing technique applied.

Solid - liquid separation: The simplest and most widespread treatment of both raw slurry and digestate is the solid - liquid separation, especially using a mechanical process i.e. sieves, presses or centrifuges. The liquid fraction contains a larger part of the original N, especially in ammonium form, while solid fraction has a higher content of organic substances and contains a larger fraction of phosphorus (Bustamante et al., 2012). The efficiency of separation and its energy consumption varies depending on several factors i.e. type of separator, manure characteristics and use of chemical additives. Data on the efficiency of separation for raw slurry and digestates are reported by many authors (Balsari et al., 2006; Mantovi et al., 2009).

Ammonia stripping: This technique is used to remove and recover the ammoniacal N from livestock slurry or digestate. Removal efficiency varies from 60 to 90% (Fabbri et al., 2011). Ammonium-N in the solution is transferred into gaseous form (NH_3) and absorbed in a strongly acidic solution (typically a solution of sulfuric acid), which normally leads to the production of ammonium sulphate, which can also be crystallized and precipitated in a solid form. The most common process is based on a combination of stripping and washing (by a scrubber) to intercept volatilized NH_3. Ammonia stripping should always be combined with solid / liquid separation to avoid the presence of coarse particles during the process. The efficiency of the process increases with high concentrations of NH_4^+ in the effluent, high pH and temperatures; in that respect, it is more suitable for biogas digestate than raw animal waste treatment (Guštin & Marinšek-Logar, 2011).

Nitrification/denitrification: Nitrification and denitrification are based on the ability of micro-organisms to assimilate N, oxidize ammonium to nitrite or nitrate in aerobic conditions, and, after a rapid shift into a highly anoxic environment, on reduction of nitrite/nitrate to N_2. These processes are performed by different microbial populations. The nitrification/denitrification systems utilized for civil wastewater treatment are costly due to the amount of electricity used, the frequent need to add external available C inputs for the denitrification process and the heavy management of processes (Zhang et al., 2011)

Evaporation: Evaporation utilizes thermal energy (heat) to release the digestate water and increase both nutrient and solids concentration. The final solid concentration will be dependent on the desired product, but concentrations of up to 20% of dry matter (DM) can be achieved. During the process high temperatures will cause NH_3 losses. This can be overcome by decreasing the pH of the digestate, typically with acid, prior to evaporation (Provolo, 2012).

Struvite precipitation: The crystallization and recovery of struvite (magnesium ammonium phosphate hexahydrate) from effluents can be achieved in reactors with suitable conditions (pH > 8) for its controlled precipitation. Struvite precipitation efficiently removes phosphorus (up to 80%) but less N (20-30%). Moreover, since ammonium form of N allows struvite precipitation, this treatment is more suitable with digestate rather than raw slurry (Liu et al., 2013).

2.3 Digestates characterization and composition

Feedstock, AD process and treatments strongly affect final composition of digestates and their fertilizer value.

Möller and Müller (2012) reported a review of digestates characteristics compared with undigested animal manures. Table 1 summarizes and expands this review, including further experimental results.

Table 1. Range of main characteristics of digestates (untreated and liquid and solid fractions from solid/liquid separation) in comparison with undigested animal slurries.

	Unit	Digestate*		Liquid fraction of dig.**		Solid fraction of dig.**	
		Absolute values	*Difference digestate minus raw*	Absolute values	*Difference with liquid undigested*	Absolute values	*Difference with solid undigested*
DM	%	1.5-13.2	*-1.5 to -5.5*	1.6-6.6	*-0.6 to -0.9*	13.4-24.7	*-0.3 to +0.3*

Total C	% DM	36.0-45.0	*-2 to -3*	33-48	*-0.7 to -10.7*	39.6-42.9	*+0.8 to +1.0*
Total N	kg Mg^{-1} FW	1.20-9.10	*≈ 0*	2.0-5.1	*≈ 0*	4.2-6.5	*≈ 0*
NH_4^+/N	%	44-81	*+10 to +33*	40-80	*+6 to +13*	26.0-49.4	*+3 to +5*
C:N ratio		3.0-8.5	*-3 to -5*	2.4-4.8	*-1.6 to -3.1*	11.2-19.3	*-2.9 to +0.1*
Total P	kg Mg^{-1} FW	0.4-2.6	*≈ 0*	0.2-1.0	*-0.24*	1.7-2.5	*+0.4 to +0.8*
Total K	kg Mg^{-1} FW	1.2-11.5	*≈ 0*	2.6-5.2	*-0.13 to -0.17*	2.4-4.8	*+0.5 to +0.6*
pH		7.3-9.0	*+0.5 to +2*	7.9-8.4	*+0.66 to +1.19*	8.5-8.7	*+0.5 to +0.7*

* Data from Möller and Müller (2012)

** Data from Möller and Müller (2012) and from Monaco et al. (2010)

Digestates have higher ammonium NH_4^+-N : total N ratio and a narrow C:N ratio in comparison with animal slurries, especially when they derived from feedstock with a high degradability end/or a high N-content (e.g. cereal grains, poultry and pig manures).

Expected effects of AD processes on chemical characteristics of digestate are: decrease in the total and organic C contents, reduce of biological oxygen demands (BOD), higher pH values and more reduced viscosities than undigested animal manures. The pH increase is usually due to formation of ammonium carbonate ($(NH_4)_2CO_3$) and the removal of CO_2, but several components influence digestate reaction.

The liquid digestate contains less than 10 % of DM, while the solid digestate usually contains more than 15 % DM. The composition of treated digestate often presents a relationship between nutrients (i.e. N: P, N: K) not balanced for the purposes of plant nutrition.

3. Experiments and studies on digestates

Researches aimed at evaluating the fertilization value of digestates are quite recent and still few, especially if compared with those on animal manure (Nkoa, 2014). In particular, the long-term effects of digestate utilization on soil fertility have not yet been sufficiently investigated.

In the present report, the scientific publications have been divided among three experimental approaches, representing different scales, methodologies and objectives:

- laboratory investigations mainly focusing on C and N dynamics in amended soils under controlled environmental conditions (paragraph 3.1);
- agronomic experiments carried out in pot or in field with the aim of evaluating the effect of digestate use on crop, N efficiency and soil fertility (paragraph 3.2 and 3.3);
- studies aimed at assessing the overall biogas plant system and management options, including the field utilization of digestates (paragraph 3.4).

Most of the investigations on digestate application to soils have been carried out in comparison with reference animal manures and mineral N fertilizers.

3.1 Experiments on soil nitrogen dynamics under controlled environmental conditions

Several experiments on digestates, both raw and processed have been carried out through laboratory aerobic incubations focusing on the study of C and N dynamics after soil application (see Attachment 1). These studies help understanding the early dynamics and fate of digestate-N applied to the soil in relation with its characteristics and soil properties. They have been mainly developed for evaluating the mineralization-immobilization turnover in amended soils.

In the Attachment 1, specific protocols and main findings of some of this type of experiment applied to digestate in comparison with animal manure or other bioenergy by-product are shown. Main general findings on digestates application to soils under controlled environmental conditions are:

- **increase of the rapid availability of N** in comparison with animal manure is expected due to high N in NH_4^+ form applied with all types of digestate. Albuquerque et al., 2012a found that highly biodegradable digested materials (e.g. digestates from cattle slurry–glycerine mixtures) caused a high soil respiration and led to N-immobilisation and/or denitrification after their application to soil. In the contrast, for less biodegradable digested materials (e.g. cattle slurry digestate) less soil respiration was induced and ammonium was rapidly nitrified in soil—being an available N source for crops;

  - the type of digestate has a very low effect on **nitrification rate** i.e. the transformation of NH_4^+ in NO_3^- with high mobility which is more dependent on soil OM and soil microbial biomass (Galvez et al., 2012; Rigby & Smith, 2013);**- N_2O emissions**: Although not significant from an agronomic point of view (i.e. the amount of N lost as N_2O is always limited), N_2O emissions have highly relevant environmental consequences in terms of greenhouse gases emissions. The application of digestate with low contents in easily degradable C may reduce soil N_2O emissions compared with raw animal slurry, probably because there is less energy source for denitrifiers (Nkoa, 2014). Some in field studies (Attachment 2) have shown lower N_2O emissions on land spread with digested slurries (Amon et al., 2006; Chantigny et al., 2007; Collins et al., 2011; Petersen, 1999). Other laboratory studies highlight the effect of the type of digestate and the interaction with the soil type. For instance, Abubaker et al. (2013b) found that the effect of two different types of digestate generated from urban and agricultural waste was different in three different soil: in the sandy soil digestate with higher DM contents caused higher emissions compared with untreated slurry, in the clay soil both types of digestate caused higher emissions, while in the organic soil untreated cattle slurry emitted more N_2O than both digestates;

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- **NH_3 emissions**: digestates have a higher fraction of NH_4^+-N and higher pH, which increase NH_3 volatilization potential. However, due to the reduced DM content, digested slurry can infiltrate more rapidly into the soil reducing potential NH_3 emissions after application to the soil in some conditions (Webb et al, 2013);
- **microbiological aspects:** several researches showed that micro-organisms population and activity are different after digestate soil application compared with raw animal manure, but alterations in the soil functioning have not be recorded (Abubaker et al., 2013a; Galvez et al., 2012);

3.2 Agronomic experiments (pots and fields)

Direct agronomic evaluations of digestates for crop fertilization are based on pot or field experiments. Digestate is often compared with raw animal manures and/or mineral N fertilizers.

In Attachment 2, a summary of protocols and main findings from this type of experiment is reported.

Main findings on digestate application to soils using pots and field trial are:

- **Crop N availability:** the crop N availability of digestate is influenced by its chemical composition and by N losses after application in the field. AD increases NH_4^+–N content, the stability of the residual OM and considerably decreases the C/N ratio, resulting in a product with a large proportion of directly available N (Webb et al., 2013). The fraction of crop N uptake often is higher with all types of digestate than livestock manure if NH_3 losses and NO_3^- leaching are prevented, with correct timing of application and immediate incorporation into the soil (Cavalli et al., 2012; Gunnarsonn et al., 2010; Loria et al., 2007; Odlare et al., 2008);
- **Fertilizer long term residual effect:** repeated applications of organic materials to soils result in an increase in N mineralization potential and a higher mineral N release during the year if mineralization conditions are favourable. The residual effect (after the year of their application) increases with high amounts of organic N applied, and can represent a great source of N for plant growth (Monaco et al., 2010) as well as a risk in terms of NO_3^- leaching when organic applications are continuous throughout the years. Compared to raw manure liquid digestates have a lower amount of OM, so that a smaller residual fertilizer-effect may be expected. However, results on long-term applications on digestate in cropping systems are lacking;
- **Fertilization value and crop productions:** The fertilisation value of biogas residues is in general high due to the high content of NH_4^+-N and other micro-and macro-nutrients such as P, K, Ca and Mg that are stable at the digestion temperatures and microbiologically preserved during AD. Several experiments have demonstrated that digestates can sustain high crop productions (Abubaker et al., 2012; Morris & Lathwell, 2004; Walsh et al., 2012);
- **Crops and cropping systems**: different digestates have been tested for fertilization of several crops and cropping systems, using different methods and timing of application, as well as integration with mineral fertilizers. Alburquerque et al. (2012) found that co-digestate produces higher marketable yields than cattle manure for horticultural summer crops, while lower when compared with mineral fertilizer in winter crops; Moller et al. (2008) reported that in organic dairy farm the digestion of pig slurry increased

N uptake and crop yields when incorporated to the soil and that digestion of crop residues and cover crops further increase N uptake of the system; Sieling et al. (2013) found that in maize monoculture N use efficiency of co-digestate was high and similar to mineral fertilizer, while in perennal ryegrass it was low and similar to cattle slurry;

NH_3 losses: large emissions of NH_3 have been measured following surface application of digestate, reaching more than 30% of applied NH_4^+-N in presence of strong wind (Quakernack et al., 2012), although the low DM content in digestates can help infiltration into the soil in some conditions (i.e. bare soil with low water contents). The more secure and effective NH_3 abatement techniques, such as injection or immediate incorporation into soil, are usually very effective in increasing N uptake (Moller et al., 2008).

- **Nitrate leaching:** digestates supply high amounts of inorganic N that is usually nitrified in few days. Timing of application is then very important to reduce the risk of NO_3^- leaching of the digestate available-N. Moreover, the reduced content of organic N in the digested slurry means that the potential long-term NO_3^- leaching losses from mineralized N are reduced compared with animal manure, but the literature on this aspect is very limited. In a field experiment with maize, Svoboda et al. (2013) assessed NO_3^- leaching through the direct measurement of concentrations in soil solution and the integration of these data with a water flow model. The author found that in the short-term biogas residues showed similar NO_3^- leaching potential in comparison with animal slurry;
- **Soil properties**: few works focus on the effects of repeated digestate application on soil physical and chemical properties (Beni et al., 2012), especially if compared with long-term experiments carried out for animal manure. The heavy metals concentration of digestate is usually low (Albuquerque et al., 2012b).

3.3 Nitrogen use efficiency

Nitrogen use efficiency can be applied at different scales, i.e. plant scale, field scale and farm scale (Webb et al., 2013). In the analysed scientific literature (see Attachment 2), NUE of digestates has been assessed at plant and crop scale using three main methods of calculation:

1) crop N uptake relative to total N applied with digestate (hereinafter called as NUE);

2) crop N uptake relative to ammoniacal N applied with digestate (hereinafter called as NUE-NH_4);,

3) NUE or NUE-NH_4 relative to mineral fertilizer-NUE (hereinafter referred as Mineral Fertilizer Equivalent and called MFE or MFE-NH_4,)

Reported assessments of N use efficiency usually refer to first-year availability, since a low residual effect of digestate-N is expected and results on long-term experiments with digestates are lacking. Moreover, experiments are mainly based on simplified fertilization plans while the integration between digestate and mineral fertilization for calculating an overall N use efficiency are not usually taken into account.

The following experimental results give an overview on N use efficiency of different digestates:

- In field maize followed by It. Ryegrass, Cavalli et al. (2012) measured following NUE-NH_4 (average of two years): 75,5% for ammonium sulphate, 65% for co-digested slurry, 18% for raw slurry.Reported results seem to demonstrate 1) higher N efficiency with co-digestate in comparison with raw dairy cow slurry; 2) more stable N efficiency values in the short-term for co-digestate in comparison with dairy cow slurry;
- In pot with It. Ryegrass, Gunnarsonn et al. (2010) reported a NUE-NH_4 of 76% for digestate from plant materials (grass and sugar beets leaves) compared with 83% for mineral fertilizer. Reported results

demonstrate that NH_4 applied from this type of digestate has a similar efficiency compared with mineral fertilizer;

- In field lettuce, Montemurro et al. (2010) reported a MFE of 90% and 52% for stabilized and not stabilized digestate distillery wastewater, respectively; this result demonstrates that very high N use efficiency can be also achieved using some types of digestate from food industry waste;
- In a rotation experiment with co-digestate of manure and maize, Sieling et al., (2013) found NUE of 70, 63 and 54% for maize monoculture, maize-wheat-It. Ryegrass and periennal ryegrass, respectively; this results highlight that the NUE of biogas residue application depended on the crop rotation;
- Moreover, Webb et al. (2013) reported the results of Pedersen (2001) in field experiment with wheat; NUE values were 57, 74 and 82% for injected cattle slurry, pig slurry and co-digestate, respectively (64% if digestate was applied on the soil surface); these results demonstrate 1) higher N efficiency with co-digestate in comparison with livestock manure, 2) that the incorporation of digestate is very important to increase NUE;

  Webb et al. (2013) also reported results from De Boer (2008); in a pot experiment with ryegrass he measured MFE of 75 and 95% for pig slurry and digestate, respectively; these results demonstrate 1) higher N efficiency with digestate in comparison with livestock manure, 2) digestate sometimes, but not always can have a similar efficiency than as mineral N fertilizers.

3.4 Full case studies of anaerobic digestion plants

Full scale case studies of anaerobic digestion plants are usually aimed at evaluating energy and environmental performance of biogas and digestate utilization options, both based on applied technologies and scenario analysis (Chen et al., 2012). Borjesson and Berglund (2007), comparing biogas system options to reference energy and agricultural systems, concluded that environmental improvements are often due to indirect benefits of changing land use (e.g. energy crops, cover crops) and handling of digestate (i.e. reduction of N leaching, NH_3 and methane emissions). In a life cycle assessment of two real biogas plants, De Meester et al. (2012) concluded that anaerobic digestion induce significant resource savings, although it is necessary to control emissions in the biogas production chain, including digestate application to soils. Therefore, in order to better evaluate the effects of in fiel d digestate applications, it is necessary to assess N fluxes and NUE at farm scale using case studies and scenario analyses.

4. Conclusions

This report summarizes the main aspect of agronomic use of digestate, with reference to scientific literature. Digestates can have a high variation in composition, based on feedstock, anaerobic digestion parameters and treatments, which strongly influence nutrient dynamics after application to soils. Moreover, pedoclimatic and cropping systems characteristics further increase the variability of digestate behaviour.

However, it is possible to draw some conclusions on digestates in comparison with mineral N fertilizers and animal manures:

- Digestates potentially show a high fertiliser value due to their contents of available N, P, K and micronutrients and can sustain high crop yields. However, the nutrient concentrations and the balance between nutrients may vary considerably. This high variability of digestate quality (depending on feedstock, AD process and treatments) highlights the importance of specific analysis before digestate can be efficiently included in any fertilisation plan;
- The AD process reduces and stabilizes effluents OM, with potential benefits from an environmental point of view (reduce uncontrolled emissions of methane, CO_2 and nitrate leaching). The total N amount is not reduced during AD, but the inorganic ammonium form increases. This aspect improves the short-term availability of N for crops, so that a high N efficiency may be reached in the first year of application if digestate is properly applied (e.g. timing and rate, method of application);
- Achievable crop N use efficiencies of the first-year of application are often higher than after application of livestock manure and can be similar to that of reference mineral N fertilizers. However, experimental results on N use efficiency of long-term digestate applications are lacking;
- Environmental problems potentially associated to digestate-N when it is applied to the soil are similar to problems caused by raw livestock manures. However, digestates potentially have a higher risk of NH_3 emissions and short-term NO_3^- leaching if it is not properly applied. A lower residual N release due to mineralization is expected compared with livestock manures, with a positive effect on potential risk of NO_3^- leaching. Although a reduction on N_2O emissions of digestates compared with raw materials has been proved in several experiments, interactions among digestate type and soil can reverse this result; this aspect also need further investigations;Digestate processing modifies quantity and quality of nutrients in the biogas effluents. The agronomic performance of treated digestate applications may increase (e.g. liquid fraction with low DM and high NH4+/N ratio) but processing options must be analysed in an overall assessment of biogas plant system, taking into account by-product disposal and the integration in cropping systems and fertilization plans.

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Attachment 1. **Summary of protocols and main findings from aerobic incubation experiments under controlled environmental conditions using different types of digestate.**

Author	Manure types	Environmental conditions of incubation	Fresh matter or N amount	Studied effect on amended soils	Main findings
Abubaker et al., 2013	Two biogas residues (urban and agricultural waste), cattle slurry and control unfertilized.	+20 °C for 120 days. Three soils: sandy, clay and organic clay soil	70 kg NH_4^+-N ha^{-1}	Bacterial community structure and microbial activity changes	Differences appear in terms of bacterial community structure between biogas residues and cattle slurry. However, the observed differences in microbial community structure induced by the biogas residues appeared to be smaller than those induced by raw cattle slurry, and those changes did not translate into altered microbial functioning.
Abubaker et al., 2013	Two anaerobically digested biogas residues (urban and agricultural waste), cattle slurry and control unfertilized.	+20 ◦C for 24 days. Three soils: sandy, loam and organic clay soil	70 kg NH_4^+-N ha^{-1}	Nitrous Oxide Production	In the sandy soil, digestate with higher DM contents caused higher emissions compared with untreated slurry, in the clay soil both types of digestate caused higher emissions, while in the organic soil untreated cattle slurry emitted more N2O than both digestates.
Alburquerque et al., 2012	Six digestates from co-digestion of cattle or pig slurry with agro-industrial wastes (without post-treatments)	26 ◦C for 56 days	96 m^3 ha^{-1} (140 to 380 kg N ha^{-1})	Dynamics of C-mineralisation and inorganic-N	Highly biodegradable digested materials represented in the present study by digestates from cattle slurry–glycerine mixtures caused a high soil respiration and led to N-immobilisation and/or denitrification after their application to soil. Contrastingly, for less biodegradable digested materials less soil respiration was induced and ammonium was rapidly nitrified in soil—being an available N source for crops.

Author	Manure types	Environmental conditions of incubation	Fresh matter or N amount	Studied effect on amended soils	Main findings
Bertora et al., 2008	Untreated pig slurry, solid and liquid fraction of pig slurry, liquid fraction of digestate, unfertilized and urea	25 °C for 58 days	170 kg N ha^{-1}	N_2O and CO_2 emissions, denitrification and soil mineral N	No differences between liquid fraction and the anaerobically digested liquid fraction in comparison with the original slurry for any of the studied parameters.
Cayuela et al., 2010	Ten by-products from different bioenergy chains, including two biogas residues (cattle manure and pig slurry digestates)	20 °C for 60 days; sandy soil	150 kg N ha^{-1}	CO_2 and N_2O emissions	Manures and their digestates showed the same level of Global Warming Potential (combining total N_2O and CO_2 emissions).
Galvez et al., 2012	Four bioenergy by-products, including pig slurry digestate, and three commonly used organic amendments	20 °C for 30 days; two soils	20 t ha^{-1}	Nutrient availability and microbial content and activity	According to their impact on soil biochemical properties, the materials can be ranked as follows: rapeseed meal, bioethanol residue > anaerobic digestate, sewage sludge > composts > biochar. For each measured parameter, soil properties did not affect the response pattern found for the different treatments, but modified the magnitude of the response.
Monaco et al., 2012	Untreated pig slurry, liquid fraction of untreated pig slurry and liquid fraction of anaerobically digested pig slurry	20°C for 6 days; two arable soils: silty-loam and loam	90 kg NH_4^+-N ha^{-1}	NH_3 emissions of different treatment options	Surface application of liquid fraction of untreated and digested slurry decreased emissions by 50 and 39%, respectively, in comparison with raw material due to lower dry matter.
Rigby & Smith, 2013	Four industrial and urban digestate types in addition to a mineral N and unamended control	25°C for 48 days; three arable soils	200 kg N ha^{-1}	N availability	N release was a function of digestates properties (e.g. mineral N content and mineralisable N fraction). Soil type can greatly influence the N availability and the loss of digestate N.

Author	Manure types	Environmental conditions of incubation	Fresh matter or N amount	Studied effect on amended soils	Main findings
Thomsen et al., 2013	No treatment (feed), anaerobic digestion (digested feed), consumed by cattle (faeces), consumed by cattle and anaerobic digestion (digested faeces)	20 °C for 245 days; coarse sand soil	3.6, 2.0, 2.1 and 2.1 mg C g^{-1} soil for feed, faeces, digested feed and digested faeces, respectively	The fate of C in ruminant feed treated differently before addition to soil	Long-term soil C sequestration is not influenced by treatments if the initial amount of C in feed is considered. However, low amount of labile organic matter in anaerobic biogas residues most likely affects soil microbial activity that is in fact reduced when residues are anaerobically digested for biogas before being applied to soil

Attachment 2. Summary of protocols and main findings from pot and in field experiments using different types of digestate.

Author	Experimental conditions	Crop	Experiment duration	Fertilizer types	N amount	Digestate distribution technique	Main results	Nitrogen efficiency
Abubaker, 2012	Pot experiment; growth chamber; sandy soil.	Spring wheat (*Triticum aestivum* L.)	Three months	Four different biogas residues (urban), pig slurry and mineral fertiliser.	Calculated on the basis of NH_4^+—N level: 35, 70, 140 Kg NH_4^+-N ha^{-1}	Added manually and incorporated to the soil	Fertilisation with biogas residues gave similar biomass yields but increased nitrogen mineralization capacity and ammonium oxidation rate in soil compared with mineral fertilizer. Pig slurry gave the overall highest yields and nitrogen mineralization capacity, but an ammonium oxidation rate comparable to most biogas residues.	All organic fertilisers increased potential N mineralisation and potential ammonium oxidation rates.
Alburquerque, 2012	Field experiment; Mediterranean climate; soil: sandy loam, pH 8.0	Watermelon (*Citrullus lanatus*); cauliflower (*Brassica oleracea*)	Two-year period of double crops (watermelon-cauliflower-watermelon-cauliflower)	i) Co-digestate (pig slurry + slaughterhouse and biodiesel wastewaters);cattle manure; mineral fertiliser (fertigation); iv) unfertilized	240 kg N ha^{-1} for watermelon and 280 kgN ha^{-1} for cauliflower	Added manually and incorporated before planting (between four and eight weeks).	Watermelon (summer crop): digestate and mineral fertilisation produced higher marketable yields than cattle manure. Cauliflower: lower yields with digestate and manure than with mineral fertilizers.	Digestate provided high ammonium N amount, rapidly nitrified and directly available to crops in the short-term and scarce residual effect. It is therefore more suitable for summer than for winter crops.

Author	Experimental conditions	Crop	Experiment duration	Fertilizer types	N amount	Digestate distribution technique	Main results	Nitrogen efficiency
Amon et al., 2006	Field experiment; summer application in Austria	Grassland	48 hours	Untreated slurry, biogas slurry, separated slurry (liquid and solid phase), aerated slurry and slurry that was Covered with a layer of chopped straw	40 m^3 ha^{-1} of sllurry	Band spreading	After field application, an increase of c.18% in NH_3 emissions for biogas slurry compared to untreated slurry was observed. On the contrary, the low dry matter content of digested slurry resulted in a reduction of N_2O emissions.	No data on N efficiency are reported here.
Beni et al., 2012	Field experiment; Mediterranean climate	Winter lettuce (*Lactuca sativa L.*)	2 growing seasons	i) Unfertilized, ii) split mineral fertilization, iii) compost from farm residues, iv) distiller's residue, v) AD distiller res, vi) AD + mycorrhizas, vii) organomineral fertilizer, viii) mycorrhizas	140 kg N ha^{-1} y^{-1}	Four weeks before transplanting	Compost, anaerobic digestate, and mycorrhizas applied for 2 years enhanced the soil physical fertility and the mechanical strength resistance.	No data on N efficiency are reported here.
Cavalli et al., 2012	Field experiment; Sub-continental climate; soil: silty-loam, pH 5.8	Silage maize followed by unfertilised Italian ryegrass crop	2 growing seasons	i) Raw and ii) co-digested dairy cow slurry, iii) liquid and iv) solid fractions of co-digestate, v) ammonium sulphate, vi) unfertilized	Calculated on the basis of NH_4^+—N level: 155 Kg NH_4^+-N ha^{-1}	First year: trailing hose spreader and immediately incorporation with a rotary harrow. Second year: injection.	Apparent Nitrogen Recovery of NH_4^+-N in digestate was similar to that of ammonium sulphate.	NUE-NH_4 (average of two years) are 75,5% for ammonium sulphate, 65% for co-digested slurry, 18% for raw slurry.

Author	Experimental conditions	Crop	Experiment duration	Fertilizer types	N amount	Digestate distribution technique	Main results	Nitrogen efficiency
Chantigny et al., 2007	Field experiment in Canada with loam and sandy loam soils	Timothy (*Phleum pratense* L.)	3 growing seasons	i) Raw pig slurry, and ii) digestate, iii) decanted, iv) filtered v) flocculated pig slurry; vi) mineral fertilizer	140 kg N ha^{-1} and split 80 kg ha^{-1} in spring and 60 kg ha^{-1} after the first harvest	Surface applications	NH3 emissions were lower for digested than untreated pig slurry probably due to a lower dry matter contents that increase the infiltration rate. N_2O losses were 54 to 69% lower with the digested than with raw slurry in the loam soil and 17 to 71% lower in the sandy loam	No data on N efficiency are reported here.
Collins et al., 2011	Field experiment in the Washington State (US) in irrigated silt loam	Silage corn	2 growing seasons	i) urea, ii) raw liquid dairy manure, iii) digested dairy slurry, iv) digested fiber, v) unfertilized	224 kg N ha^{-1} before planting, 112 kg N ha^{-1} as top dressing	Band spreading	The total inorganic soil N during the growing season was similar for mineral, digestate and raw slurry In both years. Cumulated N2O emissions were higher for liquid manure than digested slurry and digested fibers.	No data on N efficiency are reported here.
Gunnarsonn et al., 2010	Pot experiment; sandy soil	Italian ryegrass *(Lolium multiflorum* Lam.*)*	Six months	i) Digested plant materials (grass/clover and sugar beet leaves), ii) inorganic fertilizer, iii) unfertilized	Calculated on the basis of NH_4^+—N level: 75 and 150 Kg NH_4^+-N ha^{-1}	Added manually and incorporated to the soil	Mineral N in effluent from biodigested plant materials was almost as effective as the NO_3^--N applied as inorganic for plant growth.	NUE-NH_4 of 76% for digestate from plant materials (grass and sugar beets leaves) compared with 83% for mineral fertilizer.

Author	Experimental conditions	Crop	Experiment duration	Fertilizer types	N amount	Digestate distribution technique	Main results	Nitrogen efficiency
Kouřimská et al., 2012	Greenhouse experiment with 20l pots; peat-bark substrate	Tomato (*Lycopersicon lycopersicum L.*) and pepper (*Capsicum annuum L.*)	Five years for tomatoes, two years for peppers	i) control, ii) mineral (NH4)2SO4, iii) digested pig slurry, iv) combined mineral and digestate	N/A	fertilizers were split (50% at planting, 50% added after 30 days)	The highest increase of tomatoes and green peppers yields with combined with application of mineral fertilizer was the best management system for increasing tomatoes and green peppers yields	No data on N efficiency are reported
Kováčiková et al., 2013	Field experiment in seminatural grassland	Grassland	Two years	i) control unfertilized, ii) digestate from 100% cattle/pig slurry, iii) digestate from 80% slurry + 20% phytomass, iv) igestate from 60% slurry + 40% phytomass	40 kgN ha^{-1} + 20 kgN ha^{-1} after the first cut	N/A	The highest increase in dry matter production was found with digestate from 60% slurry and 40% phytomass.	No data on N efficiency are reported
Loria et al., 2007	Field experiment in two sites in Iowa - US; soils: fine loamy.	Maize *(Zea mays* L.)	3 growing seasons	i) Raw swine manure and ii) anaerobically digested swine manure	3 manure levels (0, 87, 168 kgN ha^{-1}) and six NH_4NO_3 levels after planting (0 to 225 kgN ha^{-1})	In the late fall with a sweep injector applicator	No difference between raw and digested swine manure as a source of N for plant use in the year of application or in the residual year.	Apparent N recovery of both raw and digested swine manure to maize varied between years from 44 to 100% (68% on average).

Author	Experimental conditions	Crop	Experiment duration	Fertilizer types	N amount	Digestate distribution technique	Main results	Nitrogen efficiency
Losak et al., 2014	Two pot experiments with heavy soil	Kohlrabi (turnip cabbage) (*Brassica oleracea* Gongylodes group)	Two years	i) mineral N, ii) mineral N, P, K, Mg, iii) co-digestate frompig slurry and maize silage , iv) control unfertilized	250 mgN kg^{-1} dry soil	Applied by soil watering and were thoroughly mixed	Digestate and NPKMg fertiliser treatments increased bulb weight compared with the N-only urea treatment. Digestate gave a low nitrate content in bulbs.	No data on N efficiency are reported
Moller et al., 2008	Field experiment in organic dairy farm; continental climate; soil type: silty-loam.	Mixed system with arable crops rotation (70% of the area) and grassland (30%)	3 growing seasons	i) Farmyard manure, ii) undigested and (iii) digested slurry, (iv) dig. slurry + field res, (v) dig. slurry + field res + ext. substrates	177 kg N ha^{-1} on average	Time of application and splitting differentiated among fertilizer types	The digestion of the liquid slurry increased N uptake and crop yields with early soil incorporation.	Cover crops and crop residues digestion increase the above ground N uptake of the cropping system (+ 8%) and therefore Nitrogen Use Efficiency.
Moller and Stinner, 2009	Field experiment in organic dairy farm; continental climate; soil type: silty-loam.	Mixed system with arable crops rotation (70% of the area) and grassland (30%)	3 growing seasons	i) Farmyard manure, ii) undigested and (iii) digested slurry, (iv) dig. slurry + field res, (v) dig. slurry + field res + ext. substrates	177 kg N ha^{-1} on average	Time of application and splitting differentiated among fertilizer types	Biogas co-digestion of field residues, with additional energy yields, resulted in lower nitrate leaching risk and lower nitrous oxide emissions. Ammonia volatilization after application from digested slurry was higher than the volatilization from undigested slurry.	No data on N efficiency are reported here.

Author	Experimental conditions	Crop	Experiment duration	Fertilizer types	N amount	Digestate distribution technique	Main results	Nitrogen efficiency
Montemurro et al., 2010	Field experiment; Mediterranean climate; clay soil	Lettuce *(Lactuca sativa L.)*	3 growing seasons	i) Digestate of wine distillery wastewater, ii) farm compost, iii) mineral fertiliser, iv) slow N release, v) unfertilized	140 kg N ha^{-1}	Applied and incorporated 30 days before transplanting; inorganic fertilizer was supplied in two times.	No significant difference in N efficiency between digestate and inorganic fertilizer treatment.	MFE of 90% and 52% for stabilized and not stabilized digestate distillery wastewater, respectively;
Morris & Lathwell, 2004	Two pot experiments; two soil types: fine-loamy alkaline and coarse-loamy acid	Maize *(Zea mays* L.)	1 growing season	First exp.: i) digested dairy manure, ii) $(NH_4)_2SO_4$ iii) 0N. Second exp.: i) undigested and ii) digested dairy manure, iii) $Ca(NO_3)_2$, iv) NH_4NO_3, v) $(NH_4)_2SO_4$, vi) 0N	First experiment: 100, 200, 300 mg N Kg^{-1} dry soil; Second experiment: 200 mg N Kg^{-1} dry soil	Added manually and incorporated into the soil	Digestate was equal or more effective than inorganic fertilizer in sustaining maize growth in early stages of development.	No data on N efficiency are reported here.
Odlare et al., 2008	Field experiment in Eastern Sweden	Oats (*Avena sativa*) and spring barley (*Hordeum vulgare*)	Four growing seasons	i) Compost (2 rates), ii) liquid biogas residues (2 rates), iii) digested sewage sludge, iv) pig manure v) cow manure, vi) inorganic fertilizer, vii) unfertilized	100 kg total applied N ha^{-1} (organic + mineral fertilizers)	Compost, sewage sludge and cow manure spread in late autumn; digestate and pig manure before stem elongation; mineral N at sowing.	Biogas residues increased potential ammonia oxidation rate, N mineralization capacity as well as the specific growth rate constant of denitrifiers.	No data on N efficiency are reported here.

Author	Experimental conditions	Crop	Experiment duration	Fertilizer types	N amount	Digestate distribution technique	Main results	Nitrogen efficiency
Quakernack et al., 2012	Field experiment; marshland region in Northern Germany; silt-clay soil	(a) 2-year rotation of maize, wheat and It. Ryegrass, (b) maize and (c) per. ryegrass	Two growing seasons	i) digestate (30% pig slurry, 70% grass and wheat) ii) Calcium ammonium nitrate, iii) unfertilized	Three levels (0, medium and high). Additional mineral N (50kgN ha^{-1}) at sowing	Applied by trail hoses without subsequent incorporation	NH_3 losses with biogas residue: up to 30% of NH_4-N applied, with consequent decrease in yields, especially perennial ryegrass.	No data on N efficiency are reported here.
Petersen, 1999	Field experiment in Denmark; sandy loam soil	Spring barley (Hordeum vulgare L.).	Two growing seasons	i) Untreated slurry ii) digestated slurry iii) calcium ammonium nitrate and iV) urea	100 and 80 kg NH4+-N ha-1 of organic fertilizer in the first and second year, respectively. Different timing of applications were considered	Immediately incorporate when applied before sowing; band spreading at top dressing	Lower N2O cumulated emissions for digestate compared with untreated slurry	No data on N efficiency are reported here.
Sieling et al., 2013	Field experiment in two sites in northern Germany; site 1: sandy loam, site 2: humus sand	i) maize, (ii) maize–wheat - It. ryegrass, (iii) maize grain-wheat-mustard as a catch crop and (iv) per. ryegrass		(i) calcium ammonium nitrate, (ii) cattle slurry, (iii) pig slurry, and (iv) digestate from pig slurry and silage maize	Four levels (maize: 0 to 360, wheat: 0 to 360, It. ryegrass: 0 to 160, Per. Ryegrass: 0 to 480 kg N ha^{-1})	Generally applied using trail hoses and split in two or three applications	N use efficiency of biogas residue application depended on the crop rotation and was in general higher than that of raw manure.	NUE of 70, 63 and 54% for maize monoculture, maize-wheat-It. Ryegrass and periennal ryegrass, respectively

Author	Experimental conditions	Crop	Experiment duration	Fertilizer types	N amount	Digestate distribution technique	Main results	Nitrogen efficiency
Stinner et al., 2008	Field experiment in Germany; silty-loam soil	Six crops (two legumes and four non-legume crops)	Three growing seasons	Stockless system: common mulching compared with digestion and return to soil of i) field residues, ii) field residues + ext. substrates	184 kg N ha^{-1} on average	No information is available	Digestion of field residues and cover crops increases DM and N yields and reduces the risk of N losses.	No data on N efficiency are reported here.
Svoboda et al., 2013	Field experiment; two sites in Northern Germany	Silage maize grown in monoculture	Two growing seasons	Raw i) pig and ii) cattle slurry, digested iii) maize and iv) maize + pig slurry, v) mineral N fertilizer	0, 120, 240 and 360 kg N ha^{-1}, split into two dressings	Organic fertilizers were generally applied using a dribble bar system.	In the short-term, digestate showed similar nitrate leaching potential in comparison with animal slurry.	No data on N efficiency are reported here.
Tilvikiens et al., 2010	Field experiment; light loam soil	Pure swards of cocksfoot (*Dactylis glomerata* L.)	Two years	i) mineral N fertilizer (two levels), ii) digested pig manure and grass residues (five levels)	90, 180, 270, 360 and 450 kgN ha^{-1} for digestate. 180 and 360 kgN ha^{-1} for mineral N fertilizer	Split in three applications. In spring, after the first cut and the second cut.	Nitrogen applied in digestate to grassland was as efficient as mineral fertilizer nitrogen. Cocksfoot harvested from plots applied digestate had a higher C content suited for biogas production.	No data on N efficiency are reported

Author	Experimental conditions	Crop	Experiment duration	Fertilizer types	N amount	Digestate distribution technique	Main results	Nitrogen efficiency
Vaneeckhaute et al., 2013	Field experiment; sandy-loam soil	Maize *(Zea mays* L.)	One growing season	i) L. fractions of digestate, ii) wastewater of ammonia stripping, iii) mixture of digestates, iv) mineral fertilizers and v) animal manure	150 KgN ha^{-1}	Liquid fraction was applied Manually; the fertilization of the mixture of digestate, as well as pig manure, was conducted by use of pc controlled injection	Treated slurry caused small increase in maize yield compared with animal manure and mineral fertilizers	NUE: 69% pig slurry; 66% mixture of digestate and liquid fraction of digestate; 77% liquid fraction of digestate.
Walsh J. et al., 2012	Pot experiment; sandy clay loam–textured	i) *Lolium perenne*, ii) -mixture of *Lolium perenne* and *Trifolium repens* L.	One growing season	i) Undigested slurry, ii) liquid fraction of digestate, iii) ammonium nitrate, iv) fertilizer compound, v) unfertilized	100 Kg N ha^{-1} + 50 Kg N ha^{-1}	Surface-applied in two stages	Replacing inorganic fertilizers with liquid digestate can maintain or improve yields from grassland systems	No data on N efficiency are reported here.

Attachment 3. Short description and number of digestates reviewed in Attachment 1 and 2.

Digestate types	**Number of digestate types in the reviewed experiments**
Digested animal slurries	13
Co-digested of animal slurry and energy crops or other agricultural biomass	7
Co-digested of animal slurry and food industry wastes	2
Digested energy crops or other agricultural biomass	5
Digested food industry wastes	4
Digested urban waste	5
Co-digested urban and agricultural waste	2
Co-digested industrial and urban waste	4
Liquid and/or solid fractions of digested slurry	4
Wastewater of ammonia stripping	1