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# Efficient Carbon, Nitrogen and Phosphorus cycling in the European Agri-food System and related up- and down-stream processes to mitigate emissions

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## D1.3 Assessment of novel amendments compared with business-as-usual on elemental soil cycles

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**TABLE OF CONTENTS**

**Executive summary**
This deliverable presents the main findings on the effect of applying novel soil amendments (Task 1.1) and innovative measures to increase internal cycling (Task 1.2) across the different case studies (CS1, CS2, CS3, CS4 and CS5) within the Circular Agronomics WP1: Plant-Soil-Interactions. We include a comparison of the different amendments for one site and, when possible, the cross comparison between different sites. The potential or challenges of each fertilizers or measures are summarized in the green boxes at the beginning of each section. We present the potential of three fertilizers: (1) the nitrogen-depleted rest-product from vacuum degasification of digestate; (2) digestates of different forms; and (3) struvite. We also highlight the effect of using three measures to potentially improve nutrient cycling: (1) fertigation of microfiltered digestate, (2) separating different fractions from slurry and (3) precision feeding of livestock. For each fertilizer or measure tested, we present relevant results on crop yield, soil organic carbon stocks, soil nutrient contents and/or greenhouse gas emissions to enable a broad assessment of their effects. Concerning novel amendments, we show that nitrogen-depletion via degasification of digestates produces a fertilizer that limits N losses in the form of nitrate to the subsoil. This is particularly relevant in sandy soils that are prone to N losses. Despite the benefits on N losses, it remains challenging to maintain identical yields as "business-as-usual" fertilizers. Struvite, recovered from wastewater streams, appears as a very promising circular P and N fertilizer. We demonstrate that the slow-release properties of struvite limits nutrient losses, especially in the form of $N_2O$ emissions (a strong global warming potential greenhouse gas) compared to "business-as-usual" N fertilizer (e.g., urea), while maintaining a sufficient yield and nutrient uptake. The use of microfiltered digestates also reduces nutrient losses by limiting ammonia emissions. Further, decoupling the application of solid slurry and liquid slurry appears to be a promising strategy to maximize nutrient use efficiency. Overall, we present some promising novel amendments and improved field management strategies that can increase the circularity of agriculture systems by either limiting losses to the environment or improving the nutrient use efficiency.

## 1. The use of novel fertiliser to increase internal cycling

### 1.1. Effect of nitrogen-depleted rest-product on crop yield, soil carbon stocks and fertility

Reducing losses of nitrogen to the environment via pathways such as nitrogen leaching or nitrous oxide emissions is a major challenge in conventionally managed croplands and grasslands. These losses are particularly amplified in soils with coarse textures, i.e. dominated with sands, such as arable soils in North-East Germany (CS2) and grasslands in Gelderland in the Netherlands (CS5). In this context, and within the frame of the Circular Agronomics project, the company Pondus developed a new technology to recover the nitrogen (ammonia removal) from digestates through vacuum degasification. We tested the capacity of the obtained nitrogen-depleted rest product to maintain (or improve) crop yield, soil fertility and organic carbon stocks.

**CS2 (Brandenburg, Germany)**

Highlights:

- Maize yield was slightly lower after the application of nitrogen-depleted rest-product (versus untreated digestate), but higher than with no fertilizer.
- The application of nitrogen-depleted rest product limited nitrate leaching to the subsoil and slightly increase SOC stocks.

In this field experiment implemented in CS2, we tested the effect of four different fertilizer treatments (digestate, vacuum-degasified digestate, i.e., nitrogen-depleted rest product, calcium ammonium nitrate (CAN) and an unfertilized control), applied to maize. All fertilizers were applied at equivalent nitrogen content parity. **Table 1** and **2** show the main physico-chemical characteristics of the soil used in this experiment. At the end of the growing season, the maize yield was quantified and the soil was sampled using soil cores down to one meter depth, and measured for SOC stocks and nutrient contents. As expected, the application of fertilizers (both untreated and treated) increased the maize yield compared with the control (**Fig. 1**). The application of untreated digestate resulted in the highest maize yield, followed by the nitrogen-depleted rest product. The slightly lower yield in the latter could be explained by the fact that the nitrogen-depleted rest product contained less nitrogen compared with the other fertilizers, and thus double the volume of this fertilizer had to be applied, resulting in high liquid applications to the soil that could have affected maize growth. It has to be noted that the nitrogen-depleted rest product had a strong odor, which most likely reflect the high biological activity within the residue. It can be hypothesize that the removal of ammonia resulted in a faster decomposition of organically bound nitrogen, and therefore an increase in nitrogen availability to the plant. In the top 10 cm, SOC stocks were the highest for the untreated digestate (**Fig. 2A**). Nitrate was leached to the subsoil when using CAN, but not when using circular fertilizers. (**Fig. 2B**) Contrary to the untreated digestate, the nitrogen-depleted rest product did not increase the soil available phosphorus content but increased the soil pH (**Fig. 2D**).

**Table 1:** Main physico-chemical properties of the soil from CS2 (Brandenburg, Germany).

| Depth | pH-CaCl$_2$ | | GW | | TC | | OC | | TN | | DON | | N-NH$_4^+$ | | N-(NO$_3^-$, NO$_2^-$) | | CaCl$_2$-P | | BD | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| cm | | | % | | g kg$^{-1}$ | | g kg$^{-1}$ | | g kg$^{-1}$ | | mg kg$^{-1}$ | | mg kg$^{-1}$ | | mg kg$^{-1}$ | | mg kg$^{-1}$ | | g cm$^{-3}$ | |
| | Mean | SE | Mean | SE | Mean | SE | Mean | SE | Mean | SE | Mean | SE | Mean | SE | Mean | SE | Mean | SE | Mean | SE |
| 0-10 | 5.7 | 0.2 | 12 | 0.5 | 7.1 | 0.4 | 7.1 | 0.4 | 0.7 | 0.0 | 3.3 | 0.2 | 1.2 | 0.7 | 5.8 | 0.7 | 4.5 | 0.4 | 1.70 | 0.07 |
| 10-20 | | | 10 | 0.3 | 6.6 | 0.3 | 6.6 | 0.3 | 0.6 | 0.0 | | | | | | | | | 1.82 | 0.03 |
| 20-40 | 5.9 | 0.3 | 9 | 0.4 | 4.6 | 0.2 | 4.6 | 0.2 | 0.5 | 0.0 | 2.8 | 0.3 | 0.3 | 0.1 | 2.9 | 0.4 | 4.8 | 0.3 | 1.77 | 0.03 |
| 40-80 | - | - | 8 | 1.3 | 1.8 | 0.8 | 1.3 | 0.4 | 0.2 | 0.1 | - | - | - | - | - | - | - | - | 1.78 | 0.03 |
| 80-100 | - | - | 9 | 1.3 | 4.4 | 3.2 | 1.1 | 0.2 | 0.2 | 0.0 | - | - | - | - | - | - | - | - | 1.90 | 0.06 |

**Table 2:** Soil texture at CS2 (Brandenburg, Germany).

| Depth | Sand | Silt | Clay | Soil texture USDA*** |
|---|---|---|---|---|
| cm | % | % | % | |
| 0-10 | 69 | 19 | 11 | Sandy_loam |
| 10-20 | 73 | 17 | 10 | Sandy_loam |
| 20-40 | 75 | 16 | 10 | Sandy_loam |
| 40-80 | 65 | 24 | 11 | Sandy_loam |
| 80-100 | 55 | 24 | 21 | Sandy_clay_loam |

***Measurement on one replicate

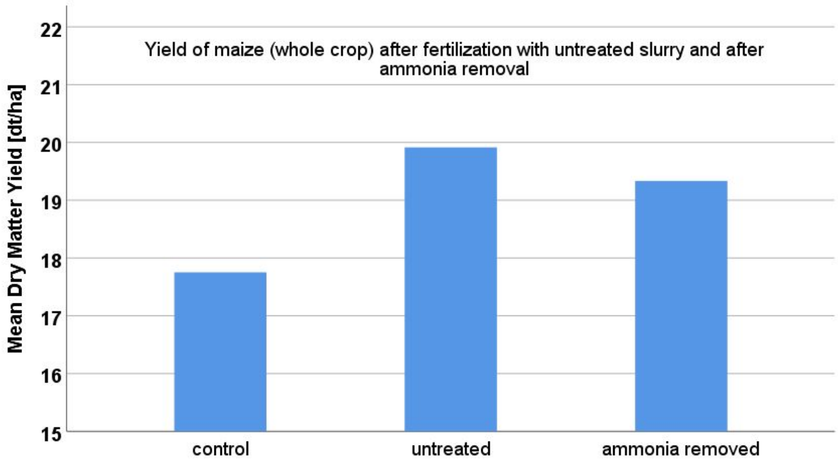



**Fig. 1**: Different effects of untreated digestate (untreated) versus nitrogen-depleted rest product (ammonia removed) on the yield of silage maize in a field experiment. An unfertilized control treatment is added for comparison. The untreated digestate is used as the “business as usual” fertilizer.

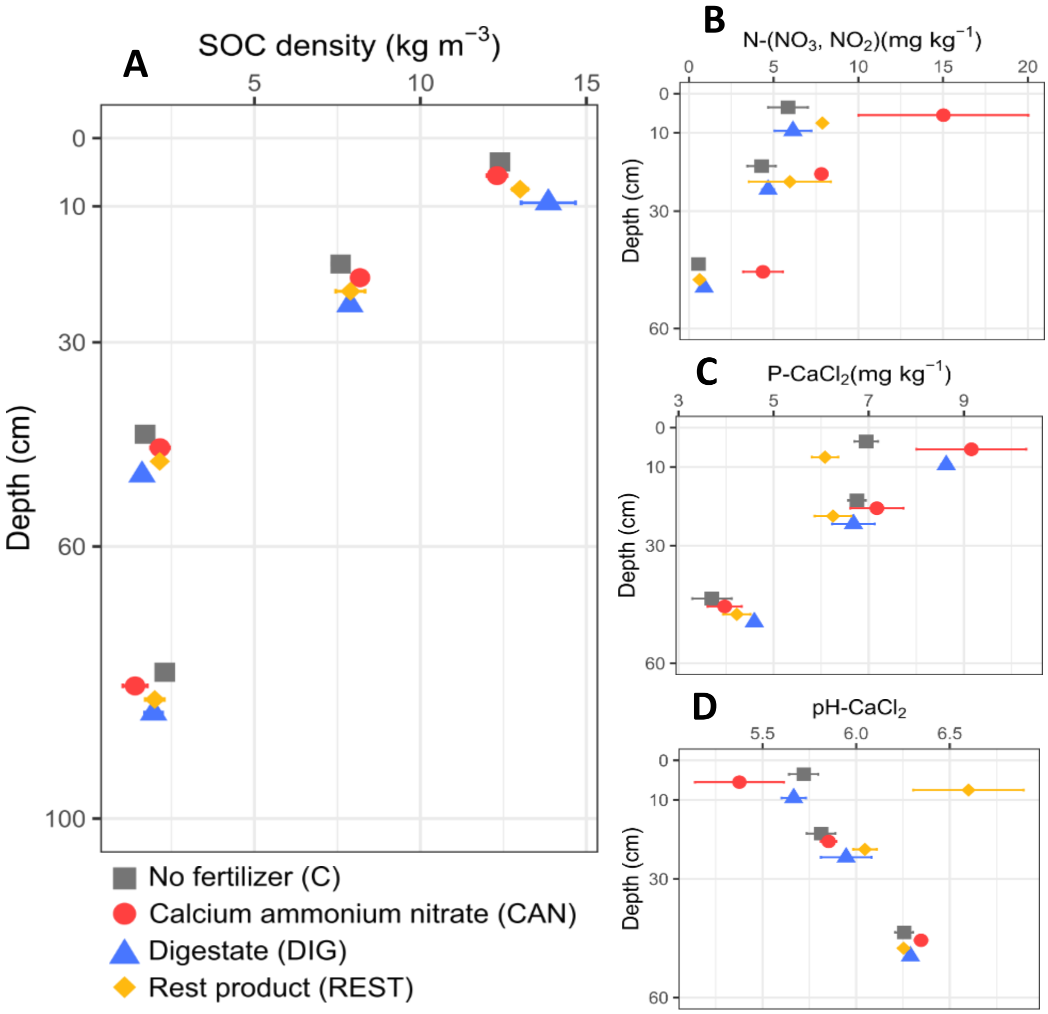



**Fig. 2:** Effects of nitrogen-depleted rest product (Rest Product) compared with untreated digestate, calcium ammonium nitrate and no fertilizer on (A) soil organic carbon density, (B) soil nitrate/nitrite content, (C) available phosphorus.

**CS5 (Gelderland, The Netherlands)**

Highlight:
- After six fertilization-harvest cycles, the use of digestate and rest-product affect the soil nutrient contents and pH, but not the SOC stocks and $N_2O$ emissions.

This field experiment implemented in CS5 lasted one year during which we completed six fertilization-harvest cycles of six weeks each and measured $N_2O$ emissions, on average twice per week. The experimental field is located at Bornsesteeg in Wageningen where the soil is sandy (85.6 %), typic endoaquoll (Soil Survey Staff, 1999) with an initial pH of 6.02 ($CaCl_2$), a P-PO4 content of 1.8 mg/kg ($CaCl_2$) and a soil organic matter content of 3.3 %. We tested the effect of four different fertilizer treatments (digestate, vacuum-degasified digestate, calcium ammonium nitrate (CAN) and an unfertilized control), applied to two different plant communities (a monoculture of Lollium perenne and a mixture of five plant species (*Lolium perenne*, *Festuca arundinacea*, *Phleum pratensem*, *Trifolium pratense*, *Trifolium repens*)). All fertilizers were applied at equivalent nitrogen content parity (382 kgN ha$^{-1}$ over one year). Soil was sampled using soil cores down to one meter depth, and measured for SOC stocks and nutrient contents. SOC stocks were barely affected by fertilizer type and plant community composition (**Fig. 3A**). Nitrate was leached to the subsoil when using CAN, but not when using circular fertilizers. (**Fig. 3B**) Circular fertilizers increased cation contents (K, Na and Mg) and pH (**Fig. 3D**), as well as available phosphorus (**Fig. 3C**). The application of circular fertilizers to a mixture of plant species (versus traditional grassland species and calcium ammonium nitrate) did not significantly increase $N_2O$ emissions (**Fig. 3E**).

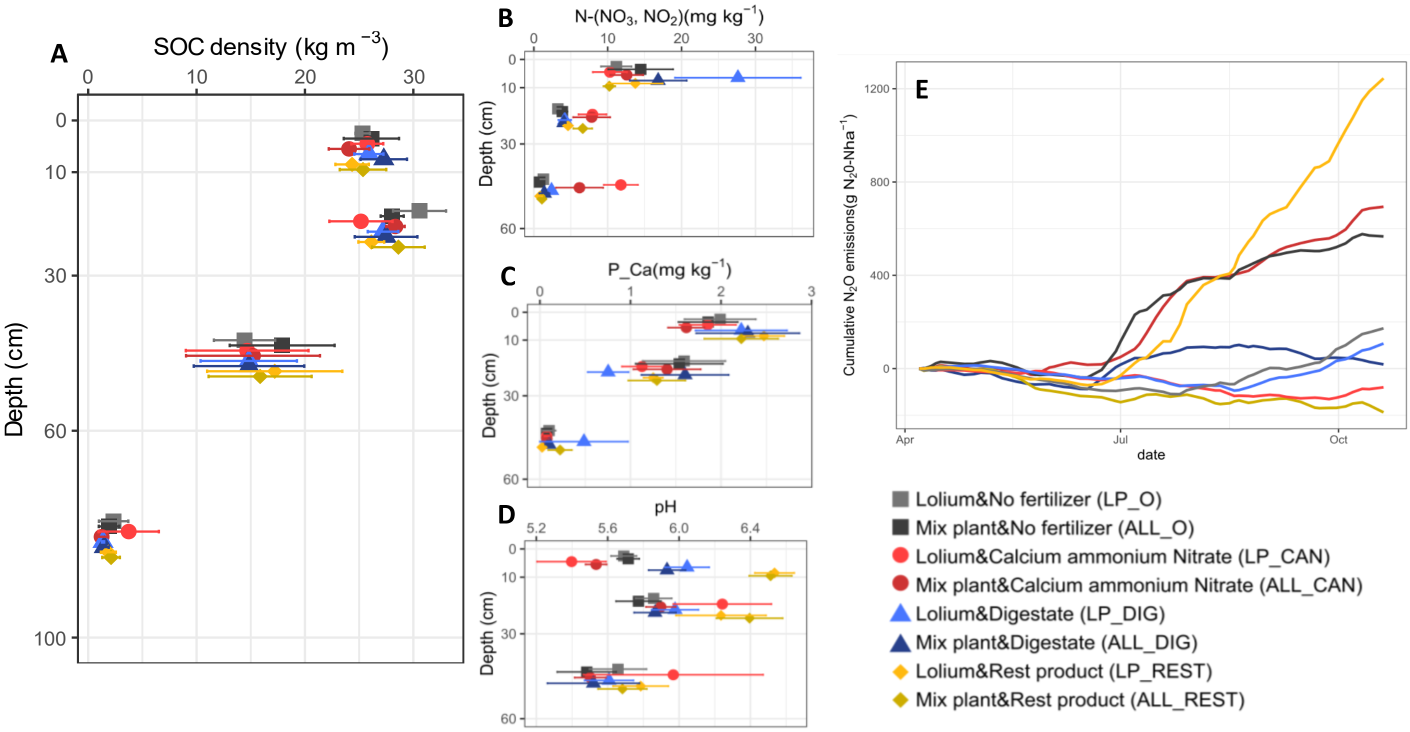



**Fig. 3:** Effects of nitrogen-depleted rest product (Rest Product) compared with untreated digestate, calcium ammonium nitrate and no fertilizer on (A) soil organic carbon density, (B) soil nitrate/nitrite content, (C) available phosphorus, (D) pH and (E) nitrous oxide emissions. The different fertilizers were applied on two types of plant communities: a monoculture of *Lollium perenne* and a mixture of five plant species (*Lolium perenne*, *Festuca arundinacea*, *Phleum pratensem*, *Trifolium pratense*, *Trifolium repens*).

**Cross-site comparison between CS2 and CS5**

The same fertilizers were applied on the plots of CS2 and CS5, on a maize crop field and grassland, respectively; allowing for a partial cross-site comparison. While the circular fertilizers had no effect on the topsoil SOC stock of the grassland, it slightly increased in the cropland that had low initial SOC stock as typically observed for this type of soil in the North-East of Germany. The application of nitrogen-depleted rest product increased the topsoil pH in both sites. The main outcome for both sites was that the application of circular fertilizers at equivalent nitrogen content parity limited nitrogen leaching to the subsoil (30-60 cm). We can conclude that the effect of applying untreated digestate and nitrogen-depleted rest product on the soil carbon stock and soil fertility is highly dependent on the initial soil characteristics and the land use. Yet, regardless to the latter factors, it appears as a promising alterative to limit nitrogen leaching in arable sandy soils.

### 1.2. The use of digestates

Digestate, i.e., the by-product from anaerobic digestion, has gained a lot of interest in the last decades. Yet, despite the continuous increase of digestion plants in Europe (especially Germany), the management and valorisation of digestate remains the bottleneck parameter to ensure a full-sustainable alternative to mineral fertilizers. We tested the effect of digestates with different origin on the crop yield and potential phytotoxicity.

### 1.2.1. Pig manure digestion product

**CS1 (Catalonia, Spain)**

Highlights:

- Anaerobic digestion by-products of pig slurry can replace mineral fertilizers ("business as usual") to obtain similar yields and grain N concentrations in extensive crops such has wheat, barley, triticale and pea.

Pig manure digestate use as fertilizer is a potentially valuable management practice in regions where pig production is highly concentrated. Low cost post-treatments such as solar drying and acidification of digestates can increase the fertilizer value and facilitate storing, transport and application of the product. A field experiment was established in CS1 Sucs (Lleida) to test these products compared to mineral N fertilizer. The field experiment was irrigated, as it is a usual practice in the area. The untreated digestate (UD) and the dried acidified digestate (DAD) had respectively: 60 and 917 g DM $kg^{-1}$ FM; 104 and 65 g total N $kg^{-1}$ DM; and 69 and 33 g $N\text{-}NH_4$ $kg^{-1}$ DM. The field was of clay loam texture, with a pH of 8.3 and 38 g $kg^{-1}$ of soil organic matter. Five different winter crops were grown for three seasons under irrigation, since these types of systems are a viable alternative to increase productivity, while reducing water consumption comparing to irrigated summer crops. The tested fertilizer products were applied at a rate of 140 kg total N $ha^{-1}$. Digestates were applied as basal-dressing and mineral fertilizer (MF) as basal- and top-dressing (except for pea, according to current legislation guidelines). The results indicated that anaerobic digestion by-products of pig slurry can replace mineral fertilizers (considered business as usual) to obtain similar yields in field crops such has wheat, barley, triticale, and pea (**Fig. 4**), with slight differences in performance depending on the crop.

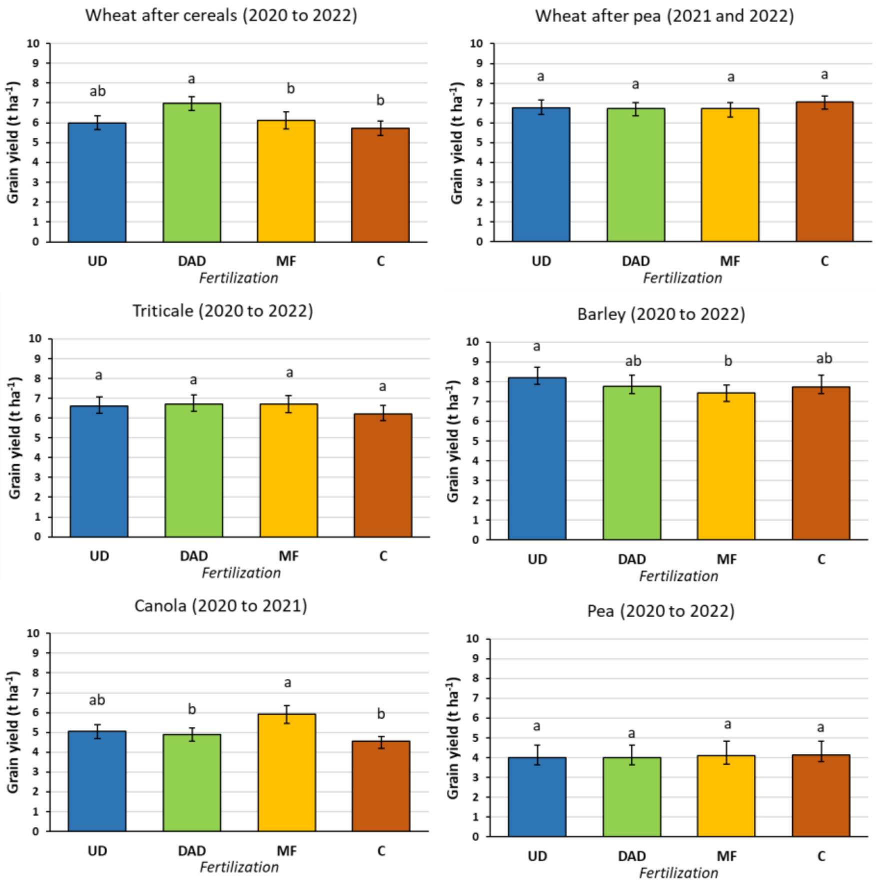



**Fig. 4:** Grain yield (t $ha^{-1}$, dry matter) of several field crops as affected by fertilization treatments. Values within parenthesis indicate harvest years. UD: Untreated digestate, DAD: Dried Acidified Digestate; MF: Mineral Fertilizer "business as usual"; C: Control without fertilization. Different letters within a graph indicate differences according to Tukey HSD test ($p<0.05$).

Wheat yields in a rotation with other cereals responded particularly well to the novel Dried Acidified Digestate, with high yields significantly different from the mineral fertilizer. Barley showed better yield results with the untreated digestate rather than the mineral fertilizer. Triticale yields showed a non-significant trend suggesting that the digestates are a feasible option to fertilize them. The N uptake efficiency (NUpE) of cereals was similar between digestates and the MF **(Table 3).** Still, the NUpE tended to be higher with the dried acidified digestate than with the untreated digestate, likely due to N loss reduction after application. Pea yield, as well as wheat after pea did not show any difference between fertilization treatments, suggesting that the nitrogen fixation levels by *Rhizobium* sp. were sufficient to homogenise yield levels during the pea crop, and this effect was extended to the next season. Differences in the NUpE of pea shows that fertilisation with digestates can be reduced, since only 50 kg N ha$^{-1}$ of mineral fertiliser was applied. On the other hand, canola responded better to the mineral fertilizer and, to a lesser extent, to the untreated digestate. Canola responded well to the split-application of the mineral fertilizer, ultimately resulting in higher NUpE. In conclusion, the dried acidified digestate is a suitable fertilization product for several field crops except for canola, which responded better to the business-as-usual fertilizer (mineral).

**Table 3:** N Uptake Efficiency (NUpE) of several field crops affected by fertilization treatments. UD: Untreated digestate, DAD: Dried Acidified Digestate; MF: Mineral Fertilizer. Different letters within a column indicate differences according to Tukey HSD test ($p<0.05$)

| Seasons<br>Crop | 2020-2022<br>Wheat (cereals) | 2021-2022<br>Wheat (pea) | 2020-2022<br>Triticale | 2020-2022<br>Barley | 2020-2021<br>Canola | 2020-2022<br>Pea |
|---|---|---|---|---|---|---|
| UD | 0.52 ± 0.04[a] | 0.50 ± 0.05[a] | 0.53 ± 0.06[a] | 0.46 ± 0.04[a] | 0.44 ± 0.05[b] | 0.48 ± 0.06[b] |
| DAD | 0.62 ± 0.07[a] | 0.74 ± 0.16[a] | 0.56 ± 0.08[a] | 0.50 ± 0.05[a] | 0.54 ± 0.04[b] | 0.47 ± 0.05[b] |
| MF | 0.58 ± 0.07[a] | 0.75 ± 0.20[a] | 0.58 ± 0.06[a] | 0.52 ± 0.05[a] | 0.77 ± 0.07[a] | 0.57 ± 0.09[a] |

### 1.2.2. Maize crop with digestate or slurry

**CS1 (Catalonia, Spain)**

Highlights:

- Using digestates from biogas plant on irrigated maize is at least as efficient as applying pig slurry, at the same N rate, but it doesn't achieve mineral fertilizer efficiency results.

In this field experiment, implemented in CS1, at La Tallada d'Empordà (Girona, Catalonia), the tested fertilizer products were applied adjusting at a rate of 170 kg ha$^{-1}$ of N in all cases. For digestate and pig slurry, the total amount was applied at pre-sowing; for the mineral fertilizer treatment, the fertilizer was applied at two moments (100 kg N ha$^{-1}$ at pre-sowing and 70 kg N ha$^{-1}$ as top-dressing).

Soil was sampled before maize sowing (**Table 4**) at the end of a black oat catch crop, for each fertilization treatment, in which the same applications have been carried out for 4 years. Top-soil (0-0.3 m) texture is loam (51.0 % sand, 12.9 % clay), pH is moderately alkaline and electrical conductivity is low and non-limiting for the crop. From the fertility point of view, organic matter content is low, total nitrogen (N Kjeldhal) content is medium-low and available phosphorus and potassium are both low.

**Table 4:** Characterization of the main chemical fertility parameters and texture of the top soil (0-0.3 m) at corn 2019 pre-sowing, for each treatment, carried out at La Tallada d'Empordà, Baix Empordà.

| Parameter | Digestate (0-0.3 m) | Pig Slurry (0-0.3 m) | Mineral (0-0.3 m) | Units |
|---|---|---|---|---|
| pH (ext. 1:2.5 H2O) | 8.30 | 8.33 | 8.30 | |
| ELEC. COND. 25ºC (1:5) | 0.14 | 0.13 | 0.14 | *mS/cm* |
| Total Organic Matter (W&B) | 1.3 | 1.2 | 1.2 | *% (p/p)* |
| TOTAL N (Kjeldahl) | 0.081 | 0.082 | 0.077 | *% (p/p)* |
| PHOSPHORUS (Olsen) | 7 | 5 | 4 | *mg/kg* |
| POTASSIUM (Ammonium acetate) | 79 | 77 | 74 | *mg/kg* |

Organic fertilizer products also were sampled and analysed for each application (**Table 5**). Nitrogen content is quite similar between digestate and pig slurry for each application moment (5.5 and 5.0 kg N/m$^3$ for digestate and pig slurry respectively at pre-sowing and 6.2 and 6.1 kg N/m$^3$ for digestate and pig slurry respectively at top-dressing).Phosphorous content in digestates are more stable (3.6 and 3.6 kg $P_2O_5$/m$^3$ at pre-sowing and top-dressing, respectively) than in pig slurry which ranges from 1.2 to 5.5 kg $P_2O_5$/m$^3$ between pre-sowing and top-dressing application moments. Pig slurry has higher potassium content (4.7 kg $K_2O$/m$^3$ on average) than digestate (1.7 kg $K_2O$/m$^3$ on average).

The applied rates have been made following the N criteria in all the cases, applying a maximum total amount of 170 kg N/ha, which is the maximum that is allowed to be applied on irrigated corn with organic fertilizers, according to Catalan regulations (DECRET 153/2019).

**Table 5:** Characterization of organic fertilizers applied at corn pre-sowing, carried out at La Tallada d'Empordà. Baix Empordà, for 2019 and 2020 corn crop cycles.

| PARAMETERS | 2019 | | 2020 | | Units *(*)* |
|---|---|---|---|---|---|
| | Digestate D | Pig slurry PS | Digestate D | Pig slurry PS | |
| DRY MATTER 105ºC | 5.7 | 3.5 | 5.7 | 9.6 | % f.m. |
| TOTAL N (N), measured on fresh sample | 9.4 | 13.6 | 10.6 | 6.1 | % d.m. |
| ORGANIC N (N) | 5.1 | 4.2 | 4.2 | 2.5 | % d.m. |
| AMMONIA N (N) | 4.2 | 9.4 | 6.4 | 3.6 | % d.m. |
| PHOSPHORUS (P) (acid ext.) | 2.7 | 1.5 | 2.6 | 2.4 | % d.m. |
| POTASSIUM (K) (acid ext.) | 3.1 | 10.9 | 1.7 | 3.8 | % d.m. |
| ORGANIC MATTER | 70.3 | 58.8 | 70.9 | 70.7 | % d.m. |
| pH (ext. 1:5 H2O) | 8.7 | 8.7 | 8.6 | 8.7 | UpH |
| ELECTRICAL CONDUCTIVITY 25ºC (ext. 1:5) | 4.2 | 6.6 | 4.8 | 4.8 | dS/m |

*(*): f.m.: units expressed on fresh matter basis; d.m.: units expressed on dry matter basis.*

Corn was furrow irrigated which is the standard management in the area. An average of 6 - 8 irrigation events were carried out (approximately every 10 days), providing a total water volume of 4000 m$^3$/crop cycle, approximately.

Results show that using digestates from biogas plant on irrigated maize is at least as efficient as applying pig slurry (business-as-usual), at the same N rate, but it doesn't achieve mineral fertilizer efficiency results (**Fig. 5**).

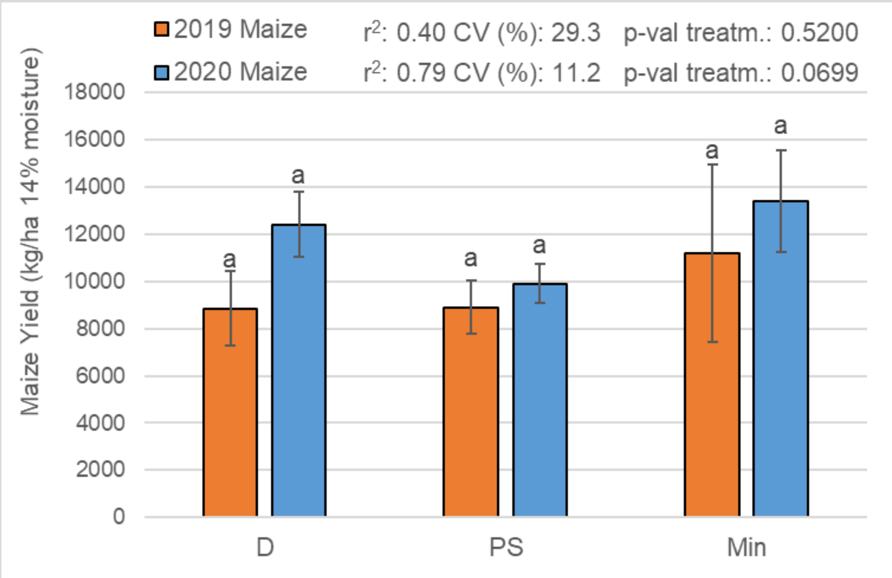



**Fig. 5:** Grain yield (t ha$^{-1}$, 14% moisture) of two years (2019 and 2020) of irrigated maize crop as affected by fertilization treatments. D: Digestate from a biogas plant fed with dairy cow slurry, PS: Pig slurry; Min: Mineral fertilization "business as usual". Different letters within a graph indicate differences according to Tukey HSD test ($p<0.05$).

### 1.2.3. Phytotoxicity assays of pig manure digestate-derived products

**CS1 (Catalonia, Spain)**

Highlights:
- Germination Index (GI) results showed a higher phytotoxic effect for the non-separated digestates, dried digestates (DD) and dried acidified digestate (DAD) than the dried solid fractions (DASF). The liquid fraction of the digestates was shown to cause the main phytotoxic effect, explained by its high conductivity and ammonium content. Thus, their direct application in horticulture it would be not recommended

In this pot experiment performed at CS1, the germination index (GI) of pig-manure derived digestates shows that the non-separated digestates had a higher phytotoxicity effect, compared to the dried solid fractions (**Fig. 6A**). In the case of non-separated digestates, the acidification aggravated the phytotoxicity effect, reducing the GI even more. However, in the case of solid fractions, the acidification did not affect the germination. Many factors, such as electrical conductivity, can influence seed germination. This was the case with the dried and acidified digestate (DAD), which had the highest value of electrical conductivity (EC) and consequently, the lower GI, with values of GI <70%, which indicates toxicity to the plants. These results indicate that separation as a first step can increase the fertilizing value of digestates, and that acidification (applied normally to reduce the GHG emissions) would not have a negative effect in germination if used in the solid fraction. The application of the mixtures showed that the stripped liquid fraction (SLF) (normally considered a waste stream) can be further valorise as part of a fertilizing product, as the GI increased with and increasing ratio of SLF to Acidified solid fraction (ASF). The dose applied did not have a significant effect on the plant biomass (**Fig 6B**) within each treatment; however, non-acidified products led to a higher biomass in general than the acidified counterparts. Furthermore, plants treated with >30% extracts of DAD died, indicating a growth inhibition due to the high EC and $NH_4^+$ concentrations found in this treatment. After observing Zn concentrations higher than law limits (Zn >800 mg kg$^{-1}$) in the chemical analyses of the DASF, the concentrations of metals in plant tissue were analyzed, to measure if they were within the average values for lettuce. The results showed no significant differences in Zn uptake in plants treated with DASF compared to plants treated with the non-acidified DSF. Other elements analyzed in the tissue of lettuce were within the normal range, and elements such as Cd, Co, Cr, Cu, Ni, and Pb were below the detection limit.

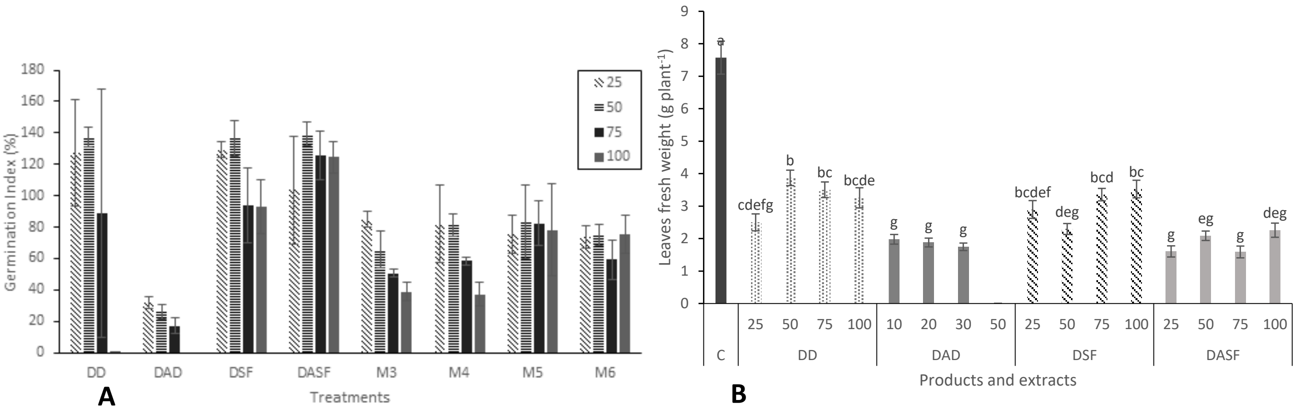



**Fig. 6**: A) Germination index and B) Leaves fresh weight obtained in lettuce seeds and lettuce seedlings respectively, after the application of 4 extracts concentrations (25, 50, 75, 100%) from different fertilizing products derived from digested pig manure. The products were: i) dried digestate (DD), ii) dried and acidified digestate (DAD), iii) dried solid fraction of digestate (DSF), iv) dried and acidified solid fraction of digestate (DASF). Furthermore, four mixtures (DM3, DM4, DM5, DM6) produced by mixing the Acidified solid fraction (ASF) and the stripped liquid fraction (SLF) collected in the biogas plant at different ratios : DM3 (ratio ASF:SLF (in wet mass): = 1:1, in wet mass); DM4 (ratio ASF:SLF = 1:2, in wet mass); DM5 (ratio ASF:SLF = 1:4 , in wet mass); DM6 (ratio ASF:SLF and = 1:8 , in wet mass) were also tested for germination.

### 1.3. Struvite, a novel compound that improves soil fertility while limiting greenhouse gas emissions

Struvite, also known as magnesium ammonium phosphate hexahydrate, forms during the treatment of waste water, and potentially could provide a significant source of phosphorus and nitrogen for plants (Hertzberger et al., 2020). Yet, struvite has a low water solubility (varying according to struvite granule size) compared to classical phosphorus fertilizers, which could limit the availability of phosphorus for plants (Degryse et al., 2017). We tested the potential of struvite as a phosphorus fertiliser in the field. As struvite also contains nitrogen, we also tested its potential to mitigate nitrogen losses and environmental impact by reducing nitrous oxide emissions.

#### 1.3.1. Effectiveness of struvite as a P fertilizer

**CS5 (Gelderland, The Netherlands)**

Highlights:
- We found that the effectiveness of struvite as a P fertilizer has been previously underestimated in greenhouse studies; in the field it is just as effective for grassland as conventional fertilizer.

During a 1.2 year field-based mesocosm experiment implemented in CS5, we applied various P fertilization treatments and monitored grass yield. The soil was a sandy soil classified as having a low-P status in the Dutch system collected from the topsoil of a field in Achterberg that received no phosphorus fertilisation for a period of 25 years. The initial organic matter was 3.8 % and the P-$PO_4$ content was 0.2 mg kg-1 ($CaCl_2$). All treatments received P, with the exception of the negative control and the - P treatment, at the rate of 97.5 kg P ha$^{-1}$, spread over five applications. Similarly, all treatments received ample N, with the exception of the negative control. The P was applied either as triple super phosphate (positive control) or as struvite. Two kinds of struvite were used: an ammonium struvite ($NH_4MgPO_4$ • 6 H2O) produced in a pilot plan of the project and a potassium struvite ($KMgPO_4$ • 6 $H_2O$) produced under laboratory conditions. Some general chemical characteristics of the struvite are presented in **Table 6**.The purity of these two kinds of struvite varied: the laboratory-processed K struvite was very pure and actually contained less K than the $NH_4$ struvite that was produced in the pilot plan. Yet, regardless of the purity, both struvite performed just as well as the control conventional fertilization (**Fig. 7**). This is in contrast with some earlier greenhouse-based studies that found that struvite was not as efficient a fertilizer as conventional ones. It suggests that the artificial growing conditions of a greenhouse, where plants grow at a much faster pace than they would in the field, does not enable the struvite to dissolve fast enough to meet plant's need. In the field however, the plant needs and the struvite dissolution are better aligned and struvite thus behaves as an “on demand” P fertilizer, minimizing the risk of P losses in soil were P is abundant, but also of P originating from fertilizer adsorbed to reactive soil particles before it can be taken up by the plant.

**Table 6**: chemical characteristics measured for struvite ($NH_4MgPO_4 \cdot 6$ H2O). EU limits are also included.

| Element | Unit | Value | EU limit |
|---|---|---|---|
| N total | $g.kg^{-1}$ | 44 | |
| P total | $g.kg^{-1}$ | 122.12 | |
| Mg | $g.kg^{-1}$ | 103.54 | |
| K | $g.kg^{-1}$ | 16.41 | |
| As | $mg.kg^{-1}$ | 0.00 | 40 |
| Cd | $mg.kg^{-1}$//[mg $kg^{-1}$ $P_2O_5$]? | 0.07 | 60 |
| Cr | $mg.kg^{-1}$ | 0.4 | 2 |
| Cu | $mg.kg^{-1}$ | 1.1 | 600 |
| Ni | $mg.kg^{-1}$ | 0.3 | 100 |
| Pb | $mg.kg^{-1}$ | 1.0 | 120 |
| Zn | $mg.kg^{-1}$ | 11 | 1500 |

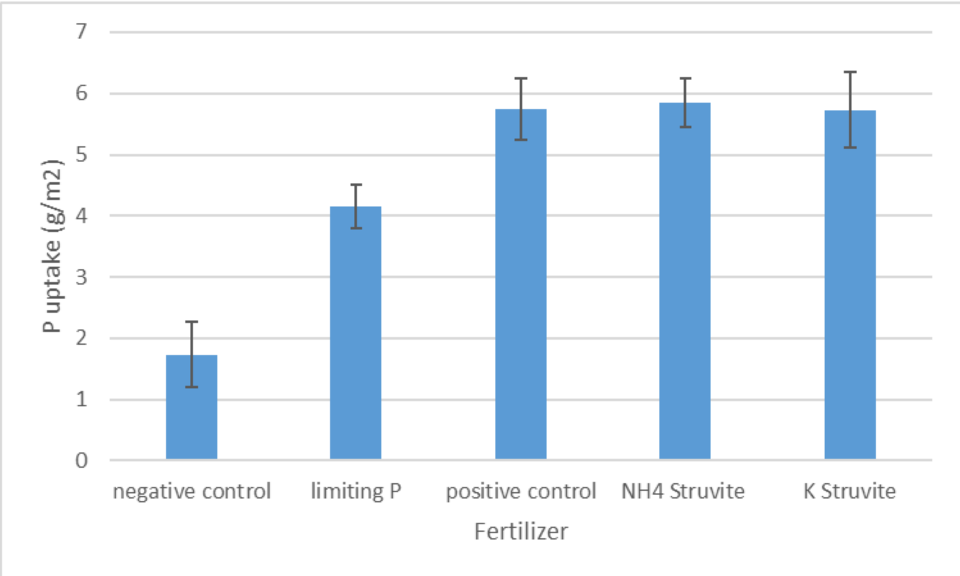



**Fig. 7:** Phosphorus uptake of grass following various fertilizer application over the course of the experiment. N=5, error bars indicate standard errors. Triple super phosphate was used as “business as usual” fertilizer for the positive control.

### 1.3.2. Struvite strongly mitigate nitrous oxide emissions

**CS5 (Gelderland, The Netherlands)**

| Highlights: |
|---|
| ▪ The use of struvite strongly mitigated nitrous oxide emissions in comparison to urea in a pot experiment. |

Struvite ($NH_4MgPO_4 \cdot 6\ H_2O$) is mostly considered as a P fertilizer but it is also a non-negligeable source of N. Little is known about the performances of struvite as a N fertilizer, but its slow-release properties make it a good candidate to mitigate many N fertilizer-related issues. During a 54-day pot experiment at the CS5, we applied struvite, both in granules and in powder, as well as urea to pots containing well-developed *Lolium perenne* covers growing in a sandy soil (83 %) typical of agricultural soils of Gelderland. The soil is classified as a plaggic podzol, with initial pH of 5.05 and an organic matter content of 1.9 %. We measured nitrous oxide ($N_2O$) emissions over the course of the experiment. While the cumulative emissions originating from urea fertilisation reached around 240 g N $ha^{-1}$ emitted in the form of $N_2O$, both struvite forms were not statistically significantly different from the unfertilised control, around 35 g N ha$^{-1}$ (**Fig. 8**). Yet, the agronomic performances of struvite were better than the control both in term of yield and N uptake. The slow release property of struvite does confer it impressive $N_2O$ mitigation capabilities while still acting as a N fertiliser. In addition to its circular nature, the strong reduction of N losses from struvite is supporting its adoption as a fertiliser for more sustainable farming systems.

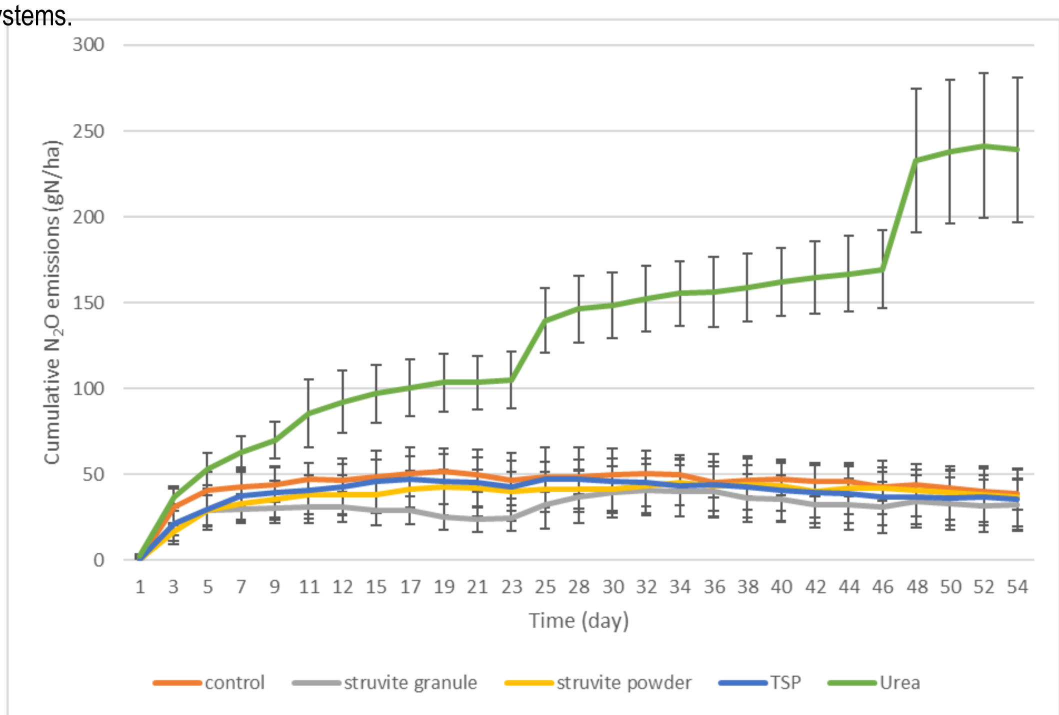



**Fig. 8:** Cumulative $N_2O$ emissions resulting from various fertilizer. N=5, error bars indicate standard errors. TSP stands for Triple superphosphate, a common mineral P fertiliser. Triple super phosphate was used as "business as usual" fertilizer for the positive control.

## 2. Management strategies to increase internal cycling

We demonstrated that the use of novel fertilizers can affect crop yield and soil properties. Yet, not only the fertiliser's type is crucial to increase the circularity of agricultural systems, but also the way fertilizers are prepared and applied. We explored different approaches to manage and apply organic fertilisers, and their consequences on crop yield and soil properties. These approaches include (1) the use of fertigation to apply organic fertilizers, (2) the separation of slurry into different fractions prior to the application and (3) the use of fertilizers produced by livestock fed with precision feeding.

### 2.1. Fertigation to reduce ammonia emission

Fertigation, i.e., injection of soil amendments into the irrigation system, represents a promising strategy to increase nutrient use efficiency and minimize nutrient losses. Yet, using organic fertilisers such as digestates in irrigation systems represents a challenge as most organic fertiliser contain a significant share of solid particles which can clog irrigation pipes. Here, the raw digestate was first separated into a solid fraction and a liquid fraction, and the latter was subjected to microfiltration to obtain the microfiltered digestate to be used on growing crops, mixed with irrigation water, through drip lines. We hypothetized that applying microfiltered digestate with fertigation would reduce ammonia emissions.

## CS4 (Emilia-Romania, Italy)

Highlights:
- Microfiltered digestate can be utilised in fertigation, including through subsurface drip irrigation systems, reducing ammonia emissions and increasing Nutrient Use Efficiency (NUE), with the possibility of completely (or almost) replacing mineral fertilisers

In the summer of 2019, we conducted an experiment in CS4 where the ammonia volatilization, as a percentage of the applied total nitrogen, was obtained using the wind tunnel method for a period of 5-6 days. The soil at this site has a clay texture, a pH of 7.5, a low P content (0.3 mg kg-1) and a low organic carbon content (< 1.5%) (**Table 7 and 8**). Tunnels were placed between the rows of the maize cultivation. Fertigation reduced ammonia emissions to ultra-low levels, less than 1% of the applied nitrogen (**Fig. 9**). **Table 9** highlight the main chemical characteristics of the microfiltered digestate used for the experiment.

**Table 7**: Soil physical properties prior to the application of treatments

| | Depth | BD | | Sand | Silt | Clay | Soil texture USDA*** |
|---|---|---|---|---|---|---|---|
| | cm | $g\ cm^{-3}$ | | % | % | % | |
| | | Mean | SE | | | | |
| **Corregio** | 0-10 | 1.51 | 0.06 | 26 | 31 | 42 | Clay |
| | 10-20 | 1.55 | 0.04 | 26 | 37 | 37 | Clay_loam |
| | 20-40 | 1.63 | 0.04 | 24 | 32 | 44 | Clay |
| | 40-80 | 1.64 | 0.02 | 23 | 31 | 46 | Clay |
| | 80-100 | 1.70 | 0.06 | 13 | 59 | 29 | Slity_clay_loam |

**Table 8**: Soil chemical properties prior to the application of treatments

| | Depth | pH-$CaCl_2$ | | GW | | TC | | OC | | TN | | DON | | N-$NH_4^+$ | | N-($NO_3^-$, $NO_2^-$) | | $CaCl_2$-P | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | cm | | | % | | $g\ kg^{-1}$ | | $g\ kg^{-1}$ | | $g\ kg^{-1}$ | | $mg\ kg^{-1}$ | | $mg\ kg^{-1}$ | | $mg\ kg^{-1}$ | | $mg\ kg^{-1}$ | |
| | | Mean | SE | Mean | SE | Mean | SE | Mean | SE | Mean | SE | Mean | SE | Mean | SE | Mean | SE | Mean | SE |
| **Corregio** | 0-10 | 7.5 | 0.1 | 17 | 0.1 | 16 | 1.2 | 11 | 0.5 | 1.3 | 0.1 | 29 | 13.1 | BDL | 0.2 | 27 | 13.8 | 0.3 | 0.1 |
| | 10-20 | | | 17 | 0.7 | 18 | 2.8 | 9 | 1.3 | 1.2 | 0.2 | | | | | | | | |
| | 20-40 | 7.5 | 0.1 | 16 | 0.3 | 19 | 2.9 | 10 | 1.4 | 1.2 | 0.2 | 15 | 3.9 | BDL | 0.2 | 12 | 3.5 | 0.5 | 0.2 |
| | 40-80 | - | - | 16 | 0.7 | 22 | 2.8 | 7 | 1.0 | 0.9 | 0.1 | - | - | - | - | - | - | - | - |
| | 80-100 | - | - | 17 | 0.2 | 25 | 1.3 | 7 | 1.8 | 0.8 | 0.2 | - | - | - | - | - | - | - | - |

*For three of the replicates, the below depth limit was above 80 cm; **No samples for three of the replicates; GW : gravimetric water content; TC : total carbon content; OC : organic carbon content; TN : total nitrogen content; Nts : Dissolved organic nitrogen content ; N-$NH_4^+$ : Ammonium content; P-$PO_4$ : Phosphorus content in form of phosphate; BDL : below the detection limit

**Table 9**: Chemical characteristics of the microfiltered digestate used for the fertigation experiment in 2019

| | pH [-] | TS [g/kg] | VS [g/kg] | TKN [mg/kg] | N-$NH_4^+$ [mg/kg] | P [mg/kg] | K [mg/kg] | TSS [g/l] | Conductivity [mS/cm] |
|---|---|---|---|---|---|---|---|---|---|
| Microfiltered digestate | 8.2 | 44.1 | 30.1 | 3667 | 2074 | 462 | 5754 | 33.4 | 21.4 |
| Irrigation water | 7.6 | 0.6 | 0.5 | 15 | 2.1 | 3 | 81 | 0.02 | 1.4 |
| Mix water + microfiltered | 8.0 | 4.8 | 3.0 | 519 | 213 | 39 | 727 | 2.5 | 3.5 |

In both years, good quantitative and qualitative crop yields were obtained. In 2019 the fertigation trials were conducted on maize yielding around 20 DM tons $ha^{-1}$, comparable to those of the "business as usual" scenario based on sprinkler irrigation and use of raw urea. In 2020, sorghum was cultivated, with the aim of verifying the possibility of obtaining a double harvest, in summer and autumn. The trial showed that it may be possible to harvest the sorghum twice over a six-month period (May-October), in this way achieving 20 DM tons $ha^{-1}$. The sorghum benefited from available water to reach full potential, with total nitrogen removals very close to those of maize (around 300 kg N $ha^{-1}$).

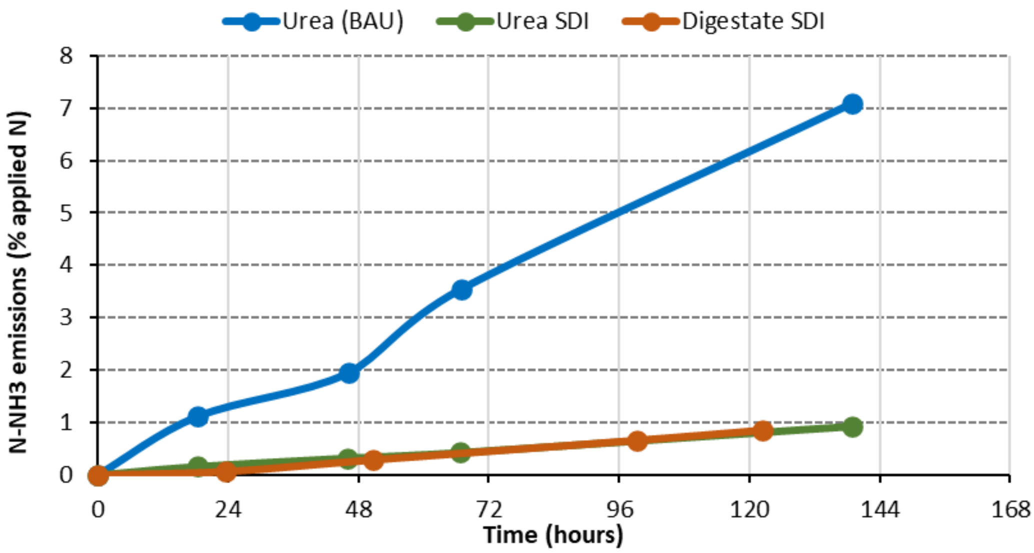



**Fig. 9:** differences in ammonia emissions, comparing the three treatments with raw urea applied on maize using a conventional method (spreading), soluble urea distributed through subsurface drip irrigation and microfiltered digestate distributed through subsurface drip irrigation (SDI). The urea treatment with conventional spreading method was used as "business as usual" fertilization strategy.

### 2.2. Separating different fractions from slurry

**CS1 (Catalonia, Spain)**

Highlights:

- The use of liquid fraction on rainfed winter cereal crops as a source of N is, at least, as effective as the application of raw pig slurry ("business as usual"), both in the case of applying full rate at pre-sowing or splitting it in two applications (pre-sowing and side-dressing).
- Solid fraction applied at pre-sowing shows lower efficiency than liquid fraction or pig slurry at the same rate. When total N rate is split in a solid fraction application at pre-sowing and an application of liquid fraction at side dressing, the efficiency achieved is similar to the use of liquid fraction or pig slurry.

In this field experiment conducted in CS1, at Tona (Barcelona, Catalonia), the tested fertilizer products were applied at a rate of 170 kg ha$^{-1}$ of N, applying the total amount at pre-sowing or split in two applications (pre-sowing and top-dressing). Crops included rainfed winter wheat (2016, 2018, 2019 and 2020) and barley (2017).

Soil was sampled at the beginning of the trial (**Table 10**). Top-soil (0-0.3 m) texture is silt loam, pH is moderately alkaline and electrical conductivity is low and non-limiting for the crop. From the fertility point of view, organic matter content is medium, total nitrogen (N Kjeldhal) is high, available phosphorus is very high and available potassium is normal-high.

**Table 10:** Characterization of the main chemical fertility parameters and texture at the beginning of the trial, carried out at Tona, Osona.

| Parameter | 0-0.3 m | 0.3-0.6 m | 0.6-0.9 m | Units |
|---|---|---|---|---|
| pH (ext. 1:2.5 H2O) | 8.09 | 8.39 | 8.50 | |
| ELEC. COND. 25ºC (1:5) | 0.20 | 0.16 | 0.15 | *mS/cm* |
| TOTAL ORGANIC MATTER (W&B) | 2.0 | 1.2 | 0.7 | *% (p/p)* |
| TOTAL N (Kjeldahl) | 0.15 | 0.11 | 0.07 | *% (p/p)* |
| PHOSPHORUS (Olsen) | 52 | 24 | 5 | *mg/kg* |
| POTASSIUM (Ammonium acetate) | 244 | 134 | 58 | *mg/kg* |
| TEXTURAL CLASS | | Silt loam | | |

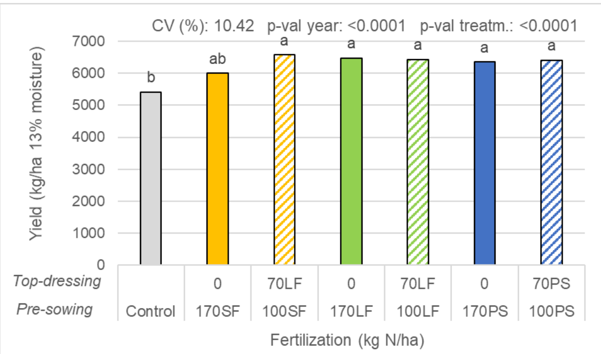
| | | | | |
|---|---|---|---|---|
| TOTAL SAND (0,05 < D < 2 mm) | 22 | 22 | 19 | % |
| COARSE SILT (0,02 < D < 0,05 mm) | 28 | 28 | 27 | % |
| FINE SILT (0,002 < D < 0,02 mm) | 32 | 33 | 37 | % |
| CLAY (D < 0,002 mm) | 18 | 17 | 16 | % |

Organic fertilizer products also were sampled and analysed in each application (**Table 11**). The solid fraction (SF) has the highest total N content (6,0 kg N/t), followed by the pig slurry (PS) with 4.7 and 3.6 kg N/m$^3$ at top-dressing and pre-sowing, respectively. Liquid fraction (LF) has low N content (3.7 and 2.8 kg N/m$^3$ at top-dressing and pre-sowing, respectively). SF has a high phosphorous content (11.2 kg $P_2O_5$/t) and LF and PS has an average of 3.3 kg $P_2O_5$/m$^3$. Potassium content is similar in all the products, between 2.0 and 2.8 kg $K_2O$/t or m$^3$. The applied rates have been made following the N criteria in all the cases, applying a maximum total amount of 170 kg N/ha, which is the maximum that is allowed to be applied on winter cereals according to Catalan regulations (DECRET 153/2019).

**Table 11:** Average characterization of organic fertilizers applied at pre-sowing and top-dressing in the trial, carried out at Tona, Osona.

| PARAMETERS | PRE-SOWING | | | TOP-DRESSING | | Units *(*)* |
|---|---|---|---|---|---|---|
| | Solid Fraction | Liquid Fraction | Pig slurry | Liquid Fraction | Pig slurry | |
| | SF | LF | PS | LF | PS | |
| DRY MATTER 105ºC | 26.0 | 2.0 | 4.5 | 3.1 | 6.9 | % f.m. |
| TOTAL N (N) measured on fresh sample | 2.3 | 15.2 | 9.1 | 12.4 | 6.8 | % d.m. |
| ORGANIC N (N) | 1.8 | 3.0 | 2.2 | 3.0 | 2.2 | % d.m. |
| AMMONIA N (N) | 0.7 | 12.0 | 6.8 | 9.5 | 4.6 | % d.m. |
| PHOSPHORUS (P) (acid ext.) | 1.9 | 3.0 | 3.2 | 4.0 | 3.1 | % d.m. |
| POTASSIUM (K) (acid ext.) | 0.9 | 9.3 | 4.9 | 6.0 | 2.8 | % d.m. |
| ORGANIC MATTER | 80.5 | 56.7 | 68.1 | 59.8 | 70.9 | % d.m. |
| pH (ext. 1:5 H2O) | 8.2 | 8.5 | 8.4 | 8.4 | 8.4 | UpH |
| ELECTRICAL CONDUCTIVITY 25ºC (ext. 1:5) | 2.2 | 5.7 | 5.7 | 6.1 | 6.0 | dS/m |

*(*): f.m.: units expressed on fresh matter basis; d.m.: units expressed on dry matter basis.*



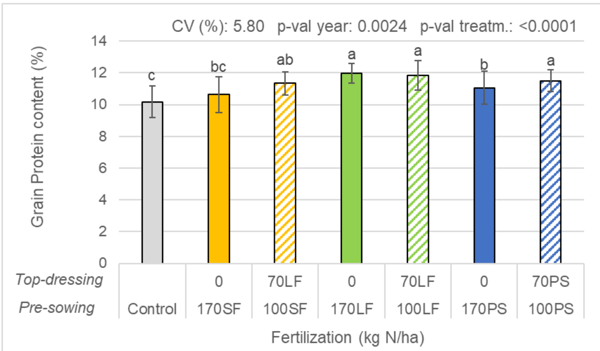




**Fig. 10:** Average (five years) grain yield (t ha$^{-1}$, 13% moisture) -left figure- and grain protein content (%) –right figure- of rainfed winter cereal crops as affected by fertilization treatments. SF: Solid fraction from pig slurry, LF: Liquid fraction from pig slurry; PS: Raw Pig slurry; Control: without fertilization. Different letters within a graph indicate differences according to Tukey HSD test ($p<0.05$). The raw pig slurry application was used as "business as usual" fertilization strategy.

Results show that the use of liquid fraction on rainfed winter cereal crops as a source of N is, at least, as effective as the application of raw pig slurry (business-as-usual), both in the case of applying full rate at pre-sowing or splitting it in two applications (pre-sowing and side-dressing) (**Fig. 10**). Solid fraction applied at pre-sowing shows lower efficiency than liquid fraction or pig slurry at the same rate. When total N rate is split in a solid fraction application at pre-sowing and an application of liquid fraction as side dressing, the efficiency achieved is similar to the use of liquid fraction or pig slurry.

## 2.3. Precision feeding

### CS1 (Catalonia, Spain)

Highlights:

- Dairy slurry from precision feeding tends to be less efficient than dairy slurry from conventional feeding.
- On ryegrass, side-dressing application of dairy slurry from conventional feeding has similar efficiency as the use of mineral fertilization. For dairy slurry from precision feeding the efficiency is slightly lower.

In this field experiment conducted in CS1, at Monells (Girona, Catalonia), the tested fertilizer products were applied at 250 and 330 kg N $ha^{-1}$ (total N content). The application times were: pre-sowing, after the 1$^{st}$ cut and after the 2$^{nd}$ cut.

Soil was sampled at the beginning of the trial (**Table 12**). Top-soil (0-0.3 m) texture is sandy clay loam, pH is moderately alkaline and electrical conductivity is low and non-limiting for the crop. From the fertility point of view, organic matter content is medium, total nitrogen (N Kjeldhal) and nitrate nitrogen content are high in both cases, available phosphorus is medium-high and available potassium is high.

**Table 12:** Characterization of the main chemical fertility parameters and texture at the beginning of the trial, carried out at Monells, Baix Empordà, during 2019-20 crop cycle.

| Parameter | 0-0.3 m | 0.3-0.6 m | 0.6-0.9 m | Units |
|---|---|---|---|---|
| pH (ext. 1:2.5 H2O) | 8.10 | 8.30 | 8.50 | |
| ELEC. COND. 25ºC (1:5) | 0.17 | 0.16 | 0.14 | *mS/cm* |
| Total Organic Matter (W&B) | 2.3 | 1.1 | 0.5 | *% (p/p)* |
| CARBONATE | 13 | 18 | 32 | *% (p/p)* |
| TOTAL N (Kjeldahl) | 0.18 | 0.11 | 0.06 | *% (p/p)* |
| NITRATE NITROGEN (N-NO3) | 23.7 | 12.7 | 9.0 | *mg/kg* |
| PHOSPHORUS (Olsen) | 23 | 10 | 5 | *mg/kg* |
| POTASSIUM | 301 | 126 | 81 | *mg/kg* |
| TEXTURAL CLASS | Sandy clay loam | | Loamy | |
| TOTAL SAND (0,05 < D < 2 mm) | 50 | 48 | 49 | % |
| COARSE SILT (0,02 < D < 0,05 mm) | 14 | 13 | 15 | % |
| FINE SILT (0,002 < D < 0,02 mm) | 12 | 14 | 15 | % |
| CLAY (D < 0,002 mm) | 24 | 25 | 22 | % |

Organic fertilizer products also were sampled and analysed in each application (**Table 13**). On average, conventional feeding slurry has higher N content (5.2 kg N/$m^3$) than precision feeding slurry (3.8 kg N/$m^3$), in both cases with high values in the pre-sowing application. Precision feeding manure has a higher proportion of Ammonium-N (43 %) than the conventional feeding manure (38 %). Phosphorous content is higher in conventional feeding slurry (2.8 kg $P_2O_5/m^3$ on average) than in precision feeding slurry (2.1 kg $P_2O_5/m^3$ on average). Potassium content is similar in both products (ranging between 3.6 and 3.8 kg $K_2O/m^3$). The applied rates have been made following the N criteria in all the cases. The maximum total rate applied with organic products is 250 kg N/ha even though, according to Catalan regulations (DECRET 153/2019), the maximum allowed for this crop is 170 kg N/ha. For mineral fertilizer, a maximum total amount of 300 kg N/ha has been applied, which is the maximum allowed to be applied with mineral fertilizer in a 2-4 cuts ryegrass according to Catalan regulations (DECRET 153/2019).

**Table 13**: Average characterization of organic fertilizers applied at pre-sowing and top-dressing in the trial, carried out at Monells, Baix Empordà, during 2019-20 crop cycle.

| PARAMETERS | PRE-SOWING | | TOP-DRESSING | | Units (*) |
|---|---|---|---|---|---|
| | Precision feeding dairy cow slurry | Conventional feeding dairy cow slurry | Precision feeding dairy cow slurry | Conventional feeding dairy cow slurry | |
| | PFS | CS | PFS | CS | |
| DRY MATTER 105ºC | 12.2 | 15.4 | 9.7 | 10.9 | % f.m. |
| TOTAL N (N) measured on fresh sample | 3.7 | 4.3 | 3.3 | 3.6 | % d.m. |
| ORGANIC N (N) | 1.9 | 2.8 | 2.1 | 2.1 | % d.m. |
| AMMONIA N (N) | 1.8 | 1.5 | 1.1 | 1.5 | % d.m. |
| PHOSPHORUS (P) (acid ext.) | 1.0 | 1.1 | 0.7 | 0.7 | % d.m. |
| POTASSIUM (K) (acid ext.) | 3.4 | 2.5 | 2.0 | 2.4 | % d.m. |
| ORGANIC MATTER | 77.6 | 80.6 | 84.1 | 83.6 | % d.m. |
| pH (ext. 1:5 H2O) | 8.8 | 8.8 | 7.5 | 7.7 | UpH |
| ELECTRICAL CONDUCTIVITY 25ºC (ext. 1:5) | 4.3 | 4.2 | 2.7 | 3.6 | dS/m |

*(*): f.m.: units expressed on fresh matter basis; d.m.: units expressed on dry matter basis.*

Results show that the second cut produced the most biomass (5,180 kg DM ha$^{-1}$) (**Fig. 11**). Yield was slightly higher using precision feeding slurry (12,304 kg DM ha$^{-1}$) than with conventional feeding slurry (12,098 kg DM ha$^{-1}$), especially on the second cut. Ryegrass protein content tended to be higher when precision feeding slurry is used as fertilizer. The most likely explanation for this is that ammonium-N is more directly available for crops than organic-N. Thus, applying precision feeding slurry (higher ammonium-N content than conventional slurry) makes N more available for a ryegrass crop, probably enhancing crude protein content. Applying slurry at pre-sowing (PS) and side-dressing (SD) increased DM yield in the second cut for both types of slurry; it also increased crude protein content. The application of N-mineral fertilizer after the second cut increased crop yield (2,767 kg DM ha$^{-1}$ when applied, in respect to 1,429 kg DM ha$^{-1}$), it also increases crop protein content (3 pp in average), specially for the conventional feeding slurry (4.3 pp). The use of slurry as fertilizer for ryegrass resulted in similar yield (12,201 kg DM ha$^{-1}$ on average) as mineral N fertilizer (12,187 kg DM ha$^{-1}$), at similar N-rate application. The use of mineral N fertilizer increased in 3.9 pp the crop protein content in respect to the use of slurry as fertilizer for ryegrass, at similar N-rate application.

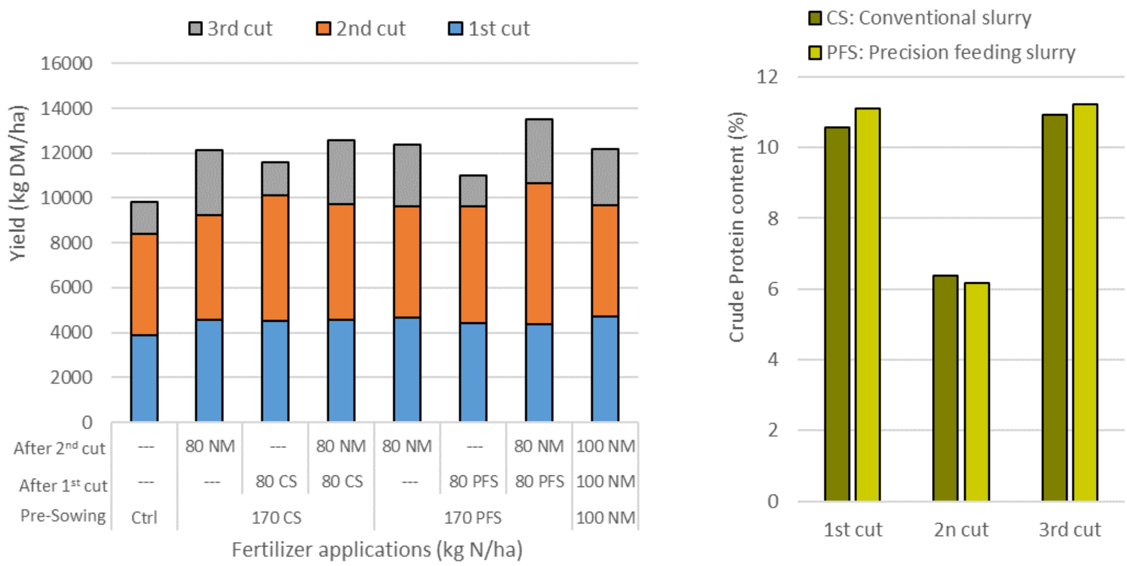



**Fig. 11:** Dry matter yield (kg DM ha$^{-1}$) –left figure- and average crude protein content (%) –right figure- of the three cuts of a rainfed ryegrass crop as affected by fertilization treatments. CS: Conventional feeding dairy cow slurry, PFS: Precision feeding dairy cow slurry; NM: Nitrogen mineral fertilizer (CAN27%); Ctrl: Control without fertilization. The application of CAN mineral fertilizer was used as the "business as usual" fertilizer and fertilization strategy.

A combined use of precision feeding slurry and mineral N fertilizer may lead to maximum achievable yields and good enough forage protein content. The application of slurry at pre-sowing and after the first cut, at agronomic rates, increased crop performance in respect to single applications at pre-sowing.

**Main outcomes and recommendations**

In this deliverable, we have shown results and discussed the potential of using novel fertilizers (e.g., nitrogen-depleted digestates, struvite) and applying more circular management practices (e.g., microfiltration). **Table 14** summaries the main outcomes from all the D1.3 experiments presented above. Concerning novel amendments, we show that nitrogen-depletion via degasification of digestates produces a fertilizer that limits N losses in the form of nitrate to the subsoil. This is particularly relevant in sandy soils that are prone to N losses. Despite the benefits on N losses, it remains challenging to maintain identical yields as "business-as-usual" fertilizers. Struvite, recovered from wastewater streams, appears as a very promising circular P and N fertilizer. We demonstrate that the slow-release properties of struvite limits nutrient losses, especially in the form of $N_2O$ emissions (a strong global warming potential greenhouse gas) compared to "business-as-usual" N fertilizer (e.g., urea), while maintaining a sufficient yield and nutrient uptake. The use of microfiltered digestates also reduces nutrient losses by limiting ammonia emissions. Further, decoupling the application of solid slurry and liquid slurry appears to be a promising strategy to maximize nutrient use efficiency. Overall, we present some promising novel amendments and improved field management strategies that can increase the circularity of agriculture systems by either limiting losses to the environment or improving the nutrient use efficiency.

**Table 14: Summary of the main outcomes**

| Topic | Fertilizer used | Case study | Main outcome |
|---|---|---|---|
| **Novel amendments** | Nitrogen-depleted rest product | CS2 (Brandenburg, Germany)<br><br>CS5 (Gelderland, The Netherlands) | Vacuum-degasification of digestate limits N losses at a small cost to yield. This is particularly verified in coarse-textured soil (e.g., sandy soils) |
| | Struvite | CS5 (Gelderland, The Netherlands) | Much more potential for struvite as P (and N) fertilizer than previously suggested. Maintain crop yield while strongly mitigating nitrous oxide emissions |
| | Anaerobic digestion by-products of pig slurry | CS1 (Catalonia, Spain) | Good potential for dried acidified digestate to replace mineral fertilizer |
| **Improved field management** | Microfiltered digestate | CS4 (Emilia-Romania, Italy) | Good potential for micro-filtered digestate to replace mineral fertilizer while reducing ammonia emissions |
| | Separating slurry fractions | CS1 (Catalonia, Spain) | Decoupling the application of solid slurry and liquid slurry appears to be a promising strategy to maximize nutrient use efficiency |
| | Slurry from precision feeding | CS1 (Catalonia, Spain) | The dairy slurry from precision feeding is not a fertilizer as efficient as the slurry from conventional feeding |

From these experiments, we have also identified some limits in using certain approaches/novel fertilizer. We would like to highlight some of these limits and share a few recommendations to better tackled these challenges in future research:

- The nitrogen-depleted digestate is obviously less nitrogen concentrated compared with the “business-as-usual” fertilizers. Thus, to apply the fertilizers at an equivalent N amount, much higher volumes of fertilizers need to be applied. This makes the application challenging and could ultimately affect plant growth. In addition, the nitrogen-depleted rest product had a strong odor, which most likely reflect the high biological activity within the residue. Thus, further research have to explore the effect of the novel fertilizer on soil microbial communities and try to limit the volume of digestate to be applied.

- Struvite is a good N fertilizer that also reduces $N_2O$ emissions, but it contains too much phosphorus to be applied at equivalent N rates compared with “business-as-usual” fertilizers. Thus, it is recommended to prioritize the use of struvite for its P fertilisation potential and blend struvite with other circular nitrogen fertilizers (e.g., nitrogen sulphate also recovered from waste streams) to provide enough nitrogen (and phosphorus) and maintain plant yield. We recommended future research to focus on this blending potential.

- Despite being a circular management strategy, using microfiltered digestates though fertigation and precision feeding of livestock require some initial investments by farmer. Future research should focus on facilitating the access for such approaches to farmers.

**References**

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