Fertilization with digestate and digestate products – potential and demonstration experiments within the project Botnia nutrient recycling

Gödsling med rötrest och rötrestprodukter – potential och demonstrationsförsök inom projektet Botnia Näring i Kretslopp

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Foreword

Modern agriculture is dependent of high levels of plant available nitrogen, N, phosphorous, P, and potassium, K, to maintain high yield levels of forage and food crops. These high levels today are maintained by import of both fodder and fertilizers to the agricultural sector in the region. Also, in the Västerbotten region, the food produced in the area is far from sufficient to feed the population. Agricultural products, game products, berries and mushrooms only covers 900 kcal per inhabitant in Västerbotten, which is less than half of the adult requirement of 1700-3200 kcal. Thus, the region imports most of it´s food from other parts of Sweden and from abroad. The nutrients from food end up in urban waste streams such as sewage sludge and source separated food waste. Some of this we use for biogas production, giving digestate as a non-profitable and under-utilized byproduct. This report focuses on the potential for replacing non-renewable fertilizers in the current agricultural production by digestate products. It reports results from field experiments demonstrating this potential in collaboration with agricultural high schools. I use Västerbotten as an example but results also are applicable in Västernorrland and Österbotten. It is part of the final report within the project Botnia Nutrient Recycling, financed by EU Interreg Botnia Atlantica, Region Västerbotten, Region Västernorrland, Österbottens förbund, Stormossen OY, Novia, Biofuel region, Vakin and Hemab. Other reports from the project could be found at the project homepage: BioFuel RegionBotnia Näring i Kretslopp - BioFuel Region

Cecilia Palmborg, Umeå, June 2022

Abstract

To increase our food security in Västerbotten we will need to become more self-sufficient of both energy, feed and nutrients that are now imported to the region. Biogas production from different waste streams is one solution to this. Biogas is produced using biowaste or sewage sludge as substrate in the major cities Umeå and Skellefteå. Biogas systems offer a range of benefits to society. Biogas production is currently prized for its climate benefits when replacing fossil fuels for the production of heat, electricity and vehicle gas, but at Bothnia Nutrient Recycling we have studied how to use the digestate, i.e. the residual product of production, as fertilizer in agriculture. We have been working to improve profitability for biogas producers and develop sustainable products from recycled nutrients, like phosphorus and nitrogen. Improving the uses for digestate increases self-sufficiency in agriculture and contributes to a circular economy.

We conducted three agricultural demonstration experiments in collaboration with agricultural high schools in Finland and Sweden to introduce digestate and digestate products to the future farmers in the regions. We found that it may be possible to replace cattle slurry with compost when growing maize despite the low levels of nitrogen, N, available to plants in the compost. In barley, NPK fertilizers gave the highest yield. Digestate from HEMAB and sludge biochar supplemented with recycled ammonium sulphate gave a smaller yield but higher than unfertilized crop. Digestate from a dry digestion biogas plant in Härnösand was better suited to barley than to grass because in an experiment on grass ley the viscous fertilizer did not penetrate the grass and did not increase the growth of the grass. Fertilizer effects on crop quality were small. There was no increased uptake of heavy metals in barley after fertilization with digestate or digestate products compared to NPK fertilization. These demonstration experiments show that more thorough scientific experimentation is needed as a foundation for recommendations to farmers.

The amounts of nitrogen and phosphorous in digestate from Västerbotten that could become used as fertilizer were modelled. It showed that if sewage sludge digestate is used to make sludge biochar and ammonium sulphate and the other available digestates are used directly in agriculture, the entire phosphorous demand but only a small part of the nitrogen demand in the county, could be covered. Thus, to achieve a true circular food production, development and increase of both the waste handling sector and agriculture is needed.

Keywords: digestate, sludge biochar, ammonium sulphate, compost

Sammanfattning

För att öka livsmedelssäkerheten i Västerbotten behöver vi bli mer självförsörjande på både energi, foder och växtnäring som nu importeras till länet. Biogasproduktion från olika typer av avfall kan vara en del av lösningen på detta. Biogas produceras i dag främs i städerna Umeå och Skellefteå med avloppsslam och sorterat avfall från t.ex. hushåll som substrat. Biogassystemet producerar många samhällsnyttor. Idag värderas biogasproduktion huvudsakligen utifrån klimatnyttan av biogasen när den ersätter fossila bränslen för värme, el och fordonsgas men inom Botnia Näring i Kretslopp har vi undersökt hur rötresten, dvs. restprodukten av produktionen, kan återanvändas. Allt för att förbättra ekonomin för biogas-producenter och utveckla en bra hållbar produkt i form av återvunna näringsämnen, t ex fosfor och kväve. En mer användbar rötrest bidrar till en ökad självförsörjning inom jordbruket och den cirkulära ekonomin.

Vi genomförde odlingstester i samarbete med naturbruksskolor i Finland och Sverige för att introducera rötrester och rötrestprodukter till blivande lantbrukare. Vi fann att det kan gå att ersätta nötflytgödsel med jordförbättringskompost vid odling av majs trots låga halter av växttillgängligt kväve. Vid odling av korn gav NPK högst skörd. biogödsel från HEMAB och biokol kompletterat med återvunnen ammoniumsulfat gav mindre skörd och ogödslat gav minst skörd. Biogödsel från HEMAB lämpar sig bättre till korn än till gräs eftersom den tjockflytande gödseln inte trängde ned genom gräset i en demonstrationsodling. Gödslingseffekterna på grödornas kvalitet var små. Gödsling med rötrestprodukter gav inga förhöjda halter av tungmetaller i grödorna jämfört med mineralgödsel. Mer omfattande försök med olika mängder och kombinationer av rötrest och rötrestprodukter behöver göras under längre tid för att kunna dra mer långtgående slutsatser.

Tillgängliga mängder av kväve och fosfor i de nuvarande biogasanläggningarna i Umeå och Skellefteå modellerades. Beräkningarna visade att om avloppsslam används till att tillverka slambiokol och ammoniumsulfat och övriga biogasrester används direkt som gödselmedel i jordbruket kan hela fosforbehovet men bara en liten del av kvävebehovet i länets jordbruk täckas. För att uppnå en cirkulär näringsförsörjning av jordbruket i länet behövs således utveckling och tillväxt i både avfallssektorn och jordbrukssektorn.

Nyckelord: rötrest, slambiokol, ammoniumsulfat, kompost

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1. Introduction

Agriculture in Västerbotten focus on animal production, mainly dairy and beef cows. The main crop is ley, managed grass/clover perennial forage crop. Farms use the cattle manure as the main source of potassium and phosphorous. Nitrogen in cattle manure, however, is only partly plant available as ammonium and this is easily lost as ammonia emissions from stables, storage and after field application. The farms mainly use nitrogen fertilizers for the leys while mineral phosphorous fertilizers are mainly used in production of annual crops. In the Västerbotten county farms used 110 metric tons of phosphorous and 2280 tons of nitrogen in mineral fertilizers in 2018/2019 (SCB 2022). Thus, the need for nitrogen fertilizers is much higher than the need for phosphorous fertilizers. Regional plant nutrient balances for the entire Sweden show that Northern Norrland, where Västerbotten is situated, had a lower nitrogen surplus (27 kg N/ha) than the more intensive agricultural regions in the south (up to 50 kg N/ha) and a phosphorous balance close to zero (1 kg P /ha) (Statistikmyndigheten 2019). The balance also shows that the agricultural use of sewage sludge is zero in Northern Norrland and covers 1 % of the nitrogen supply and 6 % of the phosphorous supply as an average for Sweden. The report does not mention other digestates.

We compiled the regional sources of digestate in Västerbotten in a state of the art-report from the first year of the Botnia nutrient project (Saarela, Palmborg et al. 2020). In the three regions, Västerbotten and Västernorrland in Sweden and Österbotten in Finland 767 tons of nitrogen and 462 tons phosphorus could be recycled from eleven larger biogas plants. For Västerbotten, these data show that the amount of P in digestates is enough to cover the agricultural demand in Västerbotten (Table 1). In contrast, the amount of nitrogen in the digestates only covers a tenth of the demand. However, the biogas plants in Västerbotten only reported the nutrients in dewatered digestate and not in the reject water produced in the dewatering process. Much of the nitrogen in the wastes is water-soluble and ends up in reject water that goes back to the wastewater plants. Currently there is no obligation for removal of nitrogen from wastewater in Northern Sweden so this valuable resource runs out into the sea.

Table 1: Available digestate resources in the region of Västerbotten per year. WW: wet weight, DW: Dry weight N: nitrogen, P phosphorous.

Biogas plant and substrate	Amount WW (tons)	DW %	Amount DW (tons)	Amount N (tons)	Amount P (tons)
Tuvan, Skellefteå Digestate from sewage sludge	6 037	21	1 268	46	30
Tuvan, Skellefteå Digestate from biowaste	1 541	25	385	20	5
Vakin, Umeå Digestate from sewage sludge	10445	28.3	2 955	148	108
Norrmejerier, Umeå Digestate from dairy wastes	13000	3.5	455	55	20
Sum for Västerbotten				282	170

We compiled some information about fertilizer products that can be made from digestate in the State of the art report (Saarela, Palmborg et al. 2020). We studied the market protential of five of these more in depth during the project (Olovsson and Saarela 2022); digestate, compost, biochar, ammonium sulphate and struvite. Four of these were used in the demonstration experiments; digestate, compost, sludge biochar and ammonium sulphate. The knowledge about these products is developing continuously and below I complement the information in the State of the art report about these four fertilizers.

Digestate varies very much in chemical composition depending on substrate, biogas digestion method and if the solid and liquid phase is separated or not. Nitrogen accumulates as ammonium during the digestion and this makes the raw digestate and the liquid phase a good nitrogen fertilizer. The solid phase can be a good nitrogen fertilizer too but it is mainly considered a soil conditioner or a phosphorous fertilizer. Phosphorous use efficiency for many different digestates was higher than for a range of composts and biochars in a pot experiment with rye grass (Vanden Nest, Amery et al. 2021). Apart from enhancing plant growth, digestate can also increase soil organic carbon content. This is most evident when using solid digestate such as sewage sludge. A two-year study from Lithuania found increased top soil carbon after grassland fertilization of both solid and unseparated digestate, but only a transient effect on soil carbon after fertilization of soil tilled every year (Slepetiene, Kochiieru et al. 2022). There are few long-term studies of other digestates than sewage sludge. A positive long-term effect on yields was found in a five year study with coxfoot in Lithuania (Tilvikiene, Slepetiene et al.

2018). In that study digestate from swine manure and energy crops gave higher yields than the same amount of N as ammonium nitrate in the last two years.

Compost has a bad reputation as a fertilizer. The plant available nitrogen is usually low since the high temperatures and high pH in compost piles make ammonia evaporate. This can be partly prevented by adding carbon rich plant material or by adding biochar (Zhao, Schmidt et al. 2020). Regular compost additions has a strong positive effect on soil carbon content (Diacono and Montemurro 2010) and also mitigates phosphorus leaching (Nest, Vandecasteele et al. 2016) compared to manure additions.

Biochar is one of few carbon capture and storage methods that is both affordable and proven to work. A review claimed that addition of sludge biochar also resulted in increased soil porosity and increased pH in soil. Sludge biochar also enhances plant growth (Yue, Cui et al. 2017, Patel, Kundu et al. 2020) and decreases plant uptake of heavy metals especially when low pyrolysis temperatures (200-500^{o} C) are used (Tian, Cui et al. 2019). Biochar made at 420^{o} C blocked uptake of most investigated pharmaceuticals in lettuce and also enhanced growth (Mercl, Kosnar et al. 2021). However, in order to efficiently destroy organic contaminants and lower the content of cadmium and mercury, higher pyrolysis temperatures are needed. There are few long-term experiments using sludge biochar and even fewer that study biochar from iron-rich sludge, which is most common in Scandinavia. Most studies also have used large amounts of sludge biochar that contain up to ten times the amount of P that is allowed to use over a five year period in Sweden, 110 kg P/ha (Chagas, de Figueiredo et al. 2021). Heavy metal applications can also be too high using such high application rates. From an environmental point or view, however, both phosphorus and heavy metals have low solubility in iron rich biochar. Thus, from an environmental perspective sludge biochar could be used in higher amounts than other organic ferilizers without risks of leaching of P or heavy metals or plant uptake of heavy metals. However, plant phosphorous availability in biochar can be improved by several different methods. For example; addition of potassium before pyrolysis (Buss, Bogush et al. 2020), oxidation and milling after pyrolysis (Muller-Stover, Thompson et al. 2021) or manipulation of pH (Haarstad and Bavor 2017).

Ammonium sulphate is a mineral fertilizer that can be recovered from ammonia rich waste streams. It is not different from ammonium sulphate made using fossil fuels. It could complement other digestate products that are low in nitrogen such as compost and biochar. The production of ammonium sulphate can be combined with sludge biochar production (Saud, Havukainen et al. 2021).

The main aim of this study was to show the potential of digestates and digestate products to the teachers and students at the agricultural high school. This report is a documentation of the lessons learned.

2. Materials and methods

We conducted three demonstration experiments in collaboration with three different agricultural high schools.

2.1 Demonstration experiment 1: Household waste based digestate to grass for horse fodder in Nordvik, Västernorrland, Sweden.

The teacher Ulf Helander and students from the agricultural high school Nordvik conducted the field experiment that was planned and evaluated by Cecilia Palmborg. A field, dominated by timothy, on sloping ground was divided into five strips running from the top to the bottom of the slope. The middle strip was left unfertilized, the strips adjacent to that was fertilized with 12 ton/ha of digestate from biowaste with 111 kg total N and 65 kg ammonium N/ha (Table 2) and the remaining field was fertilized with 60 N kg/ha of Yara 27-4 N-S (ammonium nitrate) in the middle of May 2020. The digestate had a dry matter content of 10 % and a pH of 8.6. It was broad spread with a splash plate since the school had no access to band spreading equipment. The neighbors said that the field smelled a lot after the application.

The grass field was sampled June 29 before the harvest. The length of the grass was measured and the grass was cut at three 50 x 50 cm plots in each of the fertilized strips and four plots in the unfertilized strip. We avoided sampling from the edges of the strips and the field. The samples were dried at 60^{o} C for at least 48 h and the dry weight was recorded. Three samples from the fertilized treatments and two from the unfertilized were milled to 1 mm at a Retch mill and samples were sent to Eurofins for analysis. Nitrogen was analyzed by Kjeldahl analysis and other macro and micro nutrients by acid digestion and ICP-analysis.

Table 2: Amount of fertilizers and amount of nutrients spread in the three experiments

Experiment	Fertilizer	Amount ton/ha	Ca kg/ha	Fe kg/ha	K kg/ha	Mg kg/ha	P kg/ha	N kg/ha	Inorganic N kg/ha
1 Nordvik	Digestate household waste*	12	57		40	2.7	9	111	65
	Axan (NS 27-4)							60	60
2 Optima	Compost household waste + ammonium sulphate	8.8	92	29	23	19	28	125	72
	Compost household waste	8.8	105	32	26	22	34	85	0.6
	Cattle slurry*	40			76		12	90	52
3 Röbäcks-dalen	Sludge biochar+ ammonium sulphate	1.4	35	218	2.5	4.4	58	93	75
	Digestate household waste	20	48	13	48	2.8	8.4	132	92
	NPK				48		14	100	100

* This fertilizer was not sampled for analysis, but we had to rely on data from earlier sampling occasions.

Cecilia Palmborg measuring grass length at the Nordvik grass fertilization demonstration

We sampled the silage in September using a battery powered silage corer and pooling samples from several bales to two samples from mineral fertilized grass and three samples from digestate fertilized grass. These samples were analyzed at Eurofins for microbiological properties. Aerobic microorganisms (yeast and mold) were analyzed by colony count. Enterobacteria and E-coli were analysed by AFNOR 3M 01/06-09/97. Spore forming aerobic bacteria (Bacillus) and butyric acid forming bacteria were analyzed by an internal method.

2.2 Demonstration experiment 2: Compost with digestate from household waste with and without ammonium sulphate to fodder maize.

The teacher Peter Isakas from the agricultural high school Optima in Jakobstad, Finland conducted the field experiment together with students at the school. Cecilia Palmborg, Nina Åkerback and Johan Saarela planned and sampled the experiment and Cecilia Palmborg evaluated the experiment. A flat field, approx. 1 ha, drained by open ditches surrounded by forest and suburban villas was used for the experiment. Maize had been grown on the field the previous year. The experiment was prepared by harrowing the field. A heavy rainstorm in the spring had made the soil very wet and this delayed the sowing compared to previous years. The same rainstorm also made the compost very wet and difficult to sieve before the transport to the field.

The field was divided into 7 long plots 5-16 m wide. The fertilized treatments were each conducted on two plots plus one unfertilized plot as a control (Figure 1).

All plots were fertilized on June 2 (Table 2) and the plots were mouldboard plowed the same day. The liquid ammonium sulphate was added to the compost during the loading of the solid manure spreader. Two samples of compost with ammonium sulphate and one sample of pure compost were taken during the loading and frozen before transport to the commercial lab Eurofins. Due to the difficulty to sieve the wet compost not enough compost was transported to the field. This was solved by loading sheep manure at the bottom of the manure spreader which was spread at the end of the field where no sampling was made.

Peter Isakas in front of maize fertilized with compost in Jakobstad, Finland. Photo Nina Åkerback

Maize was sown two days later after harrowing. A start fertilization with 30 kg N as a NP fertilizer was given at the sowing on the entire field. Timothy was sown between the maize rows as a catch crop. The edges of the field were sown with barley.

The maize was sampled in August 24. Five maize plants were cut at a height of 15 cm with 50 cm distance from each other at four evenly spaced places in the middle of the plots in each treatment. The length of each plant and the weight of the five plants were measured in the field. The plants were chopped in a twig chopper. Two samples were combined and the chopped material from the first two maize plants in each combined sample were thrown away to ensure that the chopped material was from the right sample. A subsample was packed tightly in designated plastic bags and sent to Valio for analysis the same evening.

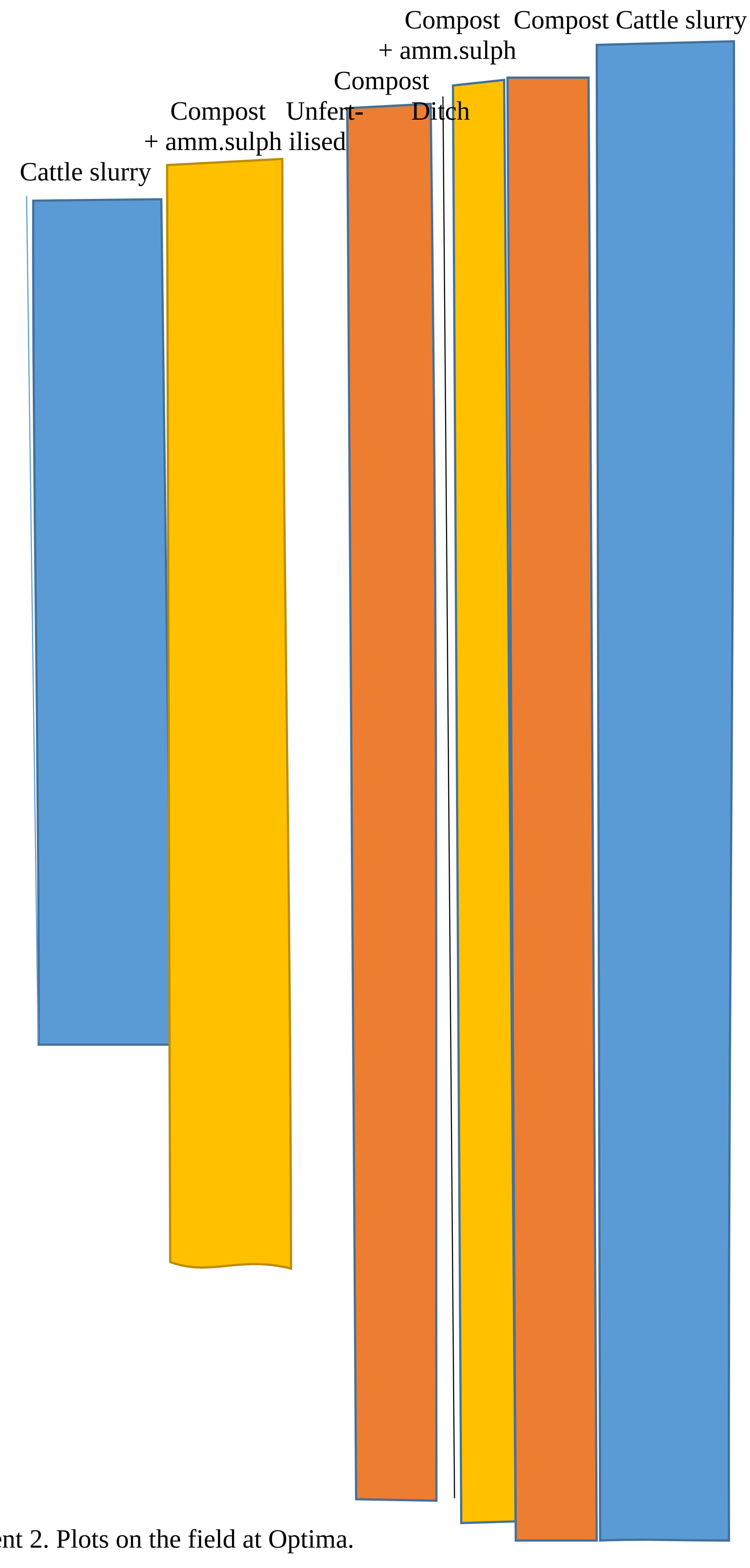

Figure 1: Experiment 2. Plots on the field at Optima.

The entire field was harvested on Sep. 1st, but no more sampling was made. The maize cobs were very small at the harvest due to the delayed sowing and cold nights in the end of August.

2.3 Demonstration experiment 3: Household waste based digestate and biochar combined with ammonium sulphate to barley.

The staff at the research station Röbäcksdalen conducted the experiment. The planning and measurements of length and No. of heads in barley was made by Cecilia Palmborg in collaboration with the agricultural high school Forslundagymnasiet in Umeå.

Harvest of experimental plots of barley in Röbäcksdalen, Umeå, Västerbotten.

The experiment was conducted on experimental plots measuring 1.5*9 m. The amounts of fertilizers and nutrients spread are shown in Table 2. Plots with the same fertilization were co-located to main plots that each had two plots of barley var. Anneli, two plots of oat and, at the border to next fertilization plot, barley var. Vilde. The oat plots, however were severely attacked by frit fly and could not be harvested. Instead the barley border plots were harvested. The digestate was spread on two main plots in one row and the other treatments were located in another row. One main plot had no fertilization, one main plot was fertilized with NPK, two main plots were fertilized with digestate from Hemab and two main plots were fertilized with biochar from sewage sludge + ammonium sulphate made from reject water.

Different students at the agricultural high school conducted an exercise of measuring the lengths of the plants of the variety Anneli at one occasion 31th of August and counting the No. of heads at two occasions 17th of August and 31th of August. The lengths were measured in the second row of each plot at five places and the No of heads were counted at 50 cm length of the second row of each plot at two places. These measurements were also repeated by Cecilia Palmborg on September 3rd and all measurements were averaged for each fertilization treatment.

Broken straws, broken heads and green heads before harvest were estimated by the field station staff. Only 1-5 % of the plants were affected and differences between treatments were small. Plots 1,5 m wide and 6.6 m long were harvested using a Haldrup machine plot combine with automatic weighing of the kernels in each plot. Two adjacent biochar plots were shortened to 6.0 m due to grazing by geese. A sample of kernels from each plot was brought to the lab for rinsing and to analyze water content. Later, these dried samples were sent to Eurofins for analysis of nutrients and heavy metals.

2.4 Modelling of nutrients possible to recover in digestate products in Västerbotten

Raw digestate made from biowaste or dairy factory waste should be possible to use more or less directly in agriculture. In an earlier study these were found to be suitable for use on grassland because of the low viscosity that allows the digestate to reach the soil if band-spread (Öling-Wärnå, Palmborg et al. 2019). However, the high water content limits the affordable transport distance.

Compost can be used as a soil conditioner and carbon source in agriculture, but only the biowaste compost meets the requirements of low heavy metal concentrations. During composting, there are always nitrogen losses of ammonium and nitrous oxide. During composting of sewage sludge, total nitrogen losses averaged 27 % in a meta analysis by (Cao, Wang et al. 2019). Thus, we calculate that 75 % of the nitrogen remains after the compost process.

Regarding sewage sludge, which contains the major amount of the P there are many public concerns about its use in agriculture, and that applies to composted sludge too. Thus, sewage sludge most likely needs further processing before application to agricultural land. Sludge biochar is a desirable product from sewage sludge since the contents of microplastics and pharmaceuticals are reduced in the pyrolysis process.

Both ammonium sulphate and struvite are preferably made from reject water. We have no data of the amount of available reject water from the biogas plants in Västerbotten. In Skellefteå the reject water is recirculated to the digester. A Finnish study made calculations on different recovery options for sewage sludge digestates (Saud, Havukainen et al. 2021). We used data from their scenario S1.2, pyrolysis with N-recovery from drying fumes and reject water, to investigate the full potential for recovery in biochar+ ammonium sulphate. They used 65000 tons of dewatered digested sewage sludge and 867000 tons of of reject water to produce 12000 ton of biochar and 3500 ton of ammonium sulphate. This amounts to 850 tons of N as ammonium sulphate. We used this proportion; 1,557 tons of recovered N in ammonium sulphate per ton of N in dewatered sludge, in the calculation of potential for ammonium sulphate recovery from reject water and drying fumes.

3. Results

None of the demonstration experiment treatments were performed on randomized replicated plots. Thus, it is impossible to tell if differences between the treatments were significant. However if differences were large we recognize them.

3.1 Demonstration experiment 1: Household waste based digestate to grass for horse fodder in Nordvik, Västernorrland, Sweden

The length of the grass was similar regardless of treatment (Figure 2). There was more biomass in the samples fertilized with ammonium nitrate than fertilized with digestate or unfertilized (Figure 3). The nitrogen and Sulphur, S, concentration in the grass was highest where it had been fertilized with ammonium nitrate and sulphur (Table 3). There was a similar trend in copper, Cu and calcium, Ca. Potassium, K, but iron, Fe, had an opposite trend with highest concentrations when fertilized by digestate. However, the variation between samples was quite large. We can conclude that the broad spreading of digestate caused poor nitrogen efficiency, probably by ammonia losses since we saw and smelled digestate at the soil surface by the grass sampling.

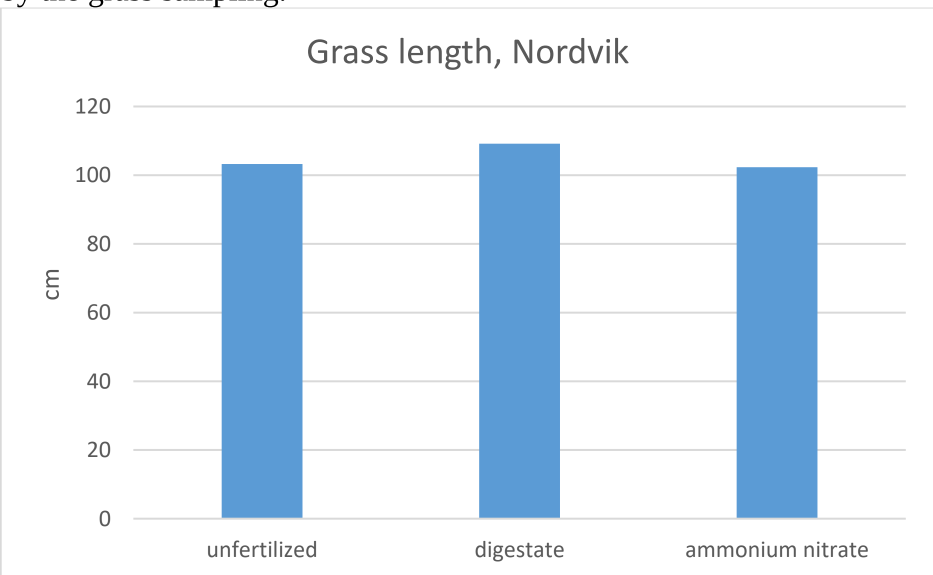

Figure 2: Grass length in the plots sampled after different fertilization treatments in Nordvik.

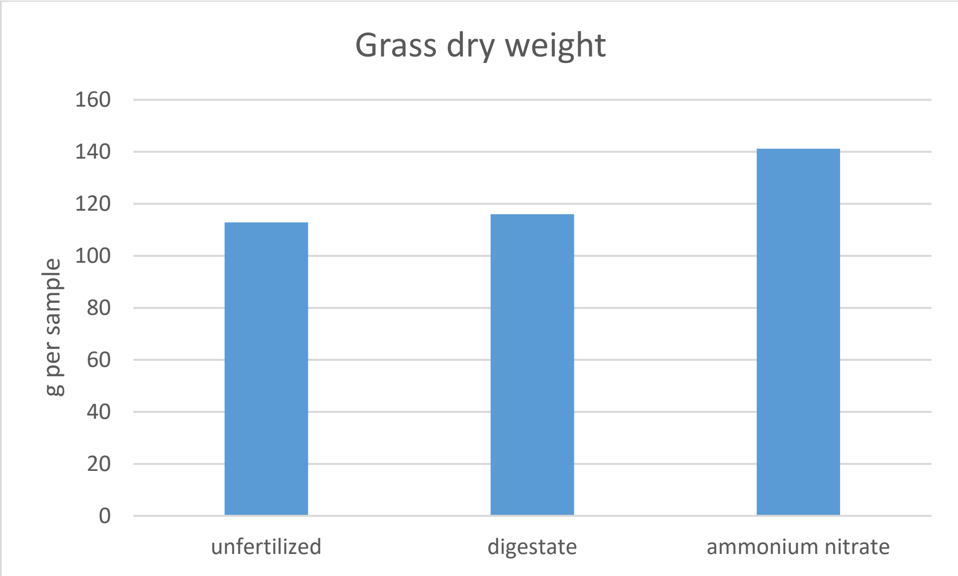

Figure 3: Grass weight after drying in the plots sampled after different fertilization treatments in Nordvik.

Table 3: Nutrient concentrations (average±standard deviation) in the grass sampled after different fertilization treatments in Nordvik, Västernorrland, Sweden.

	N	Ca	P	K	Mg	S	Cu	Fe	Mn	Zn
Treatment	%	g/kg DW					mg/kg DW			
	1.07	2.5	2.0	17.5	0.8	1.02	3.45	19	27.5	25.5
Unfertilized	±0.07	±0.4	±0.1	±0.7	±0	±0.11	±0.4	±0	±7.8	±0.7
	1.31	3.2	2.1	18.7	1.0	1.15	4.43	31.7	26.7	25.7
Digestate	±0.09	±0.7	±0.2	±1.2	±0.17	±0.18	±0.5	±8.1	±13.2	±1.2
	1.6	3.4	2.1	16.3	1.0	1.23	4.53	28.7	22	26.7
Ammonium nitrate	±0.06	±0.5	±0.1	±3.5	±0.12	±0.06	±0.4	±1.2	±8.9	±2.5

The microbiological analyses showed that there were too many spores, of both butyric acid producing bacteria and Bacillus in the digestate fertilized silage (data not shown). Both ammonium nitrate and digestate fertilized samples had too much yeast. However, after the sampling, the school had fed the silage to the horses without waiting for the answer of the analysis and the horses apparently liked it and did not become sick.

3.2 Demonstration experiment 2: Compost with digestate from household waste with and without ammonium sulphate to fodder maize.

The maize grew well in all plots were it was fertilized (Figure 4). Differences between different sampling spots in the same treatment were large. The maize plants in the unfertilized plot were both lower and lighter than the fertilized plots. Both compost treatments had almost as large and heavy plants as the cattle slurry treatment and we could see no advantage of adding ammonium sulphate to the compost.

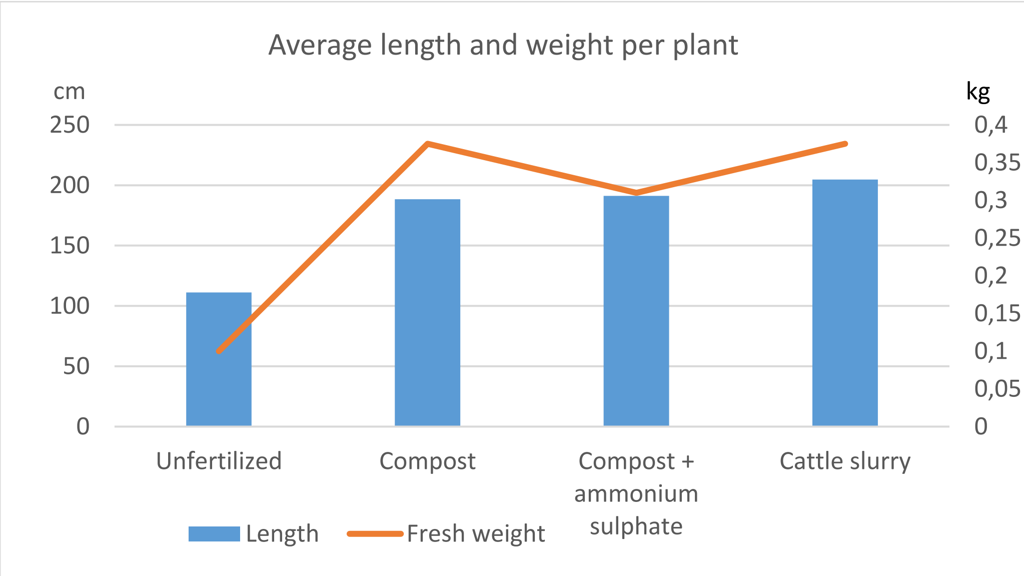

Figure 4: Length and weight of maize plants sampled August 24th after different fertilization treatments at Optima, Jakobstad.

Nitrogen concentration was lowest in the compost treatment and highest in the cattle slurry treatment. On the other hand, the unfertilized plants also had high nitrogen concentration wich indicates that the soil could provide most of the nitrogen needed at this time of the year. The growth in the unfertilized plot probably had been nitrogen limited earlier in the summer. The unfertilized maize had the highest concentrations of phosphorous and iron. This could be a dilution effect in the fertilized plants: They grew faster than the root uptake of these nutrients. The plants of all treatments had very similar contents of neutral detergent fiber (NDF) and metabilizable energy (data not shown), but the sugar concentration was higher in the fertilized plants (236-239 g/kg DW) than the unfertilized (170 g/kg DW).

Table 4: Nutrient concentrations (average±standard deviation) in maize samples from the experiment at Optima

	N	Ca	P	K	Mg	Cu	Fe	Mn	Zn
Fertilization	%	g/kg DW				mg/kg DW			
unfertilized	1.61±0.03	3.1±0.1	3.3±0.1	19±0	2.6±0.1	4.5±0.7	265±21	31±8	49±1
compost	1.44±0.14	3.1±0.3	3±0.1	15.5±0.7	2.6±0.3	5.5±0.7	125±21	27±4	40±1
Compost + ammonium sulphate	1.54±0.19	3.2±0.2	2.65±0.1	18±2.8	2.4±0.1	5±0	115±7	31±2	38±4
Cattle slurry	1.70±0.09	3.3±0.6	2.55±0.2	21±2.8	2.2±0.1	5.5±2.1	114.5±22	29±22	38±11

3.3 Demonstration experiment 3: Household waste based digestate and biochar combined with ammonium sulphate to barley.

The plants of barley variety Anneli were taller and the No of heads was larger in the NPK plots than in the unfertilized plots (Figure 5). Digestate and Biochar+ ammonium sulphate plots were intermediate in length and No. of heads. At 3 Sep it was noticed that many heads of Anneli were greener in the digestate treatment.

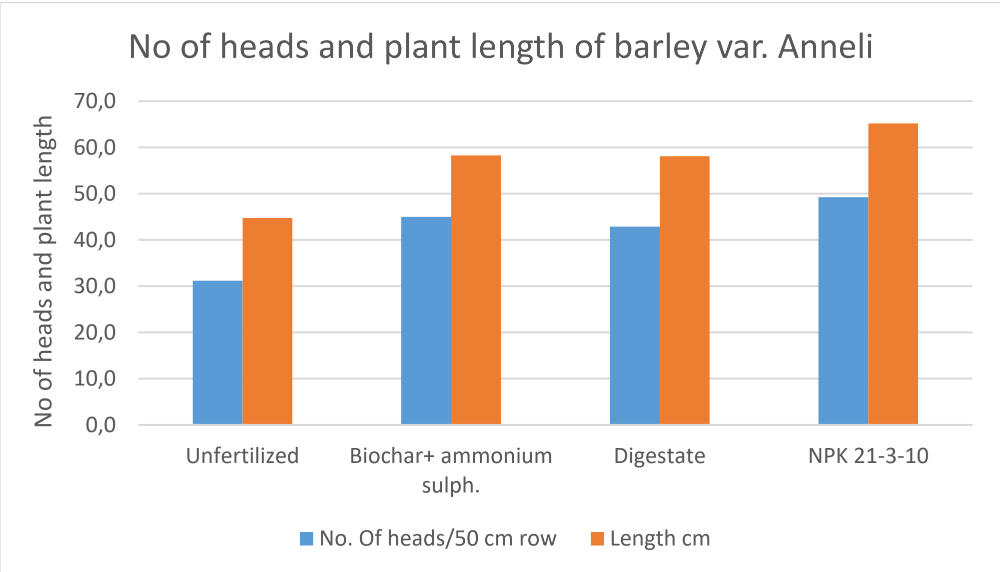

Figure 5: Plant characteristics of barley after different fertilization treatments in Röbäcksdalen, Umeå

At the harvest, the two-row barley variety Anneli had a higher water content, 29% when fertilized with digestate than any of the other treatments (21-23%). The six-row barley, Vilde, had lower water content (18 %) and very small differences between treatments. The yield was higher after fertilization with NPK than after fertilization with digestate products. The differences seemed to be larger in the earlier variety, six-row barley Vilde, than in the two-row barley Anneli (figure 6). Barley grain nitrogen concentration was, on the other hand, highest in the digestate treatment, with a more pronounced difference in Anneli (figure 7).

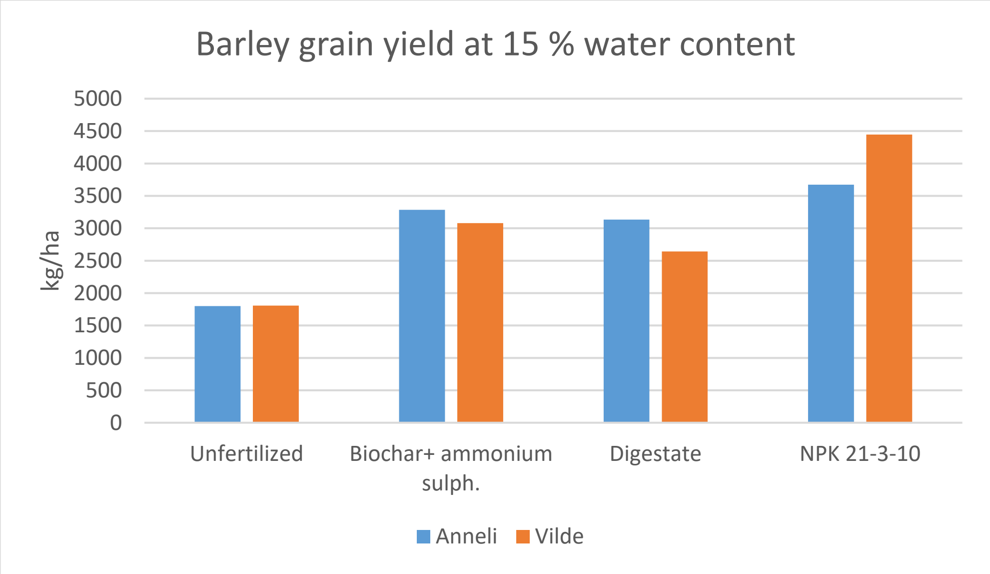

Figure 6: Barley yield of the varieties Anneli and Vilde after different fertilization treaments in Röbäcksdalen, Umeå

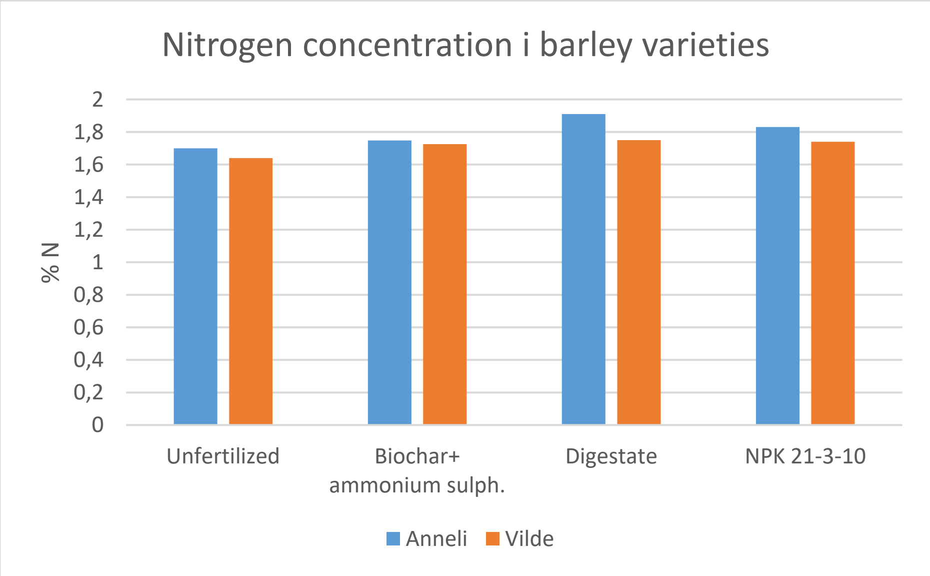

Figure 7. Nitrogen concentration in the grains of barley varieties Anneli and Vilde after different fertilization treaments in Röbäcksdalen, Umeå

The other nutrients analysed showed only small differences in concentrations, Table 5. Only potassium (K) showed the same trend as N with higher concentration after fertilization with digestate than the other fertilized treatments.

Table 5: Concentration of nutrients(average±standard deviation) in barley after different fertilization treatments.

	Ca	P	K	Mg	S	Fe	Mn
				g/kg DW			
Unfertilized	0.49±0.06	4.6±0.2	4.8±0.2	1.54±0.06	1.51±0.07	0.046±0.005	0.016±0.001
Biochar+ ammonium sulphate	0.4±0.09	4.2±0.1	4.6±0.4	1.45±0.05	1.6±0.05	0.045±0.003	0.017±0.001
Digestate	0.49±0.06	4.5±0.2	5.5±0.6	1.51±0.06	1.53±0.12	0.051±0.003	0.018±0.01
NPK	0.45±0.11	4.3±0.3	4.6±0.3	1.5±0.07	1.47±0.12	0.051±0.004	0.018±0.01

One risk with circular nutrient use is that heavy metals accumulate in the soil and are taken up by the crops. Cadmium (Cd) is of special concern since it can accumulate in our kidneys to harmful levels. Heavy metals in the barley are shown in Table 6. Copper, mercury and lead concentrations were under the detection limit for the method. Cromium (Cr) had higher concentrations in the NPK treatment than in the other treatments. The differences between the treatments for the other heavy metals were low and the digestate or biochar+ ammonium sulphate treatments never had higher concentrations than the NPK treatment. Cadmium always were below the limit recommended for grain products for humans, 0.1 mg/kg.

Table 6: Concentrations of heavy metals (average±standard deviation) in barley after different fertilization tratments.

	Cr	Ni	Cd	Zn
	mg/kg DW	mg/kg DW	mg/kg DW	g/kg DW
Unfertilized	0.38±0.03	0.32±0.09	0.021±0.005	0.38±0.006
Biochar+ ammonium sulphate	0.38±0.08	0.30±0.05	0.027±0.009	0.38±0.006
Digestate	0.36±0.06	0.33±0.04	0.033±0.011	0.38±0.006
NPK	0.63±0.14	0.39±0.07	0.034±0.015	0.38±0.006

3.4 Modelling of nutrients possible to recover in digestate products in Västerbotten

The modelling of present resources that could be used as nitrogen fertilizers shows that they are far from enough to supply Västerbotten with nitrogen fertilizers (Table 7). If the two most N-efficient product choices (digestate and ammonium sulphate) are added, they will only cover 397 tons of the 2280 tons of N in mineral fertilizers used in Västerbotten annually. The amount of available phosphorous is enough, but the largest amounts are present in sewage sludge that has a high iron content. This limits the plant available phosphorous. Long-term fertilization with sewage sludge in Skåne has shown that approximately half of the phosphorous in the sewage sludge is plant available in the long run (Gruvberger. Thorén et al. 2020). If we calculate that P in biochar is equally available to P in sludge, approximately 100 kg of mineral fertilizer P could be replaced. Long term experiments using sludge biochar are, however lacking. So the long term plant available P in biochar is very uncertain. Phosphorous demanding crops such as potatoes probably still would need to be fertilized with mineral fertilizer P.

Struvite seems not to be a feasible option. It is a very good fertilizer but the production potential is very small, since high iron content in digestate from wastewater plants in the county prevents the use of this method.

Table 7: Nutrients possible to recover in the five chosen products in the Botnia Nutrient Recycling project.

Product	Amount WW (tons)	% DW	Price SEK/ton	Amount N (tons)	Amount P (tons)
Digestate dewatered or raw Skellefteå biow. and Normejerier	14 541	3.5 -25	-50 – 10*	75	25
Compost. Skellefteå biow.	750		0 - 200	15	5
Sludge biochar. Vakin and Skellefteå sewage sludge **	1877		0-1500	56	138
Ammonium sulphate. Vakin + Skellefteå reject water and drying fumes **	3220	35	1200	322	
Struvite Skellefteå biow. and Norrmejerier	46		180	2.5	5
Max amount of fertilizer***				397	163
Sold mineral fertilizers 2018/2019				2280	110

*= long – short transport distance
**= calculated using the same efficiency as in (Saud. Havukainen et al. 2021).
***= digestate + ammonium sulphate for N and digestate + sludge biochar for P

4. Conclusions

Direct use of digestates or recovery of nutrients as compost, biochar and ammonium sulphate has great potential. It could cover most of the agricultural demand for phosphorous but only a small part of the agricultural demand for nitrogen in the region of Västerbotten. An increase of the biogas production in the area would increase the nutrient recovery potential and also make Västerbotten more self-sufficient in both energy and agricultural inputs.

The digestate products never gave as high yields as the mineral fertilizers. However, the plant size of maize after compost application was comparable to the size after cattle slurry application. The demonstration experiments show that we need a more thorough and long-term experimentation. This would give a better basis for fertilization advice to farmers.

Farmers could replace some of the nitrogen fertilizers by liquid digestates, but the application technique is crucial. Especially when digestate is applied to grass, band spreading or trailing shoe equipment needs to be used to avoid contamination of the grass and excessive losses of plant available nitrogen as ammonia emissions.

The agricultural high schools are not used to conducting research experiments. Because of this, some fertilizers were not sampled and protocols were not always followed strictly. It is obvious that close supervision of the fertilizer application is needed, something that was complicated by covid restrictions in the case of the maize experiment in Finland.

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