Biochar from separated digestate and pig manure as soil amendment

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Biochar from separated digestate and pig manure as soil amendment

Jordförbättring med biokol från separerad rötrest och svingödsel

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Abstract

The situation in and around the Baltic Sea, with large areas with hypoxia in the sea and areas in the watershed with a high concentration of animal farms, has led to a need to increase the nutrient recycling of animal manure. High levels of phosphorus (P) in the soil lead to leaching, and by reducing the P-level in organic fertilizers, this leaching can be reduced. By transporting P to areas with few animal farms, farmers' use of organic fertilizers can increase. Through the process of mechanical separation, it is possible to create a solid fraction that is rich in P and dry matter (DM). Since it has low water content, it is easy to transport it to areas with a large need of P. Screw press separation is an easy method that is cheap and that can be implemented on a large scale for separation of both manure and digestate. Screw press solids can be turned into biochar through pyrolysis because of the low water content. The use of separated material is beneficial for the carbon (C) sequestration of the soil, and biochar causes further stabilization of the material, making it even better for C storage. Several different methods can increase C in the soil with for example organic amendments or biochar.

This project aimed to evaluate biochar produced from screw press separated material from digestate and pig manure with respect to C stability and nitrogen (N) release during 50 days after the incorporation in soil. Two different pyrolysis temperatures (400 and 550°C) were used to produce biochar, and the treatments were tested with and without the application of mineral N. The properties were studied in a laboratory study, where biochar and solids were incubated with soil in 15°C. Samples were removed during the incubation in order to follow the development of N, C, pH and DM. CO_2-emission was measured using NaOH-traps to calculate C mineralization. Mineral-N was measured by the extraction of NH_4^+ and NO_3^- with KCl.

The screw press separation of digestate resulted in 25 % of the initial P in the solid fraction and 11 % of the initial N. When processing the materials, the concentration of nutrients increased, and the stability of C increased. The addition of mineral N to the treatments incorporated into the soil resulted in lower CO_2-emission. The highest emission of CO_2 came from manure solids, while biochar had very low emissions. This indicates that there was a good supply of C for microorganisms to degrade in the manure solids, and that the stability of C in biochar was high. From the added C, 37 % was lost in the form of CO_2 from manure solids while the biochar lost <2 % of the total amount of C. "Biochar 550" seemed to produce higher CO_2-emissions, but significant differences could only be found in one biochar. There were no differences in inorganic-N levels between the biochars. An addition of N caused Net N immobilization, while the biochar without N caused mineralization.

Using screw press is a good option when treating materials such as digestate and manure. There are methods that are more effective when separating P and DM but that cost more. In our study, we found that in the short term, biochar might be able to mineralize N and increase the availability to the plant, but the total amount was very low. Biochar would be a good option for organic amendments since the loss of C is much lower than for amendments from the solid material that biochar was derived from. The application rate was equivalent to 25 000 kg/ha. Other studies have seen differences in performance in the soil and on crop yield between biochars, but in this study, the biochars were very similar when looking at CO_2-emissions and N mineralization. Biochar shows potential in decreased C losses compared to their corresponding solids, and the addition of mineral N has a positive effect on CO_2-emission, is which are reduced.

Keywords: separation, screw press, incubation study, CO_2 emission, N mineralization

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Abbreviations

AD	Anaerobic digestion
Al	Aluminium
C	Carbon
Ca	Calcium
CEC	Cation exchange capacity
Cl	Chlorine
Cr	Chromium
Cu	Copper
DB	Digestate biochar
DM	Dry matter
Fe	Iron
HHT	Highest heating temperature
K	Potassium
MB	Manure biochar
Mg	Magnesium
Mn	Manganese
N	Nitrogen
Ni	Nickel
P	Phosphorus
Pb	Lead
S	Sulphur
SOM	Soil organic matter
Zn	Zink

1. Introduction

The Baltic Sea has the world's largest region of anthropogenically induced hypoxia. Deoxygenation is mainly driven by the release of nutrients into the water, but climate change and increased water temperature are also important for an increased biomass production (eutrophication) and for the accumulation of oxygen-consuming sediments. Eutrophication causes hypoxia, which impacts biodiversity and causes shifts in food web structures, disrupting marine ecosystems (Carstensen et al. 2014). The southeastern part of Sweden has a large livestock production, which has led to an accumulation of phosphorus (P) in the soils from animal manure, as well as increased risks of P leaching (Akram et al. 2019). Anaerobic digestion (AD) is an opportunity for energy production (methane) from organic waste such as animal manure, food waste and industrial waste. The residual product, with less organic matter content in more stable forms, can be returned to the fields as fertilizer, but it is problematic to transport it because of its high water content (Klackenberg 2020). There are several processes that are utilized or being studied right now to increase the possible distance to transport organic matter through mechanical separation to create a potential future fertilizer of the solid fraction that is rich in P and carbon (C) (Pantelopoulos & Aronsson 2021; Björs 2022).

In 2019, there were 280 Swedish AD plants producing 2.1 TWh biogas and 2.4 million tonnes digestate (as a residual product). Digestate usually has 3-7 % DM and can be used for land spreading directly, or be treated in some way to increase % DM (Klackenberg 2020).

Efficient nutrient use in agriculture is important since it affects not only the crop yield, but also the economy and the environment. A high application of fertilizer results in higher yield, gaining the farmer more money, and a large input of C from crop residues. On the other hand, the cost of acquiring fertilizer must be compensated by the yield increase, while the risk of losing nutrients to water or air, through leaching, is increased. A low application rate leads to lower yield and less organic matter but a lower risk of leaching (Akram et al. 2019; Mahal et al. 2019; Almaraz et al. 2021). Akram et al (2019) analysed the possibility to increase nutrient recycling from organic waste in Sweden, where there are large differences in regional nutrient balance. There are municipals with large surpluses because of a high concentration of animal farms, while other municipals have nutrient deficiency and mainly crop production. The average transport distance from Swedish municipals that has P surplus to municipals with P deficiency would be 202 km. Transportation to improve P balance does not equally increase the balance of nitrogen (N) and potassium (K), and multiple municipals would experience deficiency of these nutrients after the P balance has been established. The biggest problem when it comes to transporting organic fertilizers is the high water content and the bulkiness (Akram et al. 2019). Due to these facts, post-treatments, e.g. by mechanical separation and pyrolysis of wet organic wastes into dry and transportable fertilizer products, may enhance nutrient redistribution and improve nutrient balance in the food chain. Post-treatment is a possibility to adjust the nutrient composition of organic fertilizers, and the C can be used to improve soil functions. Some products such as biochar has the potential to sequester C (Hjorth et al. 2010; Almaraz et al. 2021).

P is an finite resource that is mainly extracted from mines. Jönsson (2019) calculated that the economic reserve of P is 266 annual consumptions, but that there is no immediate risk of shortage since there are several reserves that are economically unprofitable to mine today, but with an increased cost of P fertilizer, these will be included in the calculation of economical reserves.

A price increase of N fertilizers affects farmers more than the price of P since N application affects the harvest directly (Jönsson 2019). Nitrate, or N does not bind well to soil particles and can easily leach to water or lost to the atmosphere through denitrification outside the growing season, while soil acts as a P buffer that enables farmers to refrain from application for shorter periods. In Sweden, only 42 % of the applied P in agriculture comes from mineral P while the rest of it is mostly animal manure and some sludge and biofertilizer. This implies that the vulnerability, in case of fertilizer shortage, is not as high as for N, where 83 % is mineral N. N and K are usually in low concentrations in organic fertilizers since they are water soluble and N is additionally lost in the form of ammonia (Jönsson 2019).

In a soil with an average amount of easily accessible P, there is around 200 kg P/ha available for the plants, and the crop removes around 15-30 kg P/ha every year. This means that there is a buffer of P (Jönsson 2019). Therefore, it is not necessary to fertilize ever year. The harvest ought not to be affected for 3-10 years, depending on the size of the P reserves. The reserve of easily accessible P is refilled through the rearrangement of hard bound P when the application of mineral fertilizer is decreased (Jönsson 2019). In a long-term experiment, Withers et al. (1994) showed that P fertilization caused significant yield increase after 6 years of withholding P fertilizer on a field previously used for lays/spring cereal, and after 5 years with small yield increase on a field previously used by a dairy farmer. Kuecke et al. (2001) found that crops that did not receive P fertilizer delivered about 95 % of control yield of crops with P fertilization during six years of field trials.

The yield response to no applied P had a good relation to initial soil P (Kuecke et al. 2001).

This thesis was included in a project with the overall aim to produce solid fertilizers that are rich in P content and easily transportable from heavy and bulky animal slurry. Thereby, manure P can be transported over longer distances and contribute to improved nutrient recycling to crop production areas. To simplify implementation, the fertilizers produced from manure need to be attractive to farmers. The project, Circular NP, is situated in the Kalmar region in an area with high animal density. It is driven by BalticWaters2030 in cooperation with SLU (Swedish University of Agricultural Sciences) and RISE (Research Institute Sweden).

In this study, where animal slurry and digestate were treated through mechanical separation with screw press at *More Biogas* AD plant in Kalmar, biochar was produced from solid fractions for further investigations. The solid fractions were produced and then treated by drying and slow pyrolysis. Mineralization of N and C was evaluated through an incubation study in the lab where CO_2-emission was measured using back titration.

The aim of the study was to examine the composition, N and P fertilizer value, and C stability when biochar derived from the solid fraction of pig manure and digestate was added to soil. This was done to investigate one of the possible products that might be interesting for the market. The questions to be answered are:

- How large part of nutrients and C end up in the solid fraction?
- How is inorganic N released from different pyrolysis products, and how can they be characterized; slow- or fast-acting?
- What is the potential for C stability in the soil of the different products (solid fractions and biochars)?

2. Background

2.1 Separation methods for liquid manures

The application of organic fertilizers to arable fields is restricted in terms of how much P is allowed to be applied. On soils with a long tradition of animal production, P-levels in the soil are generally high due to high application rates. Mineral P, on the other hand, is usually only applied to the level needed for the crop to reach the desired yield, leaving the soil to maintain or decrease the P-levels (Akram et al. 2019). Mechanical separation of manure is a method used to separate DM and nutrients into solid fractions that could facilitate handling, increase transportation distances, and provide other areas with nutrients. Separation is also a requirement when producing biochar. Then, a decrease of water content before pyrolysis is needed (Gomez-Munoz et al. 2016). The liquid fraction could be returned to the farmer to supply the crops with N, which is soluble and retained in the liquid fraction (Pantelopoulos & Aronsson 2021).

There are several possible methods of manure separation that have different costs and separation efficiencies (Hjorth et al. 2010). The separation efficiency for DM, P and N can be ranked as centrifuge>sedimentation>drainage>screw press (Hjorth et al 2010). A decanter centrifuge increases the gravitational force through continuous motion and the solid and liquid fractions are transported in two different directions and collected separately. Around 71 % of P and 61 % of DM can be removed to a solid fraction by centrifuge. A screw press, also called pressurized filtration, uses a turning motion to extract the liquid while the solid is pressed against a plate at one end of the cylinder to extract additional water before depositing the solids. The separation of screw press is lower, with only 17% of total P and 37 % of DM in the solid fraction (Hjorth et al. 2010). A centrifuge, which has higher initial costs and higher energy requirements, is more expensive to use than a screw press, (Moller et al. 2000). However, to separate dry matter and P to the solid fraction, the centrifuge is most effective. The centrifuge can separate most particles >0.02 mm to the solid fraction (Moller et al. 2000) while the smallest particles successfully separated to the solid fraction by screw press were 1 mm (Guilayn et al. 2019). Other studies have used small screen openings for the screw press, which would lead to smaller particles ending up in the solid fraction (Hjorth et al. 2010; Pantelopoulos & Aronsson 2021). Most of the P is contained within the organic matter, together with other nutrients, leading to a nutrient- and DM-rich solid fraction. Since N is mostly contained within the liquid, it is harder to separate it to the solid fraction. The separation efficiency of the centrifuge increases when separating digestate compared to raw manure. A screw press uses larger screen pores and lower speed and still effectively separate DM to the solid fraction. However, it separates very little P and almost no N to the solid fraction (Moller et al. 2000). Nevertheless, there is still a lot of dry matter left in the liquid fraction (Tambone et al. 2017).

Separation can also be accomplished through the simple methods of gravity by using sedimentation or drainage. Sedimentation is a simple and cheap way of separation if time is not an issue. Manure is deposited into a commonly conical container where the solids settle at the bottom. The process can be made continuous by adding manure at the same rate as the separated fractions are removed. It can also be practiced in lagoons as large sedimentation containers. Drainage is achieved by using screens or filter belt, where the liquid is drained through the screen or filter belt by gravity. A filter belt continuously adds and removes the solid while a screen drainage uses a scraper to remove the solid fraction. These simple separation methods need additional time, but the products contain good nutrient content and dry matter (Hjorth et al. 2010).

It is possible to combine different separation methods to achieve more attractive products. For instance, drainage and screw press can be used to combine high separation efficiency and high DM concentration (Hjorth et al. 2010). Separators with low separation efficiency, such as screw presses, are more effective with substrates of large particles such as manure and lignocellulosic fibres, but can also be used as a pre-treatment for high efficiency separators like centrifuges that might take damage from larger particles (Guilayn et al. 2019).

Tambone et al. (2017) studied digestate plants where digestate was run through a screw press. This resulted in most of the dry matter (67 %) ending up in the liquid fraction together with most of the N and P (87 % and 71 % respectively). The solid fraction was still suitable for fertilizer, and the levels of heavy metal were not higher than in other organic fertilizers.

2.2 Carbon farming

Dumbrell et al. (2016) describe carbon farming as "Transferring carbon from the atmosphere into terrestrial sinks through carbon sequestration practices". Agricultural soils have the potential to bind a lot of C, which helps decreasing the net emission of greenhouse gases (GHG). Today, there are several practices in use around the world (Almaraz et al. 2021). Almaraz et al. (2021) define six different forms of carbon farming: biochar, organic amendments, silicate rock amendments, cover crops, no-till and agroforestry. Biochar is produced through the pyrolysis of different types of biomasses and increases C storage in soil as well as C stabilization. Organic amendments add C to the soil while simultaneously stimulating plant growth, which indirectly may increase soil C. When adding finely ground silicate rock particles to soil it interacts with atmospheric CO_2 and creates inorganic carbonates. Cover crops also add plant material to the soil to increase C in the soil. No-till increases the aggregation of soil and decreases CO_2-emissions that are linked to soil disturbance (Almaraz et al. 2021). Microaggregates that form over time are more resistant to decomposition, and therefore no-till might result in more C sequestration. There are some studies that do not show an increase in C sequestration. One reason for that could be the decreased crop production when implementing no-till (Ogle et al. 2012). Agroforestry intends to plant trees near crop fields to increase C through above- and belowground growth (Almaraz et al. 2021). All these methods could increase C sequestration. However, this report focuses on organic amendments and biochar, and they are explained in more detail below.

2.2.1 Organic amendments

Application of Organic amendments to soil usually increase nutrient availability and can increase soil C storage. The amendments might also affect GHG emissions from soil both negatively and positively. There are many different types of organic amendments such as crop residues, animal manure, compost and sawdust to mention a few (Almaraz et al. 2021). Smith et al. (2014) reviewed the possibilities of C sequestration by applying digestate (AD), compost and biochar. Compost resulted in more C sequestration than digestate while simultaneously providing the same amount of nutrients. Biochar also provides more C than digestate but there is a risk that the nutrients become less available. The problem with compost is that the energy lost during anaerobic composting cannot be collected in the same way as with AD and pyrolysis (Smith et al. 2014).

Compost amendment can increase the primary production in grassland with similar effects carrying over the next two years (Ryals & Silver 2013). Digestate showed good properties to use as organic amendments when tested in the lab but need further studies of the workings in the field according to Tambone et al. (2009).

Głowacka et al. (2020) tested digestate application on switchgrass (*Panicum virgatum* L.) over three years and found that the grass yield was the same or higher than mineral fertilization and that soil properties were improved in field conditions. Ryals & Silver (2013) showed that in the short term of their study (three years) the C storage increased without risking an increase of CH_4- and N_2O-emissions when adding composted organic matter to the soil. There are large emissions of GHG from manure during every step in the handling of manure from the stables to the field (Chadwick et al. 2011). In an incubation study of manure amendment, Calderón et al. (2005) found a positive correlation between N_2O and CO_2. Application of manure increased NH_4^+ in the soil during the first week. Mineral N declined during the first two weeks simultaneously as denitrification was at its highest. Denitrification declined again and after week 4 there was an increase in manure NO_3^-.

With mechanical separation of animal manure, the solid fraction has an increased emission of N_2O compared to raw slurry in storage, but AD did not increase N_2O-emissions. The emissions of CH_4 from manure are great but can be collected and used as an energy source. When applying the slurry as fertilizer the CH_4-emissions occur very fast directly after application (Chadwick et al. 2011). Fangueiro et al. (2008b) found no increased emission of CH_4, CO_2, NH_3, N_2O on landspreading of solid fraction of screw press separated cattle slurry. They found no negative effect of slurry separation on emissions but that there were possible positive effects on grass yield.

In the process of AD, Yan et al. (2018) found that, while the concentration of heavy metals increased when exposed to AD, the ecological risk was still low. Heavy metals are mainly released through the degradation of biomass by bacteria in the process of AD. Since heavy metals are not biodegradable there is a risk of accumulation in the digestate. High levels of metals can inhibit the AD process by interacting with bacterial enzymes (Lee et al. 2018).

2.2.2 Biochar

Biochar provides a possibility to increase C storage and crop yields, but there are several studies that have contradicting evidence of the positive effects of biochar (Chan et al. 2007; Abiven et al. 2014; Jeffery et al. 2017; Riddle 2018). Several factors decide how effective biochar is on yield, such as soil properties and the composition of biochar. Biochar has the possibility to increase yield, but has a larger effect on soil with low pH because of the biochar's alkaline pH (Ye et al. 2020). Soils in temperate regions have mostly high pH and produce high yields, often as a result of good fertilizer input, whereas soils in tropical areas more often are less productive and have low pH (Jeffery et al. 2017). The liming and fertilizing effect of biochar usually becomes negligible on soil with higher pH. In very acidic soils the metal toxicity is too high, and then the liming effect of biochar is not enough to increase the pH above the toxicity threshold (Jeffery et al. 2017).

In a meta-analysis, Ye et al. (2020) showed that when producing biochar, cereal residues produced the largest increase in crop yield, followed by biochar produced from animal and human waste. The highest heating temperature (HHT) is also important; the highest yield increase was caused by a HHT of ≤400°C. Temperatures between 400 and 550°C resulted in about three times lower yield and ≥550°C gave even less increase and no significant increase when compared to the fertilized control. Biochar produced at ≤400°C was mainly produced by cereal waste and ligneous materials and tested on soils with pH <6.5, while biochar produced at ≥550°C was dominated by ligneous materials and was tested on soils with pH >6.5. This makes the results uncertain and therefore, they ought to be re-evaluated in the future with a more balanced dataset (Ye et al. 2020). Temperature also influences the release of inorganic phosphate from biochar. Park et al. (2015) found that the release of phosphate increased with increasing pyrolysis temperature (300-600°C) from sesame straw biochar. Oxidation reactivity of biochar is dependent on manure type, but pyrolysis conditions are more important for deciding the reactivity. The conditions can be changed through, for example, an increase of temperature or heating rate. Flash (rapid) pyrolysis, where the oven reach the desired temperature at a much faster time than slow pyrolysis, results in higher oxidation reactivity (Zhang et al. 2009), lower pH, smaller particle size and larger surface area than slow pyrolysis (Bruun et al. 2012).

In an incubation study, Bruun et al. (2012) showed that biochar (wheat straw) had significantly lower CO_2-emissions than wheat straw, while N was mineralized by slow pyrolysis biochar but immobilized by flash pyrolysis biochar. In soil, biochar's C mineralization is strongly related to the volatile content of biochar (Zimmerman et al. 2011). Biochar derived from grass degraded faster than that derived from wood, and lower temperature biochar degraded faster. And lower pyrolysis temperature assists in degradation (Zimmerman et al. 2011). Dumbrell et al. (2016) concluded, from a survey, that the willingness to start implementing biochar in the general practice would take effort since it is not widely used, which makes it harder to try out. Therefore, it would be easier to increase the practices of for example no-till since there are farmers practicing it today and they would be able to share their experiences. In order to increase the use of biochar, it is important to communicate the benefits connected with biochar application according to Dumbrell et al. (2016).

Also, a biochar with low nutrient content has the possibility to increase yield in combination with mineral fertilizer. In a study, Chan et al. (2007) found that biochar caused an increase in pH, which decreases the amount of exchangeable Al. The crop was N limited and the effects of biochar could not be expressed. Jeffery et al. (2011) mention that biochar produced from different kinds of wood could produce different results, but that many papers do not specify from where the wood derived. This makes it difficult to draw general conclusions about how biochars affect crop growth.

Other than increasing soil pH, biochar also has the possibility to increase cation exchange capacity (CEC) and the availability of soil nutrients, especially P availability, which Jin et al. (2016) showed in an incubation study where swine manure biochar was added to clay loam and silt loam soil. P availability was primarily increased through P in the biochar, and secondly through decomposition of organic P.

It is also possible that biochar sequesters C through negative priming where, over time, soil organic matter (SOM) sorbs to the surface of biochar and hinders degradation. The potential of C sequestration could be as high as 12 % of the current anthropogenic CO_2-emission. Zimmerman et al. (2011) note that some studies, investigating certain biochar types and soil types might show positive priming in the early stages of incubation studies, but generally it shifts towards negative priming over time.

There are some risks associated with biochar application. There might be direct risks connected to biochar application, for example the dust might cause respiratory symptoms. Therefore, it is recommended to add water before application, or to keep a high moisture content when handling, for application and production. There might be toxic substances in biochar, usually in low concentration. Although repeated application might exceed set limits, this risk seems low. There are also risks of releasing heavy metals and toxins that can affect plants, fungi and, indirectly, human health. There has also been evidence that biochar application might increase leaching of phosphate and NO_3^- and CH_4-emissions under specific conditions (He et al. 2019). Biochar is generally negatively charged, which constricts the adsorption of anions such as phosphate (Riddle 2018).

Heavy metals and biochar

There have been many studies about the interaction between biochar and heavy metals, in soil or in heavy metal-rich biochar (He et al. 2019; Ayaz et al. 2021; Liu et al. 2021). Ayaz et al. (2021) showed that pig-manure derived biochar had high levels of heavy metals due to amendments to the pig fodder, but while the levels of metals increased in the soil, the metal content in plants decreased and nutrient availability of P, K, Mg and Ca increased. Pyrolysis slits the heavy metals, making them less bioavailable while simultaneously increasing the absorptive capacity of soil (Ayaz et al. 2021). Liu et al. (2021) found that it is possible to immobilize heavy metals in biochar through co-pyrolysis of calcium sulphate ($CaSO_4$) and sewage sludge, but the best result can be reached at different temperatures and $CaSO_4$ dosage. Cr, Pb and Zn are best immobilized at 750°C, while Cu and Ni immobilize better at 350°C.

Biochar and heavy metals interact both directly (through electrostatic interaction, ion exchange, complexation and precipitation), and indirectly through the interaction with soil properties such as soil pH, CEC, mineral composition and soil organic C (He et al. 2019). The indirect interactions are not fully understood. Biochar increases the adsorption of positively charged ions because of the high electronegativity. Increased pH and initial heavy metal concentration increase adsorption. Biochar also has high CEC to exchange cations such as Ca(II) and Mg(II) with metals. This makes nutrient rich biochar e.g. derived from animal manure very effective at immobilizing Cd(II) and Cu(II) while plant-derived biochars are more effective at immobilizing heavy metals through surface complexation with functional groups. It is also possible for mineral elements to form insoluble precipitants with metals. Their effectiveness depends on the mineral composition of the biochar, where biochar from pig-manure produces better results than biochar from bamboo (He et al. 2019).

3. Materials and Methods

3.1 Study site

More Biogas in Kalmar is a plant for AD and it uses a thermophilic process (55°C). They receive manure from approximately 20 farms in the area, as well as some other waste products such as household waste. *More Biogas* was the base of the pilot scale separation machines used in this study, mainly screw press and decanting centrifuge. In the project Circular NP, a multitude of treatments on separated slurry and digestate will be tested, such as composting, pyrolysis, drying and combustion. This will be done to show possibilities to produce different fertilizer products and soil amendments for the market. An AD plant is a good place to work with separation since the material is already condensed and relieved of energy through digestion, and the AD plant regularly receive a large amount of organic material and are used to handling the load. The farms that deliver manure generally have P-rich soils and a high animal density, why it is important to reduce the P concentration in the residual product (digestate) that is returned to the farm after digestion.

3.2 Sampling

The digestate that we used was a mixture of material delivered from multiple farms as well as municipal waste while the pig manure was collected from one farm. The screw press (Stallkamp PSS 2.2-400) had a sieve at 0.75 mm, with an inflow of around 7.5 cubic meters/h. Three batches of digestate and one batch of pig manure were run through the screw press. The liquid and solid fractions were collected separately and subsequently weighted. Scales were mounted under the tank for screw press liquid, and a container for screw press solids was placed on a portable scale. It was not possible to weigh the material that went into the screw press (raw digestate), but there were no losses when collecting her liquid and solids. Samples were removed to be further analysed.

The liquid samples were collected from the top of the storage tanks. The tank with digestate had continuous stirring while there was no stirring of the screw press liquid. However, samples were collected quickly after separation to avoid too much sedimentation in the tank. The screw press solids were collected using a shovel in different places of the collection container.

The digestate and pig manure solids were then dried at 100°C to constant weight and turned into biochar at 400°C and 550°C under inert atmosphere, where N_2 gas was supplied in the muffle furnace at a rate of 100 L/h using slow pyrolysis.

3.2.1 Analysis of materials

The materials were sent to *Agrilab* in Uppsala for analysis. In the lab, the samples were frozen until analysis. After thawing, the samples were dried at 105°C for 24 hours before DM was determined. The samples were grounded by hand for chemical analysis and analysed for total-N and total-C using combustion, with LECO CN928. NO_3^- and NH_4^+ were analysed colorimetrically after extraction with 2 M KCl. ICP Optical Emission Spectroscopy (ICP-OES) was used to analyse the total amount of several elements including P, K S and Ca after heat extraction with 7M HNO_3.

3.3 Incubation study

To analyse the development of the treatments over time, we set up an incubation study to observe N and C during a longer period. The incubation study consisted of 14 treatments with three replicates (Table 1). The different treatments were digestate solids, pig manure solids and biochar derived from both digestate solids and pig manure solids, later called DB and MB respectively. The raw digestate was not studied in this report. All the treatments were studied with and without the addition of mineral N (NH_4NO_3). The raw digestate and liquid fraction were also studied but were analysed and described in another master thesis (Björs 2022). For the incubation study, cups with 50 g soil were pre-incubated with MilliQ water at 50 % of the soil's water holding capacity. The soil was loamy sand with low organic matter content nutrient content (1.5 % OM, pH 6.3). Pre-incubation lasted for one to two weeks in room temperature, except for the control (soil + N) which was incubated for five days.

The biochar was sieved by hand through a 2 mm sieve while the raw solids of digestate and pig manure were passed through a 4 mm sieve to achieve a more homogenous material. The treatments were added equal to 10 g/kg soil based on their DM content (Table 1). The total amount of C and N in each treatment are shown in Table 1. Treatments with added mineral N received 1 ml of solution equal to 250 kg N/ha, which equals to 84 mg N/kg soil. All cups received MilliQ water to approximately 65 % of WHC and the cups were closed using lids (not hermetically). The cups were incubated at a maintained 15°C temperature. The cups intended for day 160 were incubated in glass jars with NaOH-traps (1 M).

The incubation study was set up for sampling for six months at day 3, 7, 14, 21, 44, (80, 120 and 160). This shorter study only included data from the first 50 days. Previous studies have shown that for the solid fraction, most parameters stabilize after about 20 days or there is no stabilization during the whole 160 days (Bruun et al. 2012; Schouten et al. 2012; Gomez-Munoz et al. 2016; Jin et al. 2016).

Table 1. Set up for incubation study. Treatments and added quantities based on dry weight (g DM/kg soil), normalized as application to 1 kg soil. Total content of C and N and added mineral N (mg/kg soil).

	Treatment (g DM/kg soil)	Total C (mg/kg soil)	Total N (mg/kg soil)	Mineral N (mg/kg soil)
Digestate solids	10	4600	246	
Manure solids	10	4650	141	
DB 400	10	5770	238	
DB 550	10	6320	209	
MB 400	10	6030	182	
MB 550	10	6690	164	
Digestate solids + N	10	4600	246	84
Manure solids + N	10	4650	141	84
DB 400 + N	10	5770	238	84
DB 550 + N	10	6320	209	84
MB 400 + N	10	6030	182	84
MB 550 + N	10	6690	164	84
Control	0	0	0	
Control + N	0	0	0	84

3.3.1 Analysis

The NaOH-traps were exchanged on day 1, 3, 7, 15, 21, 50, (80, 120, 160). The traps were back titrated using $BaCl_2$ (1M), thymolphthalein for the indicator solution and HCl (0.3 M) as titrant to estimate the CO_2 trapped.

The soil samples in the incubation study were analysed for DM, pH, NH_4-N and NO_3-N at *Agrilab* for every sampling date in the same way as the raw materials.

3.3.2 Calculations

The simple separation index (Et) (Eq. 1) was used to calculate how much of a compound ended up in the solid fraction after screw press separation, where m(x) is the mass (g) of the considered compound (x) in the solid fraction and the raw material (Hjorth et al. 2010).

$$Et(x)=m(x)_{solid}/m(x)_{digestate} \qquad (Eq.\ 1)$$

The removal efficiency (R) (Eq. 2) was also calculated, where c(x) equals the concentration (g/L) of the studied compounds as raw digestate and the liquid fraction (Hjorth et al. 2010). The removal efficiency measures how good the sampling of solid fraction was.

$$R(x)=1-(c(x)_{liquid}/c(x)_{digestate}) \qquad (Eq.\ 2)$$

The separation index shows the quantity of nutrients in the solid fraction while the removal efficiency shows the removal of nutrients from the liquid fraction. To calculate mx and cx of digestate, the weight of solids + liquid was used together with the analysis of the raw digestate. There were no expected weight losses when sampling.

To normalize the amount of CO_2-emission from each treatment, the amount of acid was equalized to CO_2-emission from 1 kg soil. The amount of CO_2-C was calculated by taking (control acid – treatment acid) * (normality of the acid * the equivalent weight of C in terms of C). The amount of CO_2-C lost from the sample was divided by the total-C to express how much C was lost as CO_2.

Net N mineralization to determine mineralization or immobilization, for the entire incubation study of 44 days, was calculated using (inorganic N (T44) – inorganic N (T0) – net mineralization of the control)/Total-N of the material. A positive result indicated mineralization and a negative value indicated immobilization of N.

3.3.3 Statistical analysis

The differences in CO_2-emission and inorganic N between treatments were tested using one-way ANOVA and Tukey's test (IBM SPSS Statistics 27). There were three replicates enabling the calculation of standard deviation in the incubation study. Biochar was analysed separately to find differences between different materials and temperatures.

4. Results and Discussion

4.1 Screw press separation

The screw press separation of digestate solids resulted in 26 % of the DM ending up in the solid fraction, as well as 19 % of total P and 8 % of total N (Table 2), using the simple separation index (Eq 1). Further calculation of the removal efficiency (Eq. 2) showed a good sampling since values were very similar.

Table 2. Separation index (%) and removal efficiency (%) of digestate solids. The results show how well the screw press separated different nutrients to the solid fraction and how much of the nutrients were removed from the liquid fraction.

	Separation index %	Removal efficiency %
DM	25.7	26.8
Total-N	7.9	7.2
NH_4-N	5.2	4.8
Total-C	29.2	31.3
Total-P	18.6	17.6
Total-K	5.8	1.9
Total-Mg	21.1	20.4
Total-Ca	13.2	14.9
Total-Na	5.4	1.0
Total-S	15.6	12.8
Total-Cu	11.3	13.6
Total-Fe	11.9	13.8
Total-Mn	8.2	8.6
Total-Zn	9.4	11.0

The separation index corresponds well with other literature (Figure 1) (Hjorth et al. 2010; Tambone et al. 2017; Pantelopoulos & Aronsson 2021), where the average separation index of DM was 36 % (n=19), total N 14 % (n=15) and total P 17 % (n=15). NH_4-N was only observed in one of these studies at 3.6 % (Pantelopoulos & Aronsson 2021) and is not enough to compare to the 5 % measured in our solid fraction. P content was notably high in our separation, but still within the range of previously reported results. There can be many reasons why different separation index was achieved such as the material and the screw press settings. One study used digestate (Tambone et al. 2017) as the tested material while the others studied different kinds of animal manure. The different screw presses also used different screen openings. Pantelopoulos & Aronsson (2021) used 0.5 mm, and the different studies referenced by Hjorth et al. (2010) used screen openings between 0.7-3.2 mm. The settings of the screw press might influence the separation of materials by how well they separate small particles.

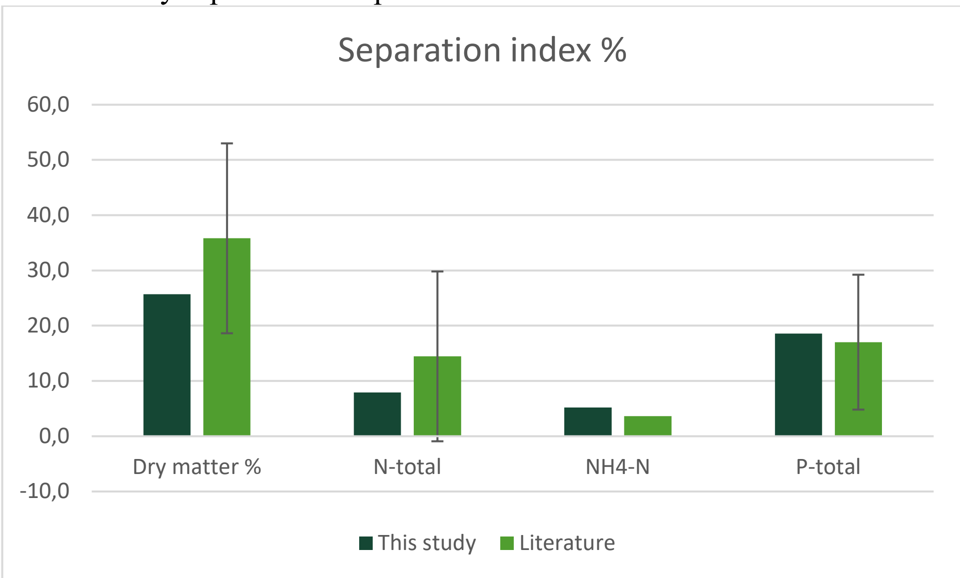

Figure 1. Separation index of the solid fraction and comparison of screw press separation in literature (Hjorth et al. 2010; Tambone et al. 2017; Pantelopoulos & Aronsson 2021). Standard deviation for the literature shown as error bars.

4.2 Materials

4.2.1 Solids

The DM content was around 25 % for the solid fraction of both digestate and manure solids (Table 3). The C/N-quota was higher in manure solids than in digestate solids (33 and 19 resp.). In general, digestate solids contained more nutrients than manure solids. During the process of AD, the nutrient concentration increased, through the loss of C in the form of CO_2 and CH_4, which led to higher concentrations in digestate solids than in raw pig manure solids. The digestate consisted of a mixture of manure (e.g. pig, cattle and chicken) as well as other organic waste which probably contribute to the lower C/N-ratio. The pig manure contained a lot of straw (bedding material), which led to a higher C/N-quota. In digestate, the organic matter was degraded in the anaerobic process resulting in no large particles remaining in the material.

Table 3. Dry matter (DM) content and nutrient composition of the different materials used in the incubation study. The materials consisted of separated solids from digestate and pig manure as well as biochar, derived from digestate solids (DB) and pig manure solids (MB), pyrolyzed at two different temperatures (400 and 550°C).

		Digestate solids	Manure solids	DB 400	DB 550	MB 400	MB 550
DM	%	24.8	25.3	98.8	98.7	99.0	99.2
Tot-N	g/(kgDM)	24.6	14.1	23.8	20.9	18.2	16.4
Tot-C	g/(kgDM)	460	465	577	632	603	669
Tot-C/Tot-N		18.7	33.0	24.5	30.7	33.4	41.2
Tot-P	g/(kgDM)	9.6	6.7	21.8	22.9	18.1	20.4
Tot-K	g/(kgDM)	11.7	5.2	22.9	25.4	14.8	16.2
Tot-Mg	g/(kgDM)	7.6	4.0	17.8	17.1	11.9	12.3
Tot-Ca	g/(kgDM)	11.3	12.1	24.5	26.1	32.7	36.3
Tot-Na	g/(kgDM)	2.4	1.3	4.7	5.2	3.8	4.1
Tot-S	g/(kgDM)	4.6	2.4	3.0	2.9	2.5	2.4
Tot-Fe	g/(kgDM)	6.0	1.4	13.0	10.2	4.4	3.6
Tot-Cu	mg/(kgDM)	118	54.0	188	184	89.8	102
Tot-Mn	mg/(kgDM)	123	110	279	324	282	308
Tot-Zn	mg/(kgDM)	138	136	281	283	329	338
pH		7.8	8.5	10.4	10.9	10.7	11.1

4.2.2 Biochar

By converting the solids into biochar, the concentration of nutrients increased compared to the raw material, except for N and S from digestate solids and S from manure solids. This could be because N and S are usually lost in gaseous forms in the combustion of organic matter. In comparison to the original material, the concentration of nutrients overall increased most in MB. The amount of N remained similar in digestate solids after pyrolysis while the other nutrients increased, except for tot-S that showed a slight decrease. Pyrolysis caused increases in all nutrients analysed for manure solids. The presence of more easily combustible C in the manure, which contained a lot of straw and did not go through the digestate process, caused a higher combustion of C when pyrolyzed. pH increased from around 8 to around 11 and seemed to reach a slightly higher level when pyrolyzed at 550°C for both digestate and pig manure (Table 3). DM reached almost 100 %.

Generally, DB contained higher levels of nutrients (for example P and K) than MB (Figure 2). This might be because these nutrients are not lost in gaseous forms unlike e.g. N, C and S. There was no constant pattern for all the elements analysed regarding original material or pyrolysis temperature. For example, MB contained higher levels of Ca and biochar pyrolyzed at 550°C clearly showed higher levels of Mn for both manure and digestate.

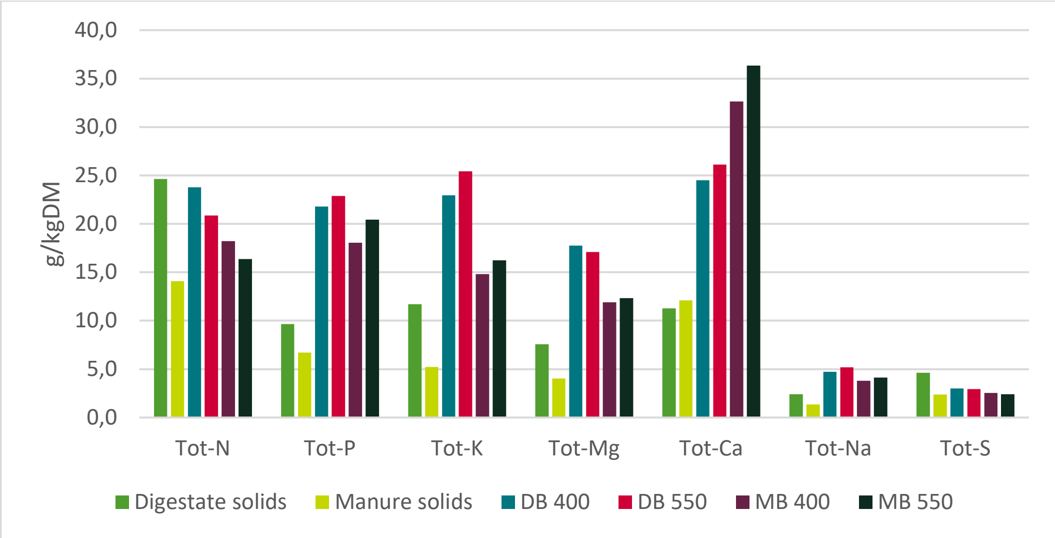

Figure 2. Comparison of nutrient content of digestate and manure solids and the solids derived biochars produced at 400C (DB 400, MB 400) and at 550 (DB 550, MB 550), respectively. (g/kgDM).

4.3 The incubation study

4.3.1 Carbon mineralization

The highest emissions of CO_2 were measured from soil amended with manure solids on day 14. Manure solids caused the highest total CO_2-emission followed by digestate solids, with 37 % respectively 16,5 % loss of total C as CO_2. The addition of mineral N caused lower CO_2-emissions in all treatments (Figure 3; Figure 4). There were some notable emissions of CO_2 from the biochar during the first 3-7 days before reaching a plateau, though much lower than from the solids (Figure 4). Only MB 400 and DB 400 + N had significantly higher emissions than DB 550 + N, though the highest accumulated CO_2-emissions only accounted for <2 % of the total C added in MB 400. Obviously, C in biochar 400 was not as stable as C in biochar 550, which lead to higher CO_2-emissions. The low emission from biochar corresponds with the low levels documented in the earlier stages of incubation studies in other literature (Schouten et al. 2012; Gomez-Munoz et al. 2016). Gomez-Munoz et al. (2016) found that after day 40 C mineralization increased significantly, which will have to be studied in the continuation of this incubation study. The AD process stabilizes C in the material and decreases the rate of C oxidation. Pyrolysis causes further stabilization of C, and the benefits to SOM have been questioned (Schouten et al. 2012).

There were lower emissions observed with the addition of N, which was probably a result of lower microorganism activity because of a readily available N source leading to a decreased need for respiration and an increased microbial biomass. When N is a limiting factor, the activity of microorganisms increases in order to mineralize nutrient-poor material (Mahal et al. 2019).

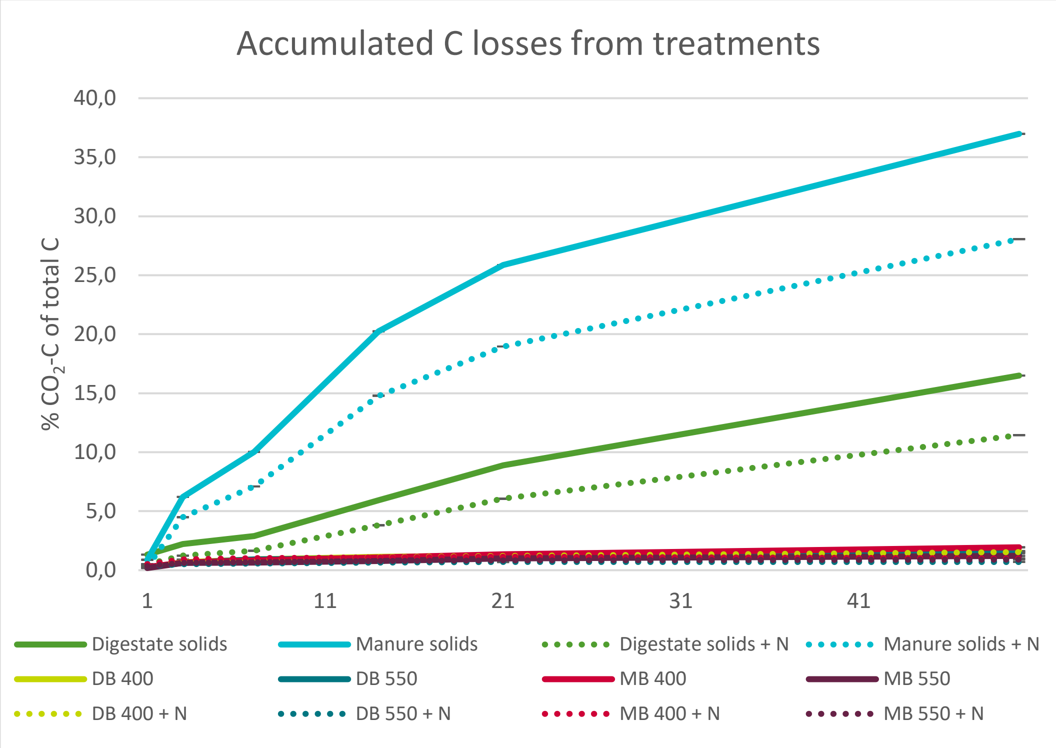

Figure 3. Accumulated C losses (% CO_2-C of initial C content) over 50 days for digestate solids, manure solids and biochars. Standard deviations are shown as error bars. When error bars not visible they fall into lines.

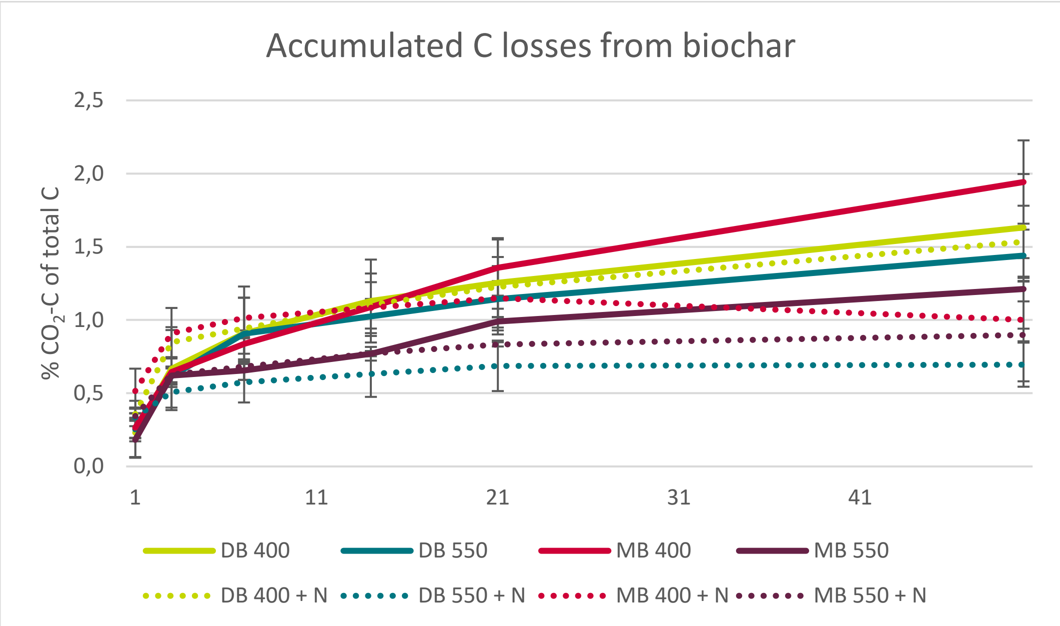

Figure 4. Accumulated C losses (% CO_2-C of initial C content) for biochar over 50 days. Standard deviations are shown as error bars.

4.3.2 Dynamics of inorganic N and pH

The samples in the incubation study were analysed for pH, NH_4-N and NO_3-N (Figure 5). During the incubation, the levels of NH_4^+ decreased to zero during the 44 days (Figure 5). NO_3^- reached the highest level between day 14-21 depending on the treatment. pH decreased slightly during the study but stayed around 6.5. The initial pH of the soil was 6.3. The lowest pH was measured in Control + N on day 44 at a mean of pH 5.4, and the highest in DB 550 at a mean of pH 7.1 on day three.

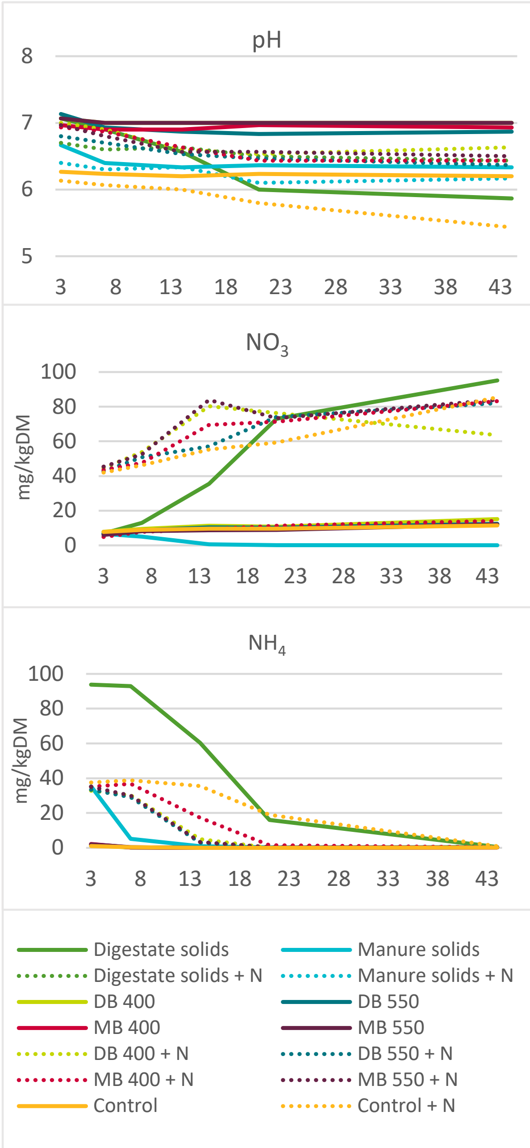

Figure 5. The development of pH, NH_4^+ (mg/kgDM) and NO_3^- (mg/kgDM) during an incubation of 44 days.

There were no significant differences between the different biochars in the different parameters. In most cases, the addition of N caused significant change compared to the same treatment without N (Figure 6). The low levels of inorganic N (NH_4-N+NO_3-N) correlate well with the CO_2-emissions for biochar. The low N supply seemed to result in lower microbial activity and thereby lower C oxidation. Digestate solids released similar levels of inorganic N to biochar + N, while manure solids were more similar to biochar without the addition of mineral N (Figure 6).

On day three, the inorganic N levels of manure solids were high because of high levels of NH_4^+ in the sample. One reason for this could be the large amount of straw in the material causing the subsamples to become very heterogenous in comparison to the other sample dates. The standard deviation of manure solids on day three was 1.5. There were some inconsistencies with the raw solids + N, where the levels of NH_4^+ and NO_3^- were ten times higher than the expected amount, which made them futile in this study.

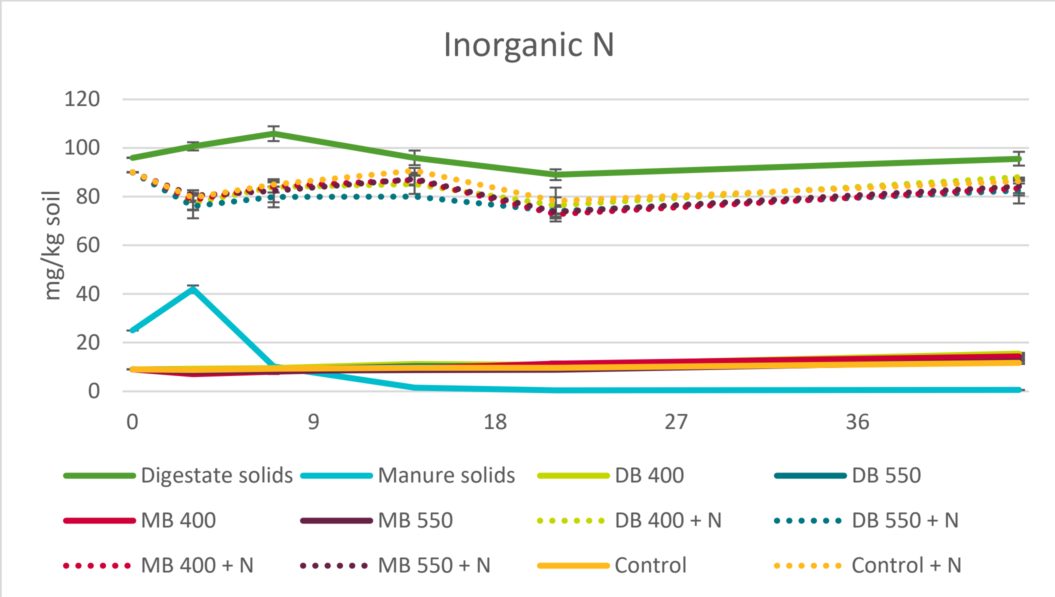

Figure 6. Development of inorganic N (NH_4-N+NO_3-N) from treatments without and with addition of mineral N during the incubation (mg N/kg soil). Standard deviations are shown as error bars.

4.3.3 Net N mineralization

During the incubation period of 44 days, there was net N mineralization in the soil with added biochar without N and DB 400 + N, while there was net N immobilization in treatments with solids as well as for the rest of the biochars with added N (Figure 7). Biochar 400 mineralized about 1.5 % of the initial N content and biochar 550 about 0.5 %, DB 400 + N mineralized 0.8 % of initial N. The immobilization of N in biochar + N-treatment was around 1.5 %. The immobilization with manure solids was stronger than with digestate solids, 7.9 % and 5.2 % immobilized respectively. There were no significant differences between treatments. The DB 400 + N only had two usable analyses, and the results were questionable. Based on this, we can conclude that there would be no net positive effect from N application in combination to biochar, but rather the opposite. There seems to be a pattern indicating that lower temperature biochar is less stable than higher temperature biochar and that biochar 400 has a higher rate of decomposition and N mineralization, without added N. Biochar has a very stable structure that makes the net mineralization unlikely to change during the remainder of this study which was planned to last until day 160. Some of the materials might turn towards net mineralization instead of immobilization.

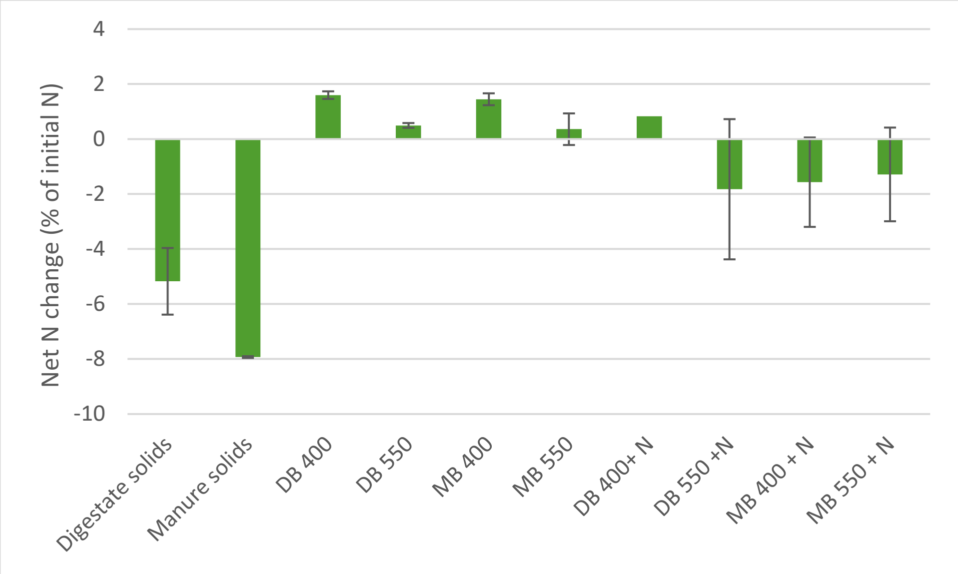

Figure 7. Net mineralization of the treatments as % of total N added to each treatment, with biochar or solids, without the net mineralization of the control. Positive value equals mineralization, and negative value equals immobilisation. Standard deviations are shown as error bars.

There was no fertilizer effect when adding solids to soil during the first 44 days. The higher immobilization in manure solids have been caused by the lower N content compared to the biochar (Table 2) and by the presence of a lot of straw in the manure. Higher C supply and lower N supply lead to higher activity of microorganisms and immobilization.

The application of biochar in combination with mineral N could have a negative effect on the plant uptake but needs to be tested in the lab and in the field to show definitive results. If that was the case, biochar application leaves a possibility for autumn application in cases of high N levels after the growing season. Biochar would then possibly increase the immobilization and decrease N leaching. It is also possible that the application of biochar + N might decrease the CO_2-emissions from N-limited soil to maintain organic matter in the soil. There are also other parameters to consider when investigating biochar. In this study, we only analyse N, but for example P must also be considered. This study is also quite short, and the long-term effects need to be considered. While biochar has a stable structure, the effect on the surrounding soil could change with time. Most changes should be seen in the beginning, directly after application, when the material is fresh and microorganisms can easily utilize the new material, but in due time, hard-bound nutrients might dissolve, which might change the pattern.

4.4 Commercial application

Digestate and manure are in good supply and are readily available for separation. Screw press separation of digestate is a good option as it is cheaper than the use of centrifuge as a separation method. In this study, 8 % of total N, 6 % of total K and 26 % of total C as well as 19 % of P ended up in the solid fraction of digestate. The removal efficiency of P was not as high as would be preferred, but still, it was functional. As a reference, decanting centrifuge can separate 71 % of total P to the solid fraction (Hjorth et al. 2010). For a farmer, the removal of 25 % P with such a simple method might be a very good investment.

The screw press used in this study (Stallkamp PSS 2.2-400) can be manually set to different settings on the pressure plate. The pressure of the pressure plate determines the release of the solid fraction from the screw press. It would be interesting to study different settings as well as different sieves in order to calibrate the screw press in order to estimate the best separation efficiency for DM and P. Using the cheaper option of screw press separation could be a good option to create a product with higher DM content and then use it as organic amendment. When using a centrifuge, it might still be valuable to use a screw press and separate large pieces to avoid breaking the centrifuge, which is a sensitive machine. The cost of a decanting centrifuge can be as high as five times that of a screw press, but according to Moller et al. (2000), the cost can be considerably reduced if the occupation rate is increased.

In our study, the release of inorganic N from biochar did not change during the incubation, and there were no differences between the different kinds of biochar. The pH decreased slightly in 44 days. C mineralization was most active during the first few days. Biochar lost less than 2 % of total C as CO_2 (Figure 4). This leads to the conclusion that biochar, from this material, is stable and that the loss of C will probably be low also during the following months. The release of CO_2 from the solids was high, up to 37 % of total C loss, but the addition of mineral N may have the potential to reduce the CO_2-emissions since the soil seem to become less N limited, and creates a more favourable environment for microorganisms and decreased C mineralization.

Producing biochar requires a lot of energy and the pyrolysis decreases the mass with a considerable amount. However, it is possible to capture the heat and to redistribute it as an energy source. As for the application rate of biochar, it will be important to study it further. In this study, we applied biochar equal to 25 000 kg/ha, which is an application rate that is similar to other studies. However, the content of P became much too high compared to what is allowed for application of organic P over five years in Sweden. This application rate results in around 500 kg P/ha compared to the allowed amount, which is 110 kg P/ha over five years (Andersson et al. 2022). If we were to reach allowed limits, the application rate of biochar ought to be around 5 500 kg/ha. The loss of 2 % C would equal to 310 kg C/ha lost in 50 days, which leaves 15 000 kg/ha of applied C in the soil to increase the C storage. N mineralization from biochar would add up to 2.6-3.7 kg N/ha, while the addition of N to biochar would cause immobilization of 7 kg N/ha of the total N in biochar. The solids caused immobilization of around 30 kg N/ha. In time, immobilization of N will turn to mineralization, but manure and digestate solids acts as slow fertilizers and could possibly benefit from application in the autumn so that N will be available when the crop needs it.

There is a need to test different application rates as well as the interaction between biochar and plants. The effect of biochar is also affected by the characteristics of the soil and should be tested on different soils. The soil in this study was low in organic content and nutrition, with a pH of 6.3. In order to gain a wider understanding of the possibilities, deeper understandings of different conditions are needed. Biochar has not reached its potential use (Dumbrell et al. 2016) yet, and more research will facilitate its incorporation in practice.

5. Conclusions

- Screw press separation of digestate resulted in 19 % of P ending up in the solid fraction together with 26 % of DM, 8 % of N and 6 % of K.
- The C stability of biochar was high with very little C lost as CO_2 (<2 % of total C) while manure solids lost 37 % of CO_2, indicating a considerably less stable material. Digestate solids were stabilized through AD and lost 16 % of total C as CO_2. There was a weak indication that biochar pyrolyzed at 400°C lost more C than biochar pyrolyzed at 550°C.
- The amendment of solids led to immobilization, making separated solids a slow-acting fertilizer, which might be good to apply during the autumn to potentially have N mineralized when the crop needs it. However, further studies are needed since this study is very short.
- Biochar amendment caused mineralization where a very small amount of N was made available, but the addition of mineral N to the soil in combination with biochar caused immobilization during the first 44 days. The continued progress needs to be further studied in order to determine if the mineralization continues making biochar a fast-acting amendment, or if this low mineralization will make it slow-acting.

References

Abiven, S., Schmidt, M.W.I. & Lehmann, J. (2014). Biochar by design. *Nature Geoscience*, 7 (5), 326–327. https://doi.org/10.1038/ngeo2154

Akram, U., Quttineh, N.-H., Wennergren, U., Tonderski, K. & Metson, G.S. (2019). Enhancing nutrient recycling from excreta to meet crop nutrient needs in Sweden - a spatial analysis. *Scientific Reports*, 9, 10264. https://doi.org/10.1038/s41598-019-46706-7

Almaraz, M., Wong, M.Y., Geoghegan, E.K. & Houlton, B.Z. (2021). A review of carbon farming impacts on nitrogen cycling, retention, and loss. *Annals of the New York Academy of Sciences*, 1505 (1), 102–117. https://doi.org/10.1111/nyas.14690

Andersson, E., Frostgård, G., Hjelm, E., Kvarmo, P. & Listh, U. (2022). *Rekommendationer för gödsling och kalkning 2022*. Jordbruksverket.

Ayaz, M., Stulpinaite, U., Feiziene, D., Tilvikiene, V., Akthar, K., Baltrėnaitė-Gedienė, E., Striugas, N., Rehmani, U., Alam, S., Iqbal, R., Toleikiene, M. & Doyeni, M. (2021). Pig manure digestate-derived biochar for soil management and crop cultivation in heavy metals contaminated soil. *Soil Use and Management*, sum.12773. https://doi.org/10.1111/sum.12773

Björs, M. (2022). *Separation and acidification of digested animal manure - Properties of the future organic fertilisers*. Uppsala: Department of Soil and environment, Swedish University of Agricultural Sciences.

Bruun, E.W., Ambus, P., Egsgaard, H. & Hauggaard-Nielsen, H. (2012). Effects of slow and fast pyrolysis biochar on soil C and N turnover dynamics. *Soil Biology & Biochemistry*, 46, 73–79. https://doi.org/10.1016/j.soilbio.2011.11.019

Calderón, F.J., McCarty, G.W. & Reeves, J.B. (2005). Analysis of manure and soil nitrogen mineralization during incubation. *Biology and Fertility of Soils*, 41 (5), 328–336. https://doi.org/10.1007/s00374-005-0843-x

Carstensen, J., Andersen, J.H., Gustafsson, B.G. & Conley, D.J. (2014). Deoxygenation of the Baltic Sea during the last century. *Proceedings of the National Academy of Sciences of the United States of America*, 111 (15), 5628–5633. https://doi.org/10.1073/pnas.1323156111

Chadwick, D., Sommer, S.G., Thorman, R., Fangueiro, D., Cardenas, L., Amon, B. & Misselbrook, T. (2011). Manure management: Implications for greenhouse gas emissions. *Animal Feed Science and Technology*, 166–67, 514–531. https://doi.org/10.1016/j.anifeedsci.2011.04.036

Chan, K.Y., Van Zwieten, L., Meszaros, I., Downie, A. & Joseph, S. (2007). Agronomic values of greenwaste biochar as a soil amendment. *Australian Journal of Soil Research*, 45 (8), 629–634. https://doi.org/10.1071/SR07109

Dumbrell, N.P., Kragt, M.E. & Gibson, F.L. (2016). What carbon farming activities are farmers likely to adopt? A best–worst scaling survey. *Land Use Policy*, 54, 29–37. https://doi.org/10.1016/j.landusepol.2016.02.002

Fangueiro, D., Senbayran, M., Trindade, H. & Chadwick, D. (2008). Cattle slurry treatment by screw press separation and chemically enhanced settling: Effect on greenhouse gas emissions after land spreading and grass yield.

Bioresource Technology, 99 (15), 7132–7142. https://doi.org/10.1016/j.biortech.2007.12.069

Głowacka, A., Szostak, B. & Klebaniuk, R. (2020). Effect of Biogas Digestate and Mineral Fertilisation on the Soil Properties and Yield and Nutritional Value of Switchgrass Forage. *Agronomy*, 10 (4), 490. https://doi.org/10.3390/agronomy10040490

Gomez-Munoz, B., Case, S.D.C. & Jensen, L.S. (2016). Pig slurry acidification and separation techniques affect soil N and C turnover and N2O emissions from solid, liquid and biochar fractions. *Journal of Environmental Management*, 168, 236–244. https://doi.org/10.1016/j.jenvman.2015.12.018

Guilayn, F., Jimenez, J., Rouez, M., Crest, M. & Patureau, D. (2019). Digestate mechanical separation: Efficiency profiles based on anaerobic digestion feedstock and equipment choice. *Bioresource Technology*, 274, 180–189. https://doi.org/10.1016/j.biortech.2018.11.090

He, L., Zhong, H., Liu, G., Dai, Z., Brookes, P.C. & Xu, J. (2019). Remediation of heavy metal contaminated soils by biochar: Mechanisms, potential risks and applications in China. *Environmental Pollution*, 252, 846–855. https://doi.org/10.1016/j.envpol.2019.05.151

Hjorth, M., Christensen, K.V., Christensen, M.L. & Sommer, S.G. (2010). Solid—liquid separation of animal slurry in theory and practice. A review. *Agronomy for Sustainable Development*, 30 (1), 153–180. https://doi.org/10.1051/agro/2009010

Jeffery, S., Abalos, D., Prodana, M., Bastos, A.C., van Groenigen, J.W., Hungate, B.A. & Verheijen, F. (2017). Biochar boosts tropical but not temperate crop yields. *Environmental Research Letters*, 12 (5), 053001. https://doi.org/10.1088/1748-9326/aa67bd

Jeffery, S., Verheijen, F.G.A., van der Velde, M. & Bastos, A.C. (2011). A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. *Agriculture Ecosystems & Environment*, 144 (1), 175–187. https://doi.org/10.1016/j.agee.2011.08.015

Jin, Y., Liang, X., He, M., Liu, Y., Tian, G. & Shi, J. (2016). Manure biochar influence upon soil properties, phosphorus distribution and phosphatase activities: A microcosm incubation study. *Chemosphere*, 142, 128–135. https://doi.org/10.1016/j.chemosphere.2015.07.015

Jönsson, H. (2019). *Fosfor, kväve, kalium och svavel – tillgång, sårbarhet och återvinning från avlopp*. (Energi och teknik, 105). Uppsala: Swedish University of Agricultural Sciences - Institute of energy and technology.

Klackenberg, L. (2020). *Produktion och användning av biogas och rötrester år 2019*. (ER 2020:25). Eskilstuna, Sweden: Swedish Energy Agency.

Kuecke, M., Jaggard, K.W. & Ehlert, P.A.I. (2001). Crop response to phosphorus. *The effect of phosphate fertilizer management strategies on soil phosphorus status and crop yields in some European countries*. 29–58

Lee, J., Park, K.Y., Cho, J. & Kim, J.Y. (2018). Releasing characteristics and fate of heavy metals from phytoremediation crop residues during anaerobic digestion. *Chemosphere*, 191, 520–526. https://doi.org/10.1016/j.chemosphere.2017.10.072

Liu, L., Huang, L., Huang, R., Lin, H. & Wang, D. (2021). Immobilization of heavy metals in biochar derived from co-pyrolysis of sewage sludge and calcium sulfate. *Journal of Hazardous Materials*, 403, 123648. https://doi.org/10.1016/j.jhazmat.2020.123648

Mahal, N.K., Osterholz, W.R., Miguez, F.E., Poffenbarger, H.J., Sawyer, J.E., Olk, D.C., Archontoulis, S.V. & Castellano, M.J. (2019). Nitrogen Fertilizer Suppresses Mineralization of Soil Organic Matter in Maize Agroecosystems. *Frontiers in Ecology and Evolution*, 7. https://www.frontiersin.org/article/10.3389/fevo.2019.00059 [2022-05-20]

Moller, H.B., Lund, I. & Sommer, S.G. (2000). Solid-liquid separation of livestock slurry: efficiency and cost. *Bioresource Technology*, 74 (3), 223–229. https://doi.org/10.1016/S0960-8524(00)00016-X

Ogle, S.M., Swan, A. & Paustian, K. (2012). No-till management impacts on crop productivity, carbon input and soil carbon sequestration. *Agriculture Ecosystems & Environment*, 149, 37–49. https://doi.org/10.1016/j.agee.2011.12.010

Pantelopoulos, A. & Aronsson, H. (2021). Two-stage separation and acidification of pig slurry - Nutrient separation efficiency and agronomical implications. *Journal of Environmental Management*, 280, 111653. https://doi.org/10.1016/j.jenvman.2020.111653

Park, J.H., Ok, Y.S., Kim, S.H., Cho, J.S., Heo, J.S., Delaune, R.D. & Seo, D.C. (2015). Evaluation of phosphorus adsorption capacity of sesame straw biochar on aqueous solution: influence of activation methods and pyrolysis temperatures. *Environmental Geochemistry and Health*, 37 (6), 969–983. https://doi.org/10.1007/s10653-015-9709-9

Riddle, M. (2018). *Phosphorus leaching from Swedish arable organic soils*. (2018:50). Uppsala: Department of Soil and Environment, Swedish University of Agricultural Sciences. https://pub.epsilon.slu.se/15642/ [2022-03-30]

Ryals, R. & Silver, W.L. (2013). Effects of organic matter amendments on net primary productivity and greenhouse gas emissions in annual grasslands. *Ecological Applications*, 23 (1), 46–59. https://doi.org/10.1890/12-0620.1

Schouten, S., van Groenigen, J.W., Oenema, O. & Cayuela, M.L. (2012). ”Bioenergy from cattle manure? Implications of anaerobic digestion and subsequent pyrolysis for carbon and nitrogen dynamics in soil”. *Global Change Biology Bioenergy*, 4 (6), 751–760. https://doi.org/10.1111/j.1757-1707.2012.01163.x

Smith, J., Abegaz, A., Matthews, R.B., Subedi, M., Orskov, E.R., Tumwesige, V. & Smith, P. (2014). What is the potential for biogas digesters to improve soil carbon sequestration in Sub-Saharan Africa? Comparison with other uses of organic residues. *Biomass & Bioenergy*, 70, 73–86. https://doi.org/10.1016/j.biombioe.2014.01.056

Tambone, F., Genevini, P., D'Imporzano, G. & Adani, F. (2009). Assessing amendment properties of digestate by studying the organic matter composition and the degree of biological stability during the anaerobic digestion of the organic fraction of MSW. *Bioresource Technology*, 100 (12), 3140–3142. https://doi.org/10.1016/j.biortech.2009.02.012

Tambone, F., Orzi, V., D'Imporzano, G. & Adani, F. (2017). Solid and liquid fractionation of digestate: Mass balance, chemical characterization, and agronomic and environmental value. *Bioresource Technology*, 243, 1251–1256. https://doi.org/10.1016/j.biortech.2017.07.130

Withers, P.J.A., Unwin, R.J., Grylls, J.P. & Kane, R. (1994). Effects of withholding phosphate and potash fertilizer on grain yield of cereals and on plant-available phosphorus and potassium in calcareous soils. *European Journal of Agronomy*, 3 (1), 1–8. https://doi.org/10.1016/S1161-0301(14)80104-4

Yan, Y., Zhang, L., Feng, L., Sun, D. & Dang, Y. (2018). Comparison of varying operating parameters on heavy metals ecological risk during anaerobic co-digestion of chicken manure and corn stover. *Bioresource Technology*, 247, 660–668. https://doi.org/10.1016/j.biortech.2017.09.146

Ye, L., Camps-Arbestain, M., Shen, Q., Lehmann, J., Singh, B. & Sabir, M. (2020). Biochar effects on crop yields with and without fertilizer: A meta-analysis of field studies using separate controls. *Soil Use and Management*, 36 (1), 2–18. https://doi.org/10.1111/sum.12546

Zhang, S.-Y., Hong, R.-Y., Cao, J.-P. & Takarada, T. (2009). Influence of manure types and pyrolysis conditions on the oxidation behavior of manure char. *Bioresource Technology*, 100 (18), 4278–4283. https://doi.org/10.1016/j.biortech.2009.04.002

Zimmerman, A.R., Gao, B. & Ahn, M.-Y. (2011). Positive and negative carbon mineralization priming effects among a variety of biochar-amended soils. *Soil Biology & Biochemistry*, 43 (6), 1169–1179. https://doi.org/10.1016/j.soilbio.2011.02.005

Populärvetenskaplig sammanfattning

Kalmarregionen har en stor djurtäthet och producerar mycket organiskt gödsel som kan användas för att producera biogas. Restprodukten, rötrest, kan användas i jordbruket som gödning eftersom den innehåller essentiella näringsämnen som grödorna behöver. Problemet är att rötrest innehåller mycket vatten, vilket gör den tungt och opraktisk att transportera. Man vill transportera rötresten eftersom den innehåller mycket fosfor, som är ett viktigt näringsämne för grödorna. Fosfor ackumuleras även i jorden om man gödslar mer än grödan tar upp under ett år och vid höga nivåer kan fosforn förloras ut i vattendrag och bidra till övergödning av sjöar och hav. Det finns regler för hur mycket fosfor som får läggas på åkern i form av organiska gödselmedel, och djurtätheten gör att det finns ett överskott på gödsel. I Kalmarregionen har man under många år gödslat med organiska gödselmedel, vilket gör att det finns mycket fosfor i jorden. I andra delar av Sverige finns det områden med låg djurtäthet som skulle gynnas av att ta del av rötresten, men för att kunna transportera rötresten måste man minska vikten genom att till exempel separera ut vattnet.

Genom mekanisk separation med skruvpress kan man producera en fast fraktion av rötresten. Den är lättare att transportera och innehåller mycket kol och fosfor, vilket är gynnsamt för växter och jord. Den fasta fraktionen kan användas direkt som gödsel. Den är långsamverkande, vilket betyder att näringen inte blir tillgänglig grödan direkt utan att den binds upp i marken under en tid. Man kan också behandla den fasta fraktionen i syfte att ändra dess näringsinnehåll, och uppehållstid i jorden för att minska CO_2 i atmosfären, genom att tillverka t ex biokol. Biokol framställs genom att man förbränner organiskt material som till exempel organiskt gödsel, halm eller träflis utan att det finns något syre i ugnen och vid väldigt hög temperatur (ca 300-700°C). Detta minskar bland annat den mängd kol som försvinner ur materialet.

Tillsatts av biokol till jord kan förbättra tillgängligheten av näring i marken och kan ha en kalkningseffekt och höja pH i riktigt sura jordar. CO_2-avgången från biokol var väldigt låg, och lite kväve frigörs till grödan redan under de första 50 dagarna till skillnad från den fasta fraktionen av rötrest, som alltså är modermaterialet. Biokol är ett spännande material. Det innehåller i princip inget vatten och kan förbättra förhållandena i jorden och kan transporteras betydligt lättare än den blöta rötresten.

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