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Manure-based recycling fertilisers

A literature review of treatment technologies and their effect on phosphorus fertilisation effects

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Manure-based recycling fertilisers: A literature review of treatment technologies and their effect on phosphorus fertilisation effects

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SAMMENDRAG/SUMMARY:

Fosfor i husdyrgjødsel blir i dag dårlig utnyttet, og det er vanlig at fosfor akkumuleres i jorden i områder med høy husdyrtetthet. Det har blitt utviklet en rekke ulike behandlingsteknologier som gjør det mulig å transportere fosfor i husdyrgjødsel fra husdyrtette områder til områder med behov for fosforgjødsel. Denne rapporten er en gjennomgang av litteraturen på de viktigste behandlingsteknologiene og deres effekt på gjødselvirkningen av fosforet i produktene.

Phosphorus in manure is currently poorly utilised, and accumulation of soil phosphorus in livestock-intensive areas is common. Several treatment technologies have been developed to facilitate re-distribution of phosphorus for more resource-efficient management. This report is a short literature review of the main technologies and their effect on the phosphorus fertilisation effect of the produced manure-based recycling fertilisers.

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Preface

In Norway, as in many other industrialised countries, animal manure is one of the most important sources of secondary phosphorus. In the project “Nutrients in a Circular Bioeconomy: Barriers and Opportunities for Mineral Phosphorus Independence in Norway (Mind-P)” we therefore explore possibilities to better utilise phosphorus in manure in addition to phosphorus in fish sludge from aquaculture in 5 different work packages (WP).

WP 1 is dedicated to project management.

In WP 2 we conduct systems analysis to identify the largest system-wide opportunities for phosphorus recycling in Norway based on geographical resolution.

In WP 3 we identify barriers and opportunities related to phosphorus recycling.

In WP 4, we develop scenarios and pathways for improved phosphorus recycling and mineral phosphorus independence in Norway.

WP 5 is dedicated to communication and outreach.

The project is led by Prof. Daniel Müller/NTNU and is a cooperation with NIBIO and DTU, as well as an advisory board with representatives from public authorities, industry and interest organisations. The project is running for 3 years (9/2017 – 3/2020) and funded by the BIONÆR programme of The Research Council of Norway.

This report has been produced as part of WP 3.1 Secondary Resources for Agriculture Use.

Ås, 26.06.18

Eva Brod

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1 Introduction

In many industrialised countries, increasingly specialised agricultural production has over time resulted in pronounced phosphorus overloads in livestock-intensive areas and in phosphorus deficits in crop production areas. In livestock-intensive areas, phosphorus in animal manure is often applied in excess of crop requirements and excess phosphorus is hence accumulating in agricultural soil, posing a risk of eutrophication of fresh waters following run-off and soil erosion. At the same time, phosphorus is imported to crop production areas, mainly as mineral fertilisers. Despite rock phosphate being a limited resource, phosphorus in manure is currently poorly managed and utilised.

In Norway, livestock density is highest in the Western part of the country with the highest density in the Rogaland county, and there is a clear and visible relationship between livestock density and the soil phosphorus status in most counties of Norway (Figure 1).

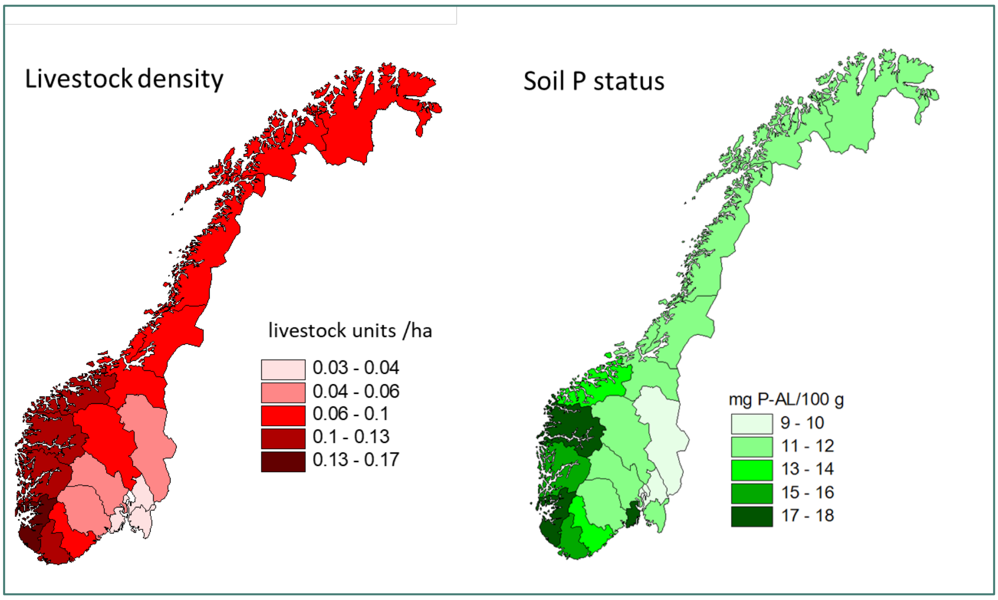

Figure 1. **Relationship between livestock density (left) and soil phosphorus status (right) in Norway (Bechmann 2014). Soil phosphorus status is expressed as mg P-AL/100g, the Norwegian standard soil test where phosphorus is extracted with 0.1 M ammonium lactate and 0.4 acetic acid adjusted to pH 3.75.**

Hamilton et al. (2017) have shown that manure alone could fulfil the Norwegian demand for phosphorus fertiliser. The yearly demand for phosphorus fertiliser was estimated to be 5800 ton year^{-1} when taking the existing plant-available soil phosphorus into consideration. Approximately 8400 ton phosphorus year^{-1} is applied as mineral fertiliser to agricultural land, in comparison to manure representing an estimated phosphorus amount of 12,000 ton year^{-1} (Hamilton et al. 2016). Still, the current total phosphorus accumulation in soil of 12,000 ton yr^{-1} is probably mainly due to over-application of manure in livestock-dense areas.

Transportation of manure from livestock dense areas to phosphorus deficient areas is one of the options to improve the utilisation of phosphorus in manure. However, since the water content in untreated cattle and swine manure is very high (4-8% and 8% dry matter on average, Daugstad et al. 2012), transportation of untreated manure over long distances is energy- and cost-intensive. There are different treatment technologies available to concentrate and separate nutrients in animal manure, including chemical, mechanical and biological technologies or a combination of these. The phosphorus fertilisation effect of untreated cattle and swine manure is usually assumed to be equally good as the fertilisation effect of mineral fertiliser (e.g. Larsen 1981; Tunney and Pommel 1987). Efficient phosphorus recycling requires therefore that concentrating and separating nutrients in manure into new recycling fertilisers does not reduce its high phosphorus fertilisation effect.

Even though treatment technologies for concentrating nutrients in manure have been under development for quite some time, e.g. in the Netherlands and Denmark, suitable treatment technologies have not yet been implemented on a large scale in Norway. The Norwegian fertiliser regulation is currently under revision, and the coming regulation is expected to impose further restrictions of phosphorus application rates per unit soil area to counteract the effect shown in Figure 1 (Norwegian Agriculture Agency 2018). Stricter regulations on phosphorus application rates per unit area will most likely encourage the development and application of transportable manure-based fertiliser products also in Norway.

The aim of this report is to review the main treatment technologies available for concentrating nutrients in animal manure, and to explore their effect on the phosphorus fertilisation effect of the produced manure-based recycling fertilisers as described in the literature. A comparison of the different treatment technologies in terms of operation costs or applicability to the Norwegian farm scale is not included in the report. We have chosen to focus on treatment technologies for cattle and swine slurry. Chicken manure has a naturally high dry matter content (33-50% dry matter, Daugstad et al. 2012). The same is the case for cattle and swine manure that is mixed with straw in-house (20% dry matter, Tveitnes et al. 1993).

2 Treatment technologies

During manure treatment and upgrading, as a first step, liquid manure is usually separated in a solid and a liquid fraction (see chapter 2.1). During solid-liquid separation, most of the phosphorus and organic nitrogen is commonly following the solid phase, whereas mineral nitrogen and potassium is mainly following the liquid phase. The liquid fraction is therefore well suited for direct application on fields in livestock-dense areas, where soil phosphorus statuses commonly are high. Also the solid fraction can be utilised directly e.g. after transportation to agricultural areas in need of phosphorus fertiliser, or further be treated by the treatment technologies described in chapter 2.2. Also solid manure (manure which is mixed with straw in-house) can be upgraded by treatment technologies presented in chapter 2.2.

2.1 Solid-liquid separation

The different mechanical treatment technologies to separate manure in a solid and liquid fraction include sedimentation, centrifugation, filtration without and filtration with pressure (Christensen et al. 2013).

Sedimentation is a rather cheap and simple technology to increase the dry matter contents of manure (Christensen et al. 2013). Sedimentation tanks have a conical shape. Manure is added batch by batch or continuously, the dry matter is settling by gravity, and the solids are removed from the bottom of the settling tanks. The dry matter content of the solid fraction is varying with the dry matter content of the manure. Approximately 55-57% of the dry matter in the original raw slurry will be collected in the solid fraction (separation index), and 41-57% of total phosphorus in the original raw slurry will be collected in the solid fraction. The dry matter content of the solid fraction is increasing with increasing sedimentation time.

Centrifugation is the most efficient mechanical treatment technology for separating dry matter and phosphorus in raw slurry in a solid and liquid fraction (Christensen et al. 2013). By increasing the gravitational force, settling time to achieve a satisfactory separation efficiency can be shortened and small particles can be removed that would not settle otherwise. The separation index of centrifugation is therefore somewhat higher compared with sedimentation, both for dry matter (60-63%) and total phosphorus (69-73%). At the same time, centrifugation results in a liquid fraction with a nearly ideal N:P:K ratio compared to crop demands for both cattle- and swine manure (Møller et al. 2007a). The downside of centrifugation is that both investment and operating costs are usually higher compared with simpler separation techniques.

Filtration without pressure comprises separation techniques that utilise screens or filters to drain the liquid fraction by gravity and retain the solid fraction (Christensen et al. 2013). The solid fraction is continuously removed by a belt separator. Filtration without external pressure results in 42-47% of the dry matter and 30-40% of the phosphorus in the original raw slurry ending up in the solid fraction. Similar to sedimentation, the dry matter content of the solid fraction is increasing with increasing drainage time.

Filtration with pressure is an attempt to increase the dry matter content in the solid fraction compared with filtration without external pressure (Christensen et al. 2013). Use of screw presses and press augers are examples for filtration with pressure. The dry matter content of the solid fraction is increased compared with filtration without pressure by compression of the cake. Even though the dry matter content of the solid fraction can be increased, the separation index for both dry matter and total phosphorus is decreasing (average separation index 35-38% and 14-20%, respectively), as small particles with particulate phosphorus are forced through the filter with pressure. Filtration with pressure is therefore the least efficient technique for separating phosphorus. Most of the phosphorus ends therefore up in the liquid fraction together with nitrogen and potassium. The advantages of filtration with pressure are a solid fraction with a high dry matter content and relatively quick separation.

In general, the separation efficiency of mechanical separators for removal of dry matter and phosphorus is ranked as follows: Centrifugation > sedimentation > filtration > pressurized filtration (e.g. Møller et al. 2007b; Hjorth et al. 2010).

Chemical pre-treatment with a flocculant or coagulant before mechanical separation can improve separation efficiencies significantly. Flocculants enhance the formation of aggregates of suspended solids and colloids, thus accelerating the settling of the smallest particles. There is a large variety of flocculants and coagulants. High-molecular weight, linear cationic polymers with a medium charge density (20-40 mol%) were found to be the most efficient flocculants to be used before mechanical solid-liquid separation of manure (Hjorth et al. 2010). In the study of Popovic et al. (2012), the highest separation indexes were achieved for polymer flocculation combined with drainage or ozonation combined with centrifugation. Up to 86% of the phosphorus originally contained in pig slurry can in theory be concentrated in the fibrous solid fraction, depending on the separation technique used (Popovic et al. 2012).

Growing (micro-)algae in liquid manure is another option to concentrate nutrients before further treatment (e.g. Mulbry et al. 2005; Franchino et al. 2016), however studies on this biological treatment process are still very few and the process and its effect on phosphorus availability is therefore not further elaborated in this report.

Electrocoagulation seems to be a promising technique to pre-treat manure before mechanical separation and to improve its settling properties (Zhang et al. 2018). Due to very few studies on the application of electrocoagulation on manure samples, this technology and its effect on the plant-availability of phosphorus in final products is not further elaborated in this report.

2.2 Upgrading of solid manure, or solid and liquid fractions of manure after mechanical separation

Following solid-liquid separation, unless utilised directly, the solid and liquid manure fractions can be treated and upgraded by a range of different technologies. Figure 2 gives an overview over the main technologies. In general, the different technologies can result in:

- Low technology products (e.g. organic fertiliser, compost amendment), or
- high technology products (e.g. mineral fertiliser products based on manure).

Short descriptions of the main technologies are given under in the sub-chapters of chapter 4 “Phosphorus fertilisation effects of manure-based recycling fertilisers”. For a detailed description and review of the various treatment technologies, the reader is referred to Jensen (2013).

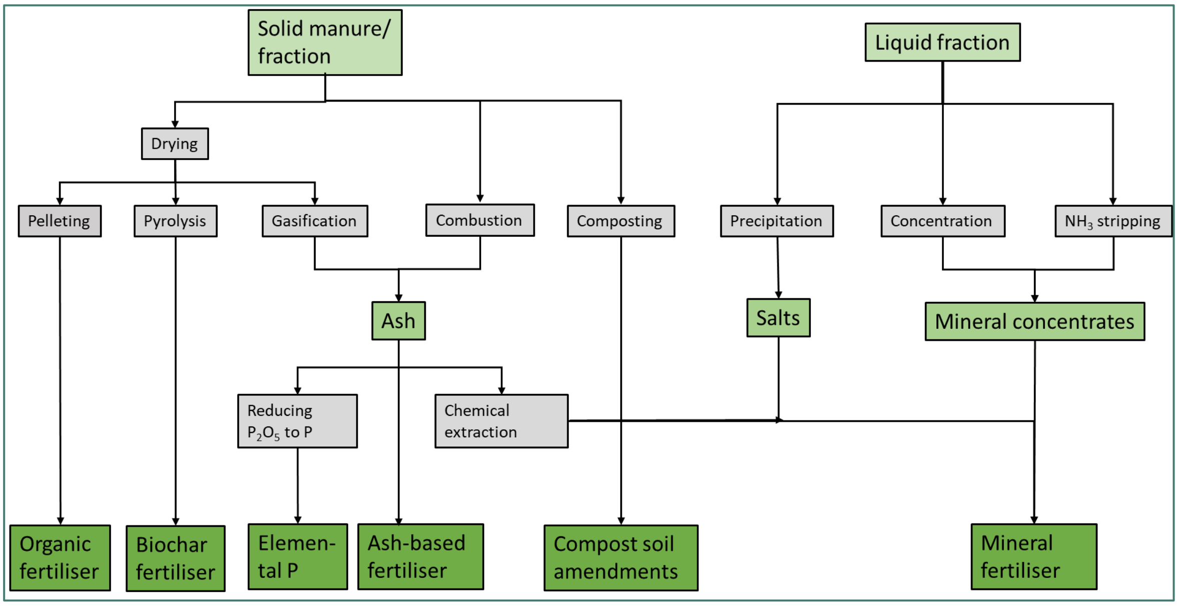

Figure 2. Schematic overview over possibilities to treat manure in order to upgrade recovered nutrients in recycling fertilisers (adapted according to Jensen 2013)

2.3 Anaerobic digestion

Even though anaerobic digestion is not a treatment technology, which can be used for concentrating nutrients in manure, it is mentioned here as it can affect the plant-availability of phosphorus in manure and manure-based recycling fertilisers (see chapter 4.4).

Animal manures are a considerable source of greenhouse gas emissions, mainly in the form of methane (CH_4) and nitrous oxide (N_2O) being formed through microbial activity during storage and application. Anaerobic digestion of animal manure is a way of reducing uncontrolled losses of greenhouse gas emissions by controlled fermentation of volatile organic components to methane, carbon dioxide (CO_2) and some hydrogen (H_2). Depending on the environment, anaerobic digestion can also reduce nitrous oxide emissions from field-applied manure (Sommer et al. 2013a). The produced biogas can replace fossile energy sources, and anaerobic digestion can hence help reducing undesired greenhouse gas emissions from agriculture. Anaerobic digestion of manure produces biogas, stabilises organic matter, and removes odour and pathogens (He et al. 2016).

In Norway, in 2008, a white paper was released proposing the aim to treat 30% of all animal manure by anaerobic digestion by 2020 to reduce greenhouse gas emissions from agriculture ("Klimautfordringene – landbruket en del av løsningen", Stortingsmelding nr. 39 2008-2009). Still, to date only 1% of animal manure is treated in anaerobic digestion plants (T. Sandberg in daily newspaper Dagsavisen, 13th of February 2018). Anaerobic digestion of animal manure is more common in EU-countries including Germany and Denmark (Holm-Nielsen et al. 2009).

Similar to untreated manure, anaerobically digested manure can be spread directly or separated in a liquid and a solid fraction by treatment technologies described in chapter 2.1 and further treated by technologies referred to in chapter 2.2. In centralised biogas plants, co-digestion of manure with easily-degradable organic waste is more common than digestion of manure alone, as animal manure has a quite low organic matter content and much of the organic matter is slowly degradable (Sommer et al. 2013b). Biogas production hence increases by co-digestion with e.g. food waste or fish sludge (Gebauer et al. 2016).

2.4 Acidification

Slurry acidification is neither a treatment technology which can be used for concentrating nutrients from animal manure. It is, however, mentioned here as it can affect plant-availability of phosphorus in manure and manure-based recycling fertilisers (see chapter 4.5).

Addition of acids to manure reduces the pH in manure and is an effective way to minimise ammonia (NH_3) volatilisation, but also methane (CH_4) emissions from manure during storage, separation and application (Petersen et al. 2012). Acidification has also been shown to delay nitrification and associated nitrous oxide emissions after field application (Sommer et al. 2013a). Slurry acidification by concentrated sulfuric acid to around pH 5.5 is currently mainly used in Denmark, where livestock farms meet very strict ammonia emission regulations. Application in other countries is scarce, and in Norway, acidification of slurry is not common.

3 Methods for determining phosphorus fertilisation effects

Phosphorus fertilisation effects of recycling fertilisers can be estimated by different methods. The methods growth experiments, incubations and chemical extractions are described below. None of these methods is standardized. For example, soils as experimental medium are varying and the results of different studies can therefore not be directly compared. Results have to be evaluated within the context of each study and in comparison, with the included reference treatments, rather than with the results of other studies.

3.1 Growth experiments

Growth experiments are the most reliable method for determining plant-availability of phosphorus in recycling fertilisers. Most studies describe pot experiments, which are conducted under controlled conditions and with nutrient-poor soil. Alternatively, field experiments can be conducted.

For evaluating phosphorus fertilisation effects in growth experiments, recycling fertilisers should be applied based on their total phosphorus contents equivalent to usual fertilisation rates per area. Further, all essential nutrients except phosphorus must be applied in sufficient amounts to ensure that only phosphorus is limiting to plant growth. Studies in which more nutrients than phosphorus were not applied, were not included in the literature review conducted here, as fertilisation effects in these cases cannot be solely ascribed to phosphorus availability in the recycling fertilisers. Usually, both biomass production and phosphorus concentration are determined, and phosphorus uptake in plants is calculated.

The fertilisation effect of recycling fertilisers in the reviewed studies was compared with a mineral fertiliser reference. Common reference fertilisers are triple superphosphate ($Ca(H_2PO_4)_2{\cdot}H_2O$), potassium phosphate (KH_2PO_4) or disodium phosphate (Na_2HPO_4). In addition, studies should include a control treatment without any phosphorus fertilisation to determine the contribution of soil phosphorus to plant uptake.

The relative fertilisation effects of recycling fertilisers (mineral fertiliser equivalents, MFE) is expressed as percent (%) of the effect of mineral fertiliser (Figure 3):

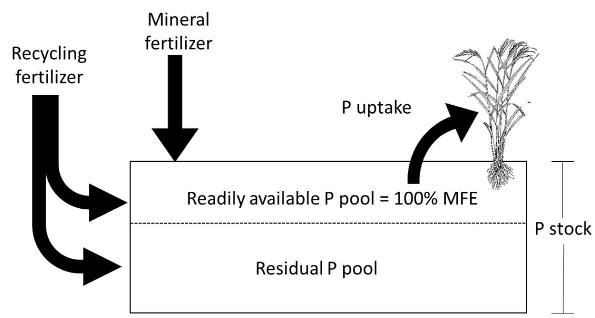

Figure 3. Conceptual drawing of mineral fertiliser equivalents adapted based on Hamilton et al. (2017)

It is the immediate effect of recycling fertilisers, which farmers will be most interest in (readily available phosphorus pool in Figure 3). In addition to the phosphorus, which is available to plants during the first growing season, some phosphorus in recycling fertilisers can become available with time (residual phosphorus pool in Figure 3). Phosphorus availability from the residual phosphorus pool is influenced by chemical and biological processes and soil processes as diffusion and mass flow. Long-term effects will therefore be dependent on the characteristics of the soil, to which the recycling fertiliser was applied.

Long-term fertilisation effects of recycling fertilisers can only be studied by cost-intensive, long-term growth experiments taking into account the main soil processes. These studies are very few, and no long-term studies were included in the literature review conducted here.

3.2 Incubations

Incubations are another widely used method for estimating the plant-availability of phosphorus in recycling fertilisers.

For incubations, recycling fertilisers are mixed with soil at usual fertilisation rates per area based on their total phosphorus contents and stored moist at a defined temperature. Soil samples are taken at given times and standard soil tests are conducted to estimate plant-available phosphorus as effect of the recycling fertiliser. The fertilised soils are compared with soil without phosphorus addition. Standard soil tests include chemical extractions (e.g. the Norwegian standard soil test P-AL) or sampling with diffusive gradients in thin films (DGT).

Incubations give good indications about the relative phosphorus solubility between different recycling fertilisers in soils and are less time-consuming and cost-intensive than growth experiments. However, incubations cannot be used to draw certain conclusions about the fertilisation effects of recycling fertilisers. Since incubations do not involve plants, which take up phosphorus and can release root exudates, their ability to reflect solubility of recycling fertilisers under equilibrium conditions in the presence of plants is limited.

3.3 Chemical extractions

Determining the solubility of phosphorus in recycling fertilisers by chemical extractions is another option to estimate the availability of phosphorus to plants.

For mineral fertilisers, chemical extractions have been used already since the 19th century to quickly determine the product's quality and it's solubility of phosphorus (Kratz et al. 2016). Standard chemical extractions for mineral phosphorus fertilisers include water, neutral ammonium citrate, citric acid and formic acid. Generally, chemical extraction methods have been developed and established on an empirical basis, and their development has been based on a large range of studies on the relationship between chemical phosphorus solubility in mineral fertilisers and the plant-availability of phosphorus in pot and field experiments.

With the emergence of recycling fertilisers of different origin, lately research has been conducted with the aim to identify chemical extraction methods which can be applied to this new type of fertilisers to determine their quality. Studies indicate that plant-availability of phosphorus in recycling fertilisers shows better relationships with weak extraction methods reflecting soil equilibrium processes such as water, iron-sink methods and Olsen-P, than with stronger extraction methods (Brod et al. 2015; Duboc et al. 2017). However, there are still few studies on the prediction of plant-availability of phosphorus in recycling fertilisers from chemical extractions, and therefore no certain conclusions can yet be drawn from the extractability of phosphorus in recycling fertilisers on their fertilisation effects.

4 Phosphorus fertilisation effects of manure-based recycling fertilisers

In the following, literature on the plant-availability of phosphorus in recycling fertilisers produced by different treatment technologies (Figure 2) will be reviewed. Products with only phosphorus compounds (elemental phosphorus in Figure 2) will not be covered as it cannot be applied directly to agricultural fields as recycling fertiliser. Elemental phosphorus compounds can be used as raw material e.g. in mineral fertiliser production or for other industrial purposes.

4.1 Manure-based organic fertilisers and composts

This chapter reviews the plant-availability of phosphorus in a range of different solid manure products produced by solid-liquid separation. Some of the products were further processed by composting or drying and/or pelleting. The reviewed studies on the phosphorus fertilisation effect of manure-based organic fertilisers or composts include products based on cattle or swine manure, also in combination with by-products such as food waste or cereal straw. The dry matter content in manure-based compost or organic fertiliser can vary between 15 and 100%.

In the study of Gasser et al. (2012), the plant-availability of phosphorus in eight different solid manure products was found to be comparable to the mineral phosphorus fertiliser reference (potassium phosphate) after 72 days of plant growth. The availability was studied in a pot experiment with oat (*Avena sativa* L.) and four soils with different phosphorus status. We calculated mineral fertiliser equivalents based on data presented in the paper on phosphorus uptake in aboveground biomass as average over the four soils. The studied products included six recycling fertilisers based on swine manure and two based on cattle manure:

- Swine manure, solid fraction after sedimentation at the bottom of an anaerobic digestor (33% dry matter, MFE = 85%)
- Swine manure, solid fraction after flocculation of digester effluent with polyacrylamide (separation technology not given), (32% dry matter, MFE = 94%)
- Swine manure, solid fraction after filtering by a rotary vacuum filter system made of diatomaceous earth (27% dry matter, MFE = 100%)
- Swine manure, solid fraction after sedimentation for two months in a storage tank (26% dry matter, MFE = 104%)
- Swine manure, solid fraction after flocculation with a mixture of polyacrylamide, soda ash and alum (separation technology not given), (24% dry matter, MFE = 94%)
- Swine manure, liquid swine manure composted with cereal straw (47% dry matter, MFE = 88%)
- Cattle manure, solid fraction after sedimentation for two months in a storage tank (15% dry matter, MFE = 97%)
- Cattle manure, solid fraction after filtration with pressure by screw press (55% dry matter, MFE = 102%)

In this study, only swine manure derived from anaerobic digestion tended to result in lower phosphorus uptake in plants compared with the other recycling fertilisers and mineral fertiliser. The reduced phosphorus fertilisation effect following anaerobic digestion might be due to the formation of calcium phosphates or struvite ($NH_4MgPO_4{\cdot}6H_2O$) during the treatment process (see also chapter

4.4). Also liquid swine manure composted with cereal straw tended to result in a somewhat lower phosphorus fertilisation effect compared with the other organic fertiliser products. Even though the overall phosphorus availability in all recycling products studied by Gasser et al. (2012) were comparable with the mineral reference fertiliser, their applicability as transportable manure-based recycling fertilisers is still limited due to low dry matter contents. The dry matter content was highest in the solid fraction of cattle manure after separation by a screw press (55% dry matter) and compost based on swine manure and cereal straw (47% dry matter). The solid fraction after sedimentation of cattle manure on the contrary contained only 15% dry matter.

Also, Kuligowski et al. (2010) compared the phosphorus fertilisation effects of organic manure-based recycling fertilisers. The study included:

- Swine manure, solid fraction after separating by a screw press before drying (MFE = 82%)
- Dried pellets from the solid manure fraction after centrifugation of anaerobically digested slurry from pig and cattle manure mixed with waste from the food processing industry (MFE = 114 – 155%)
- Anaerobically digested pig slurry which was co-digested with wastes from the food industry (MFE = 109%)

Kuligowski et al. (2010), too, found overall similar effects of manure-based organic recycling fertilisers as the mineral fertiliser reference (disodium phosphate), and there was no significant difference in the mineral fertiliser equivalents between the organic fertiliser products. Their dry matter content was not given, however is assumed to be high for the two dried products and else in the same range as for the products studied by Gasser et al. (2012). Fertilisation effects were studied by a pot experiment with pots which were pushed into soil outside and filled with a coarse sand or a sandy loam. The experimental crop was barley (*Hordeum vulgare*).

Christel et al. (2014) used chemical extraction methods (H_2O-extractable and DGT-soluble phosphorus after mixture with sand) to compare the phosphorus quality of manure-based recycling fertilisers produced by various treatment technologies. Five organic manure-based recycling fertilisers were included in the study:

- Solid fraction of anaerobic digestate (75% animal manure, mainly pig but also cattle, poultry and mink, and 25% organic waste from food industries) following centrifugation, 31% dry matter
- Mixture of the solid fraction of the anaerobic digestate with carbon-rich barley straw, 36% dry matter
- Mixture of the solid fraction of the anaerobic digestate with wood-chip char, 38% dry matter
- Compost of the mixture of the solid fraction of the anaerobic digestate with carbon-rich barley straw, 36% dry matter
- Compost of mixture of the solid fraction of anaerobic digestate with wood-chip char, 38% dry matter

In the solid fraction of the anaerobic digestate, approximately 15% of the total phosphorus was soluble in H_2O. The authors observed an increase of phosphorus solubility with both extraction methods, when barley straw or wood-chip char was mixed into the anaerobic digestate. However, since extractions were conducted for a fixed solid:solution ratio of 1:100 and the products mixed with bulking material had lower phosphorus concentrations compared with the untreated material, apparent increased phosphorus solubility might have been due to dilution of phosphorus in the solid and hence less phosphorus being extracted by the same extraction solution volume. Composting for 30 days decreased availability again, with a larger decrease with wood-chip char as bulking agent compared with straw. Christel et al. (2014) explain the negative effect of composting on phosphorus availability by immobilisation of phosphorus in microbial biomass, increasing adsorption of phosphate to binding sites present in the material mix or precipitation of phosphorus as immobile iron-phosphates. The study did not include a comparison of organic manure-based recycling fertilisers with mineral fertilisers, and direct conclusions on the fertilisation effects of the materials cannot be drawn from this laboratory study.

Christel et al. (2016) compared the effect of different mechanical separation technologies on phosphorus availability in organic manure-based recycling fertilisers using incubation in two different soils and DGT, and with triple superphosphate as mineral reference treatment. Their study included (dry matter content according to Sommer et al. 2015):

- Solid fraction of pig slurry following separation by a screw press, 27% dry matter
- Solid fraction of pig slurry following separation by a decanter centrifuge, 33% dry matter
- Solid fraction of pig slurry following drainage on a filter band separator after flocculation using polymers, 13% dry matter

The authors found that, overall, all organic manure-based recycling fertilisers included in their study increased soil phosphorus availability to a similar extent as the mineral reference treatment. However, centrifugation and filtration following chemical flocculation tended to result in higher phosphorus availability than separation by screw press. The authors explain the higher availability by a larger fraction of small particles in the solid fraction after centrifugation and filter separation following chemical flocculation compared with separation by a screw press. In manure, phosphorus is mainly bound in the smaller slurry particulate matter, which by screw presses is forced through the filter into the liquid fraction resulting in that larger particles and less soluble phosphorus is remaining in the solid fraction (see chapter 2.1). Even though the dry matter content in the fertiliser products was higher than in the original slurry (8-10% dry matter), it was still low in all manure-based recycling fertilisers included in the study (Sommer et al. 2015). The dry matter content was highest after centrifugation (33% dry matter) and lowest after filter separation following chemical flocculation (13% dry matter).

Summary

Overall, the reviewed literature indicates that mechanical separation of manure in a liquid and a solid fraction do not reduce the good phosphorus fertilisation effects of manure. Separation by screw presses, however, might result in a product with somewhat lower phosphorus fertilisation effects compared with the product from centrifugation. The flocculants or coagulants used in the reviewed studies did not reduce phosphorus fertilisation effects. There are, however, indications that the biological treatment technologies such as anaerobic digestion and composting can reduce phosphorus fertilisation effects of manure. Dry matter contents of mechanical separated manure products without further treatment are in general still quite low. Only one study was found including dried and pelleted manure-based recycling fertilisers, and in this study, these products showed similar phosphorus fertilisation effects as the mineral reference fertiliser.

4.2 Manure-based ashes and biochars

In this chapter, literature on the phosphorus availability in manure-based recycling fertilisers produced by thermal treatment including combustion and gasification (ash-based fertilisers) or pyrolysis (biochar fertilisers) is reviewed. During gasification, material is reacting at high temperatures (> 700 °C) into carbon monoxide, hydrogen and carbon dioxide and a gasification ash under controlled presence of oxygen and/or steam. Pyrolysis differs from combustion in that it happens in the absence of oxygen and results in a biochar. Advantages of combustion, gasification and pyrolysis as treatment technologies for manure include distinct volume reduction, recovery of energy, removal of pathogens and odour, increased chemical stability and increased phosphorus concentration compared with the original feedstock. However, the majority of nitrogen will be lost during thermal treatment.

Christel et al. (2014) systematically studied the effect of increasing process temperatures on phosphorus availability over time in biochar and ash based on pig slurry. Phosphorus availability in biochars and ashes was studied by chemical extractions (citric acid-extractable, H_2O-extractable, and DGT-extractable phosphorus after mixture with sand) or by extraction with DGT after incubation in three soils for six weeks. The study included:

- 8 biochars based on the solid fraction of pig slurry after centrifugation and drying, pyrolysed at 300, 400, 500, 600, 700, 800, 900 and 1000 °C
- 8 ashes based on the solid fraction of pig slurry after centrifugation and drying, incinerated at 300, 400, 500, 600, 700, 800, 900 and 1000 °C

The results indicate a general decrease of phosphorus availability in thermally treated manure compared with untreated manure. The authors concluded that both incineration and pyrolysis will result in slow-release fertilisers rather than in effective substitutes for mineral reference fertilisers. The decrease in phosphorus availability tended, however, to be more pronounced for the ashes compared with the chars. Comparing all manure-based recycling fertilisers included in the study, phosphorus availability was found to decrease with increasing degree of processing in the order: drying > composting > pyrolysis > combustion. When it comes to availability of phosphorus in soil over time, the immediate availability was highest in pig slurry without thermal treatment, however decreased quickly with time. Phosphorus availability in ash and biochar on the contrary increased slightly with time mainly in the two acid soils (sandy soil with pH 5 and loamy sand with pH 5) but also in the neutral soil (sandy loam with pH 7). Differences between phosphorus availability in soils with incubated untreated manure and ash and biochar were therefore negligible after six weeks.

Similar results were obtained in the study of Christel et al. (2016), which compared the phosphorus availability in:

- Biochar based on the solid fraction of pig slurry after centrifugation and drying, pyrolysed at 400 and 600 °C
- Biochar based on the solid fraction of pig slurry after acidification with sulphuric acid (H_2SO_4) to pH 5.5, centrifugation and drying, pyrolysed at 400 and 600 °C
- Ash based on the solid fraction of pig slurry after centrifugation and drying, incinerated at 625°C
- Ash based on the solid fraction of pig slurry after acidification with sulphuric acid (H_2SO_4) to pH 5.5, centrifugation and drying, incinerated at 625°C

The products were incubated in sandy loam (pH 7.2) and sandy soil (pH 5.1) for 12 weeks, and phosphorus availability was determined by DGT several times during the experiment. Also Christel et al. (2016) concluded that thermal treatment results in biochar and ash-based fertilisers with lower phosphorus availability compared with untreated pig slurry, especially shortly after incorporation to soil. However, in accordance with the study of Christel et al. (2014), after six and twelve weeks, incubated biochar and ash-based fertiliser resulted in equally high phosphorus availability as the untreated solid fraction of pig slurry or the mineral reference fertiliser (triple superphosphate). In contrary to the study of Christel et al. (2014), in 2016, the authors found no significant difference in the availability of phosphorus after pyrolysis and combustion.

Bruun et al. (2017) support the results of Christel et al. (2014) and (2016) by a study on the effect of pyrolysis on phosphorus compounds in biochar. The study was conducted with 6 biochars produced of the solid fraction of digestate based on 75% animal slurry from pig and dairy farms and 25% waste from the food industry. The digestate was pyrolysed after centrifugation and drying at 300, 450, 600, 750, 900 and 1050 °C. Their results explain the decreasing availability of phosphorus in biochars with increasing pyrolysis temperatures, and poor immediate availability of phosphorus in biochars produced at high temperatures. The authors found that the primary phosphorus species in the untreated solid fraction of pig slurry were simple calcium phosphates. Additionally, the presence of struvite ($NH_4MgPO_4{\cdot}6H_2O$) and other magnesium phosphates is likely. At low temperature (<600°C), pyrolysis had little effect on the phosphorus compounds in biochar. During pyrolysis at temperatures > 600°C, however, phosphorus compounds were transformed to stable calcium phosphates such as apatite. At temperatures > 1000 °C also reduced phosphorus forms were likely to be present in the biochar. The study utilized the combination of X-ray photoelectron spectroscopy (XPS), scanning electron microscopy (SEM) as well as XANES spectroscopy at the K- and L-edges for the speciation of phosphorus. The results were combined with an incubation of the recycling fertilisers in two soils, in order to study their phosphorus availability by the application of DGT devices.

Also Thygesen et al. (2011) studied the effect of increasing incineration temperatures on the phosphorus compounds and on the plant-availability of phosphorus in ash produced of various manure products. The authors estimated plant-availability of phosphorus by chemical extraction with neutral ammonium citrate. The study included:

- Pig manure separated in a laboratory centrifuge.
- 5 products based on pelleted, degassed manure. Addition of polymers before separation (separation technology not given). 87% dry matter or incinerated at 400, 700, 900 or 1050°C.
- 5 products based on pig manure, untreated mixture of faeces and straw. 18% dry matter or incinerated at 400, 700, 900 or 1050°C.
- 5 products based on mixed, degassed manure, separated by decanting centrifuge. 34% dry matter or incinerated at 400, 700, 900 or 1050°C.

The study indicated decreasing availability of phosphorus with incineration temperatures > 400°C. At the same time, crystallization of the ash-based fertilisers and the presence of hydroxyapatite increased with increasing incineration temperatures. Crystalline compounds in the ashes were identified by XRD. Based on their results, the authors suggest that incineration temperatures should be kept below 700°C to ensure high plant-availability of phosphorus in manure-based ashes. Since energy production, however, is optimal at temperatures above 800°C, the authors suggest thermal gasification as an alternative treatment.

Siegel et al. (1977) studied the effect of incineration and acidification (H_2SO_4) alone and in combination on the availability of phosphorus during two pot experiments with corn (*Zea mays* L.) and a phosphorus-deficient soil. Their experiments included 14 manure-based recycling fertilisers:

- 2 ashes based on beef manure, 50% or 100% of base equivalent acidified before incineration
- 3 ashes based on dairy manure, 0%, 50% or 100% of base equivalent acidified before incineration at 550°C. Also air-dried dairy manure.

- 3 ashes based on chicken manure, 0%, 50% or 100% of base equivalent acidified before incineration at 550°C. Also air-dried chicken manure.
- 3 ashes based on swine manure, 0%, 50% or 100% of base equivalent acidified before incineration at 550°C. Also air-dried swine manure.

The results indicate that phosphorus availability in air-dried manure was somewhat lower than in the mineral reference treatment (concentrated superphosphate). Incineration further decreased phosphorus availability compared with drying, whereas acidification increased availability with increasing acidification.

Also Møller et al. (2007b) propose that the plant-availability of phosphorus in incineration ash of pig manure is low. This is proposed based on sequential fractionation of phosphorus, suggesting that approximately 80% of phosphorus in the studied manure-based bottom ash is present as stable calcium phosphates such as apatite.

In the study of Tran et al. (2018), incineration ash of composted cattle manure resulted in equally high yields of Guinea grass (M*egathyrsus maximus*) as the mineral reference treatment ($Ca(H_2PO_4)\cdot 2H_2O$) during a pot experiment with a sandy soil (pH 7.8); phosphorus uptake, however, was significantly lower in plants fertilised with the manure ash compared with the mineral reference fertiliser.

In the contrary to the above reviewed literature, the study of Kuligowski et al. (2010) suggested overall similar total phosphorus uptake in barley following application of thermally treated manure and the mineral reference fertiliser (disodium phosphate). However, the results of the study have to be evaluated with caution as triple superphosphate resulted in > 200% of the total phosphorus uptake compared with the disodium phosphate reference. This might indicate that plant growth in the experiments of Kuligowski et al. (2010) was limited by sulphur availability even though sulphur and all other essential nutrients except phosphorus were given at a level sufficient for optimal growth, according to the authors. The following ash-based fertilisers were applied in pot experiments outside to sandy soils at equal phosphorus rates:

- Incinerated solid fraction of anaerobically digested slurry from pig and cattle manure mixed with waste from the food processing industry, after drying and pelleting. MFE = 51-123% (application in two pot experiments)
- Thermally gasified solid fraction of anaerobically digested slurry from pig and cattle manure mixed with waste from the food processing industry, after drying and pelleting. The input material was gasified in a circulating fluidized bed gasifier at a temperature of up to 730°C. MFE = 11-34 and 99-117% (application at two fertilisation rates in two experiments)
- Thermally gasified dried fraction of separated pig slurry. MFE = 95%
- Thermally gasified poultry manure. MFE = 111%

Only application of a triple load of untreated ash from thermally gasification of the solid digestate resulted in very poor phosphorus uptake in barley plants (mineral fertiliser equivalent = 11%). The authors could give no comprehensible reason for this observation. The study did not include a speciation of phosphorus in the different recycling fertilisers, which could explain the variation of fertilisation effects. Ash-based recycling fertilisers derived both from gasification and incineration processes were studied. However, the results do not indicate a difference in phosphorus availability between ash from gasification and from combustion. This might indicate that the method of thermal treatment has little influence on availability of phosphorus in the ash.

Summary

In summary, the reviewed literature indicates that thermal treatment clearly reduces the phosphorus availability in manure-based recycling fertilisers compared with untreated manure. The reduction in availability is higher, the higher the temperature which is used in the thermal treatment. There are indications that incineration and gasification reduce phosphorus availability to a larger degree than pyrolysis. During thermal treatment simple phosphate compounds in manure seem to be transformed into more complex minerals, such as hydroxyapatite.

4.3 Manure-based mineral fertilisers

Manure-based mineral fertilisers include a variety of products including salts e.g. struvite ($NH_4MgPO_4{\cdot}6H_2O$) and calcium phosphates, or acid extracts and their derivatives.

In the study of Liu et al. (2011), the effect of struvite derived from swine wastewater was compared with the effect of superphosphate and urea given at equal rates of phosphorus and nitrogen during a pot experiment with maize (*Zea mays* L.) and a sandy loam as experimental soil. Based on biomass production (height and stem circumference), the authors suggest that phosphorus in the struvite was equally available to plants as phosphorus in the mineral reference fertiliser. Phosphorus uptake in plants was, however, not analysed. The study further indicated that emissions of nitrous oxide (N_2O) can be clearly reduced, when struvite is used as fertiliser instead of urea.

In the study of Johnston and Richards (2003), the phosphorus fertilisation effect of eleven different phosphorus salts mainly derived from municipal wastewater was compared with the effect of monocalcium phosphate used as mineral reference fertilisers. The study also included a K-struvite ($KMgPO_4{\cdot}6H_2O$), which was derived from a veal manure. Phosphorus effects were studied during two pot experiments with ryegrass (*Lolium perenne*), which was harvested six times, and a sandy loam or a sandy clay loam as experimental soils. All phosphorus salts included in the study showed equally good effects measured as dry matter production and phosphorus uptake as the mineral reference fertiliser (monocalcium phosphate), including the manure-based K-struvite.

Even though studies on the phosphorus fertilisation effects of manure-based struvites are rather limited, a range of studies has been conducted on struvites from other origins during the past years. Overall, the conducted studies indicate that struvite is slowly releasing phosphorus compared with mineral reference fertilisers (e.g. Talboys et al. 2016), and that its effect is decreasing with crystal size and stability.

Achat et al. (2014) studied the phosphorus fertilisation effects of four mineral recycling fertilisers derived from pig manures. The recycling fertilisers were produced through a chemical precipitation process and contained 60% of the initial phosphorus of the pig slurry in the form of struvite and an amorphous calcium phosphate (Daumer et al. 2013). Pig manure was acidified before addition of a polymer and filtration. The liquid fraction of the acidified pig manure was then mixed with MgO before the precipitated minerals settled and accumulated at the bottom of the reactor. The recycling fertilisers still contained between 2 and 3 % organic carbon, which according to the authors probably delayed the crystallisation process of the minerals. Plant-availability of phosphorus in the products was determined by a pot experiment with a phosphorus deficient and slightly acidic soil (pH 6.5) and a gras mixtures (40% *Lolium perenne*, 60% *Festuca rubra*) as experimental crop, as well as an incubation experiment. Achat et al. (2014) found that the phosphorus in all four recycling fertilisers was as available as phosphorus in the mineral reference (triple superphosphate). Mineral fertiliser equivalents were 80-107% compared with triple superphosphate (calculated based on data on phosphorus uptake presented in the paper). The authors concluded based on their study that commercial mineral fertilisers can be substituted by recycling fertilisers produced from pig manures.

Also the study of Kuligowski et al. (2010) included two manure-based mineral fertilisers:

- Neutralised acid extract from gasified ash of the solid fraction of anaerobically digested slurry from pig and cattle manure mixed with waste from the food processing industry, derived by centrifugation before drying and pelleting (see chapter 4.2). Phosphorus was extracted by sulphuric acid (H_2SO_4) before neutralisation with potassium hydroxide (KOH).
- Dried neutralised acid extract (drying for 24 hours at 105°C)

Kuligowski et al. (2010) found in their pot experiment with barley that the mineral fertiliser equivalent of the neutralised acid extract was as high as 73-94%, whereas the mineral fertiliser equivalent of the dried neutralised acid extract was as low as 15-55% compared with the mineral reference fertiliser (disodium phosphate). The study did not include a speciation of phosphorus in the two mineral recycling fertilisers, which might have explained the variation of fertilisation effects, and the poor fertilisation effect of the dried ash extract. Also the whole growth experiment might have been limited by sulphur availability as explained in chapter 4.2, and results therefore have to be evaluated with caution. Here, total phosphorus recovery from the ash in the acid extract was only 19% after neutralisation, however could be increased to up to 50% according to the authors, if all the extract was separated from the ash by centrifugation.

Summary

Even though only few studies on the phosphorus fertilisation effect of manure-based mineral fertiliser products could be found, we can conclude that the phosphorus fertilisation effect of manure-based mineral fertilisers will vary strongly with the mineral compounds present in the end-product. Also, there are indications that the phosphorus fertilisation effects of mineral salts (e.g. struvite, $NH_4MgPO_4 \cdot 6H_2O$) will decrease with an increasing degree of crystallinity. Manure-based mineral fertilisers vary in the degree to which phosphorus is recovered in the end product.

4.4 Effects of anaerobic digestion on plant-availability of phosphorus

Studies on the effect of anaerobic digestion on phosphorus fertilisation effects of manure and manure-based recycling fertilisers without co-digestion are limited. To our knowledge, so far no study has directly compared the phosphorus fertilisation effects of recycling fertilisers based on anaerobically digested manure with the phosphorus fertilisation effect of untreated manure of the same origin.

The study of Gasser et al. (2012) included two products, which had undergone anaerobic digestion, both of which resulted in somewhat lower phosphorus uptake in plants compared with the other recycling fertilisers and mineral fertiliser. Both products had comparatively high Ca and Mg contents. The authors assumed therefore that reduced phosphorus availability could be due to the formation of calcium phosphates or struvite ($NH_4MgPO_4 \cdot 6H_2O$) during the treatment process.

Pagliari and Laboski (2013) used sequential fractionation to compare the phosphorus solubility in undigested manure, mesophilically digestated manure and separated manure after mesophilic digestion. They concluded that anaerobic digestion did not affect the distribution of phosphorus in manure compared with the undigested raw manure from the same system. Most of the phosphorus was soluble in the first two steps of the fractionation (extraction with H_2O and 0.5 M $NaHCO_3$) both in raw and digested manure. The authors also studied phosphorus solubility in the same products by chemical extraction after incubation in 5 soils, and found no effect of anaerobic digestion on the soil phosphorus tests Bray-1 and Mehlich-3.

Also, the knowledge on phosphorus forms in anaerobically digested manure is limited (Bruun et al. 2017). In pig and cattle manure phosphorus is mainly present as simple calcium- and/or magnesium phosphates. Bruun et al. (2017) hypothesize, therefore, that the effect of anaerobic digestion on the availability of phosphorus in manure and in manure-based recycling fertilisers is limited, since calcium unlike e.g. iron is not redox sensitive.

Summary

There are few studies on the effect of anaerobic digestion on phosphorus availability in manure-based recycling fertilisers and existing studies are inconclusive. Some hypothesise that previously soluble phosphates in manure might be precipitated as salts during the digestion process, whereas others hypothesise that calcium- and/or magnesium phosphates, which phosphorus in manure mainly is present as, are not redox sensitive and that anaerobic digestion will have no effect on the solubility of phosphorus in manure.

4.5 Effects of acidification on plant-availability of phosphorus

In general, studies indicate that acidification will increase the fraction of dissolved phosphorus in manure. In the study of Pedersen et al. (2017), lowering the pH to 5.5 and 3.8 by addition of sulphuric acid (H_2SO_4) dissolved between 70-80% of the total phosphorus in cattle slurry. In the study of Fordham and Schwertmann (1977), lowering the pH by addition of hydrochloric acid (HCl) dissolved phosphorus in cattle slurry mainly from calcium phosphates. In the study of Christensen et al. (2009), pH in pig slurry was adjusted by addition of perchloric acid ($HClO_4$) and phosphorus was released mainly from struvite.

Pedersen et al. (2017) also compared the phosphorus fertilisation effect of untreated, moderately and strongly acidified cattle slurry in a pot experiment with maize and a coarse sandy soil or a sandy loam as experimental soils. The study indicated that phosphorus uptake was higher in plants fertilised with acidified manure. However, this effect could have been both due to dissolution of inorganic phosphorus in the manure or due to the associated pH decrease in the soil and solubilisation of soil phosphorus. Moderately acidified slurry (pH 5.5) decreased soil pH by more than one pH unit both in the coarse sandy soil (initial soil pH 6.3) and in the sandy loam soil (initial soil pH 6.5).

Acidification does not only affect chemical but also physical properties of manure, and seems therefore to have subsequent effects on the following solid-liquid separation. In the study of Hjorth et al. (2015), an increase of larger particles could be observed, which was explained by a reduced negative charge of particles and consequently aggregation of minor organic and inorganic compounds. It was assumed that this effect could influence solid-liquid separation; however, the effect of acidification on solid-liquid separation was not evaluated in this study. In the study of Sommer et al. (2015) acidification of pig slurry with H_2SO_4 to pH 5.5 had a negative effect on the separation index of dry matter of both a screw press, drainage with a filter band following flocculation using polymers and a decanter centrifuge. The study of Sommer et al. (2015) suggests further that dissolution of phosphorus by acidification will result in an increased concentration of ortho-phosphate in the liquid fraction after separation. Based on the study of Sommer et al. (2015), Christel et al. (2016) propose that the solid fraction will contain less total phosphorus and that the retained phosphorus is likely to be organic phosphorus and inorganic phosphorus in insoluble forms. Also Cocolo et al. (2013) found an increased volume of the liquid fraction following screw pressing, decanter centrifugation or flocculation and belt thickener drainage. Approximately 30% less of the total phosphorus and 10% less of dry matter was transferred to the solid fractions after acidification compared with the untreated control manure.

Studies on the effect of acidification on plant-availability of phosphorus in the solid fraction of manure after separation by different techniques are few. The study of Christel et al. (2016) indicates however that plant-availability of phosphorus following acidification varies with the separation technique that is applied to the manure. In their study, Christel et al. (2016) compared the solubility of phosphorus in untreated and acidified pig slurry (addition of H_2SO_4 to pH 5.5) after solid-liquid separation by different techniques. Incubation studies and extraction by DGT indicated that phosphorus solubility in the solid fractions of pig slurry after separation by screw press or chemical flocculation and drainage was higher when the slurry previously had been acidified compared to untreated slurry. Phosphorus solubility in the solid fraction after centrifugation, however, was lower when the slurry previously had been acidified compared to untreated slurry. The authors hypothesize that this unexpected result might have been due to significant increases in particle size in acidified slurry, which facilitated the separation especially by centrifugation but resulted in a coarser solid fraction with lower phosphorus content mainly being present in organic or insoluble inorganic forms. The authors emphasize that it cannot be concluded from their study whether differences between acidified and non-acidified solids are due to phosphorus solubility or difference in soil pH.

Summary

The reviewed studies show that acidification increases the fraction of dissolved phosphorus in manure. Therefore, it is likely that acidification will increase the phosphorus fertilisation effect of manure. Acidification is not only affecting chemical but also physical manure properties, and the reviewed literature indicates that acidification reduces separation efficiencies for both dry matter and phosphorus. In accordance, phosphorus availability in the solid fractions of manure after acidification will probably be higher compared with untreated manure, as dissolved ortho-phosphate is following that solid phase due to the reduced separation efficiency.

5 Conclusions

A wide range of treatment technologies is available for concentrating and separating phosphorus from animal manure in transportable manure-based recycling fertilisers. Available technologies include chemical, mechanical and biological treatment or a combination of these. In this report, the main treatment technologies have shortly been presented, and their effect on plant-availability of phosphorus in the manure-based recycling fertilisers has been evaluated.

The effects of the different treatment technologies on phosphorus availability in the end-product can be summarised as follows:

- In general, there are no indications that mechanical separation of manure in a solid and a liquid phase results in a solid phase with lower plant-availability of phosphorus than in the original manure.
- Mechanical separation of manure by screw presses can, however, result in a solid phase with somewhat lower plant-availability of phosphorus compared with separation by centrifuges, because the most available phosphorus fraction follows the liquid phase.
- The flocculants or coagulants used in the reviewed studies did not reduce plant-availability of phosphorus in the solid phase compared with the original manure.
- There are indications that biological treatment by composting can decrease plant-availability of phosphorus in the compost.
- Studies on the effect of anaerobic digestion on the plant-availability of phosphorus in manure and manure-based recycling fertilisers are few and inconclusive. Some studies suggest that anaerobic digestion decreases plant-availability of phosphorus in the digestate compared with untreated manure, whereas others suggest that anaerobic digestion has no influence on plant-availability of phosphorus.
- Thermal treatment of manure (incineration, gasification or pyrolysis) decreases plant-availability of phosphorus in the end-product, and the decrease is larger for higher process temperatures. There are indications that phosphorus solubility is reduced to a larger degree in ash (incineration and gasification) than in biochar (pyrolysis).
- The phosphorus fertilisation effect of manure-based mineral fertilisers will vary strongly with the mineral compounds present in the end-product, and the degree of crystallinity of phosphorus salts.
- Acidification increases the fraction of dissolved phosphorus in manure. At the same time, there are indications that acidification has negative effects on the separation indexes of mechanical separation techniques (both dry matter and phosphorus). In general the solubility of phosphorus in the solid fraction of separated manure seems to be increased by acidification, with the exception of centrifugation.

This report shows that there are several technologies in place to facilitate re-distribution of phosphorus in manure for more resource-efficient phosphorus management, without having negative effects on the good phosphorus fertilisation effect of manure.

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NIBIO
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