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Report of SuMaNu platform

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NATURAL RESOURCES INSTITUTE FINLAND

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Preface

This report was produced in the Interreg Baltic Sea Region platform project SuMaNu (Sustainable Manure and Nutrient Management for reduction of nutrient loss in the Baltic Sea Region; www.balticsumanu.eu). The project aims to formulate and promote recommendations for more sustainable manure and nutrient management practices in agriculture and thus decrease agricultural nutrient loads to the Baltic Sea. The recommendations are targeted to a wide range of target groups from farmers to policy makers.

SuMaNu promotes the value of manure as a resource for nutrients and organic matter for crop production while also stressing that fertilization and manure use should be optimized to reduce nutrient loss to air and waters. Increased manure nutrient use efficiency will decrease the need for mineral fertilizers and enhance carbon sequestration into soil.

Work package 2 (led by RISE) synthesized knowledge on sustainable manure nutrient management practices at farm and regional level from the projects that have built the SuMaNu platform. These projects include recent Baltic Slurry Acidification, Manure Standards, GreenAgri and BONUS PROMISE, and also previous Interreg Baltic Sea Region funded projects (Baltic Manure, Baltic Deal, Baltic Compass, Baltic Compact). WP2 also analyzed manure processing as a pathway to enhance nutrient recycling in the Baltic Sea Region.

Manure can be processed into recycled fertilizer products using different technologies. Depending on the technology used, also renewable energy can be simultaneously produced. The aim can be to enhance farm level nutrient use or to reallocate nutrients regionally from surplus regions to those in deficit. This also determines the level of processing: simpler technologies are used on farm scale, while in large processing plants the processing chains may include several technology steps and produce a number of different products. In this report, the need, state-of-the-art and potential for manure processing is discussed including description of currently available technologies.

June 2020,

Minna Sarvi, Coordinator
Natural Resources Institute Finland (Luke)

Summary

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Circular economy is increasingly demanded across the world to minimize the need for non-renewable sources of materials and energy. The need to introduce new nutrients into the current demand from mineral resources could be reduced significantly via nutrient recycling. This means recovery of nutrients from different nutrient-rich side-streams and their reuse in different measures, the most significant being food production. Nutrients, especially phosphorus (P) and nitrogen (N), are vital for crops to grow. The amounts required as fertilizer products are large. Still, at the time of writing nutrients are not effectively recycled, but a significant share is lost as final disposal and emissions.

Recyclable nutrients are available in different side-streams from agriculture, municipalities and industry. The most significant recyclable material is animal manure which is traditionally used as a fertilizer. However, due to segregation of crop and animal production, manure is often regionally concentrated so that its nutrients may be available in excess to the region’s need. This may result in excessive use of manure in the regions of concentrated animal production, while the crop producing regions need to rely on mineral fertilizers. Both have negative environmental consequences.

Thus, solutions for regional manure reallocation via improving the transportability of manure are needed to reallocate the nutrients to areas in nutrient deficit. To enable such transportation over long distances and to separate P and N from each other and thus enhance their reuse, manure processing could be used.

Manure can be processed with different technologies providing various end-products. The aim of processing is usually to reduce the mass of manure and to concentrate nutrients to improve their transportability. An important aim is also to produce such fertilizer products that replace mineral fertilizers and provide reduced emissions into the environment. Several processing technologies are available and more are being developed.

At the time of writing, manure processing is still limited mainly due to challenges with profitability. The investment into large-scale manure processing as required by regional nutrient reallocation is significant and the market for the novel manure-based fertilizer products is only starting to develop. Development of practices for the storage and spreading of the products is also still required.

In this report, examples of regions in need of nutrient reallocation via manure processing are described for the Baltic Sea Region and the potential and challenges of manure processing as one solution to reduced nutrient emissions discussed. Summaries of available processing technologies and their end-products as fertilizer products are also presented.

Keywords: circular economy, fertilizer product, manure, nutrient recycling, processing

Tiivistelmä

Kiertotalouden käyttöönottoa vaaditaan enenevästi ympäri maailmaa uusiutumattomien materiaalien ja energian käytön vähentämiseksi. Mineraalisten ravinteiden tarvetta ja käyttöä voitaisiin vähentää ravinteita kierrättämällä. Tämä tarkoittaisi ravinteiden talteenottoa erilaisista ravinnepitoisista sivuvirroista ja muodostuvien ravinnetuotteiden käyttöä erilaisissa toimissa, suurimpana käyttäjänä ruuantuotanto. Ravinteet, etenkin fosfori ja typpi, ovat välttämättömiä kasvien kasvulle, ja lannoitteina tarvittujen ravinteiden määrät ovat suuret. Siitä huolimatta tätä kirjoitettaessa ravinteet eivät kierrä tehokkaasti, vaan merkittävä osuus niistä päätyy hävikkinä loppusijoitukseen tai päästöinä ympäristöön.

Kierrätettävissä olevia ravinteita on erilaisissa maatalouden, yhdyskuntien ja teollisuuden sivuvirroissa. Merkittävin kierrätettävä materiaali on kotieläintuotannon lanta, jota perinteisesti jo hyödynnetään lannoitteena. Kasvin- ja kotieläintuotannon eriytymisen vuoksi lanta kuitenkin keskittyy monin paikoin alueellisesti siten, että sitä on liikaa saman tuotantoalueen ravinnetarpeeseen nähden. Tämä voi johtaa liialliseen lantaravinteiden levitykseen kotieläintuotannon alueella, kun samalla kasvintuotannon alueilla joudutaan käyttämään mineraalilannoitteita. Molemmilla on negatiivisia ympäristövaikutuksia.

Näin ollen ratkaisua lannan alueelliseen uusjakoon tarvitaan parantamalla lannan kuljetettavuutta ja siten siirtoa ylijäämäalueilta ravinteita tarvitseville alueille. Pitkänkin kuljettamisen mahdollistamiseksi sekä lannan fosforin ja typen erottelemiseksi ja niiden käytön tehostamiseksi lantaa voidaan prosessoida.

Lannan prosessointiin on erilaisia teknologioita, jotka tuottavat monenlaisia lopputuotteita. Prosessoinnin tavoite on yleensä lannan massan vähentäminen ja ravinteiden väkevöiminen kuljetettavuuden parantamiseksi. Tärkeä tavoite on tuottaa käyttökelpoisia kierrätyslannoitevalmisteita, joilla voidaan korvata mineraalilannoitteita ja vähentää ruuantuotannon päästöjä ympäristöön. Monenlaisia prosessointiteknologioita on tarjolla ja lisää kehitetään.

Tätä kirjoitettaessa lannan prosessointi on varsin vähäistä pääasiassa sen heikon kannattavuuden vuoksi. Investointikustannus lannan suuren mittakaavan prosessointiin on merkittävä, ja markkinat kierrätyslannoitevalmisteille vasta alkamassa kehittyä. Myös valmisteiden varastoinnin ja levityksen ratkaisuja on vielä kehitettävä.

Tässä raportissa kerrotaan esimerkkejä Itämeren maiden alueista, joilla lannan alueellista uusjakoa tarvitaan ja joilla lannan prosessoinnista voitaisiin hyötyä. Lisäksi arvioidaan lannan prosessoinnin mahdollisuuksia ja haasteita ravinteiden kierrätyksen ratkaisemisessa. Raportti sisältää myös tiivistelmiä tarjolla olevista prosessointiteknologioista ja kuvaa niistä muodostuvia kierrätyslannoitevalmisteita laatuineen ja käyttömahdollisuuksineen.

Contents

1. Introduction

Circular economy is increasingly demanded across the world to minimize the need for non-renewable sources of materials and energy. European Union launched an Action Plan for the Circular Economy in 2015 (COM/2015/0614 final, update COM/2020/98 final) and the work towards improved reuse of materials has increased. During the recent years, EU funding instruments have supported research and innovation towards improved circular actions and one of the emerging important issues is nutrient recycling.

Nutrients, especially phosphorus (P) and nitrogen (N), are vital for food production and are given to crops as fertilizers to enhance growth. The amounts required are large. The total external inputs of nitrogen to EU cropland and livestock production/agricultural food system were approximately 17 Mt/year in 2004, consisting of mineral fertilizers (11 Mt), imported feed (2.7 Mt), and other sources, such as atmospheric deposition and N-fixation (Leip et al. 2014). The total external phosphorus input was 1.8 Mt, consisting of mineral fertilizers (1.4 Mt) and imported feed (0.4 Mt; van Dijk et al. 2016).

Of the total nutrient flow in the EU, however, only 20% of nitrogen is estimated to reach the consumers in the form of food products, while 80% ends up in different wastes and side-streams or is lost to the environment (Leip et al. 2014). The respective numbers for phosphorus are estimated at 30% and 70% (van Dijk et al. 2016), with a significant share of unused phosphorus binding to the field soil increasing soil P stock. In the EU crop production, nutrient use efficiency, i.e. the amount of added nutrients that end up in the crops, is estimated to be approximately 50% for nitrogen and 70% for phosphorus. For livestock production the nutrient use efficiencies are markedly lower and approximately 18% and 29%, respectively, end up in the animals or their products (Leip et al. 2014, van Dijk et al. 2016), while the rest mostly end up in animal manure.

In the EU and in many other regions in the world, livestock production and crop production have become segregated due to the need to improve production efficiency and profitability by specializing in certain products. Especially livestock production is more and more concentrated to certain areas or regions in most countries. An example is the Baltic Sea region (BSR) where there are areas with large animal populations and subsequent challenges with sustainable manure fertilization despite limitations to livestock density in relation to availability of agricultural land to spread the manure.

Many regions with intense livestock production continuously import more nutrients in feed and fertilizers than they export in product. The excess nutrients are largely found in manure. As the N:P ratio of manure is lower than optimal for most crops, fertilization with manure may lead to overfertilization with phosphorus due to maximizing the use of its nitrogen. Much of the surplus nitrogen is lost to the environment through gaseous emissions and leaching and not accumulated in field soils. However, the excess phosphorus binds to soil particles and accumulates over time increasing soil P stock and decreasing the need for phosphorus fertilization. Subsequently continuous spread of manure increases the risk of phosphorus losses to waterways. In contrast, simultaneously in regions specializing in crop production soil P stock is often low and even decreasing and mineral fertilizers are used to supply the phosphorus needed.

These regional differences with areas having a surplus of (manure) nutrients and others having to import mineral fertilizers are driving the idea of nutrient recycling, i.e. finding circular solutions to regional scale sustainable nutrient management. Using the surplus nutrients more efficiently to offset the need for mineral fertilizers can decrease the negative environmental impact of the excess nutrients. Simultaneously it can conserve limited phosphorus resources, reduce the need for fossil fuels in nitrogen fertilizer production and increase regional self-sufficiency in nutrients. Of all organic side-streams in society, manure clearly has the largest potential to provide a pathway for such nutrient recycling (Table 1).

Table 1. EU nutrient recycling potential, total amounts and average amounts per year on agricultural land in the EU if spread evenly (Eurostat 2016, Leip et al. 2014, Velthof et al. 2015, van Dijk et al. 2016, Sutton et al. 2011, Buckwell & Nadau 2016). For comparison, annual mineral fertilizer use (Eurostat 2016).

	N total Mt	N average kg/ha/a	P total Mt	P average kg/ha/a
Manure	7–9	41–52	1.8	10.5
Biowaste	0.5–0.7	2.9–4.1	0.1	0.6
Slaughterhouse waste	ND	ND	0.3	1.7
Sewage	2.3–3.1	13.3–18.0	0.3	1.7
Mineral fertilizer	10.9	63	1.4	8.1

ND = no data

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2. Manure processing to reallocate manure nutrients

The regional concentration of livestock production has created a situation where manure based nutrients are not utilized according to crop requirement. Regional nutrient imbalance is further increased by importing feed from the crop production regions, leading to nutrient concentration in animal production regions. While the fertilizer use of manure on the livestock farms producing it remains a valid practice, its use needs to be advanced also on crop farms and in the regions specializing in crop production. This already would enable a partial reallocation of the valuable manure nutrients to fields and areas currently more dependent on mineral fertilizers. Simultaneously, the organic matter in manure could be returned to a wider range of soils assisting in maintaining its higher organic matter content.

However, more effective regional reallocation of manure nutrients is not feasible with raw manure. Currently, manure is usually used on the livestock farm or in its close vicinity as manure transportation is costly; the low nutrient content of manure per ton often exceeds the value of the nutrients. Furthermore, depending on the fertilization limits, either phosphorus or nitrogen is preferred causing inefficient utilization of the other: with phosphorus as the limiting nutrient, too little nitrogen is applied for the crop's need, while with nitrogen limiting the spread, too much phosphorus is given.

Thus, to enable efficient regional nutrient reallocation with more cost-effective transportation of manure nutrients and with better use of the valuable nutrients, manure processing to more concentrated, transportable fertilizer products becomes necessary. Efficiency is further improved, if phosphorus and nitrogen are simultaneously separated into different fertilizer products. Various processing technologies and technology chains are available and can be chosen depending on the case-specific need.

In this section, examples of regions with excessive manure nutrients and a need to reallocate part of the manure nutrients are presented for the Baltic Sea Region, while processing technologies and their prerequisites are introduced in the following sections.

2.1. Examples of regional nutrient availability and need in the BSR

2.1.1. Finland

Use of mineral phosphorus fertilizers in Finland increased significantly since the Second World War and reached its peak in 1975 with an average use of 34 kg/ha (Ylivainio et al. 2014). Since then, P fertilization recommendations have been lowered closer to the crop requirement, partly to tackle the eutrophication of surface waters due to the excess fertilization. Currently the use of mineral P fertilizers averages at about 5 kg/ha. Due to the excessive fertilization in the past, the P content in Finnish field soils has increased to a level where the soil's own P reserves fulfill the crop requirement on about half of the agricultural field area (Ylivainio et al. 2014). The regions with the highest soil P content are also the regions with the most intense livestock production (Fig. 1).

Contrary to the use of mineral P fertilizers, the amount of manure phosphorus has remained at a constant level (Ylivainio et al. 2014) and is currently about 7.6 kg/ha if spread evenly across all cultivated fields (Luostarinen et al. 2020). According to the recent estimates (animal statistics and Finnish Normative Manure System, Luostarinen et al. 2017a,b), all manure produced in Finland (ex housing) contains about 17,200 tons of P. The majority of it originates from cattle (9200 tons), followed by fur animals (2800 tons), poultry (2300 tons) and pigs (2200 tons). The Western coast of Finland has regions with a high density of cattle, pigs, poultry and fur animals, the South-Western Finland with a high density of pig and poultry production and in the Eastern part of Finland cattle production dominates (Fig. 1).

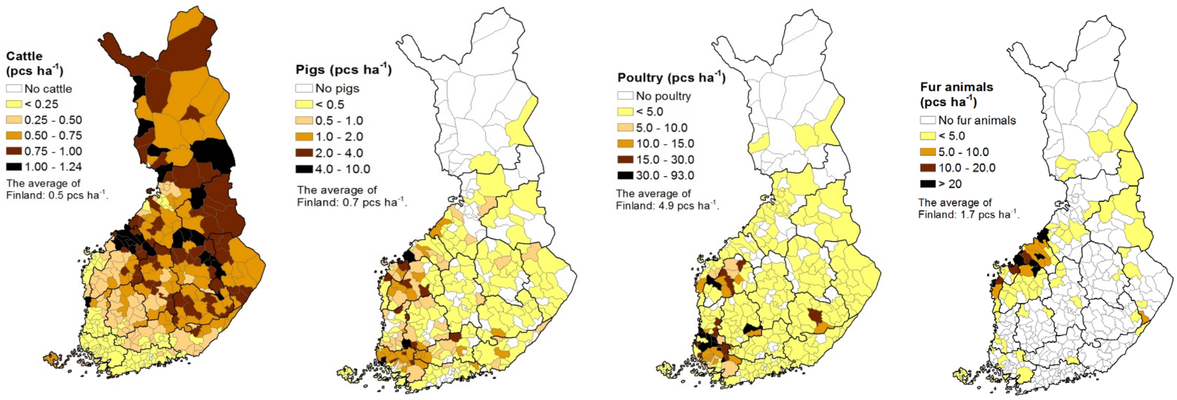

Figure 1. Location of farm animals in Finland (animals per hectare of arable land) highlighting the regional concentration of animal production (Ylivainio et al. 2014). In Northern Finland there is very little arable land, thus the cattle density seems higher than in reality.

According to the crop requirement (Valkama et al. 2011), average P fertilization need in Finland is about 8 kg/ha when considering the soil P status (Fig. 2). Consequently, the manure P produced in Finland could nearly satisfy all crop P requirement in Finland if it could be transported to regions in need, e.g. from P surplus regions to regions with P deficiency (Fig. 2). However, due to the segregation of crop and livestock production, especially in the Western Finland, the P surplus can be up to +194 kg/ha at a municipal level, whereas in the Southern Finland negative P balances are common, with the lowest estimate being -15.4 kg/ha (Ylivainio et al. 2014).

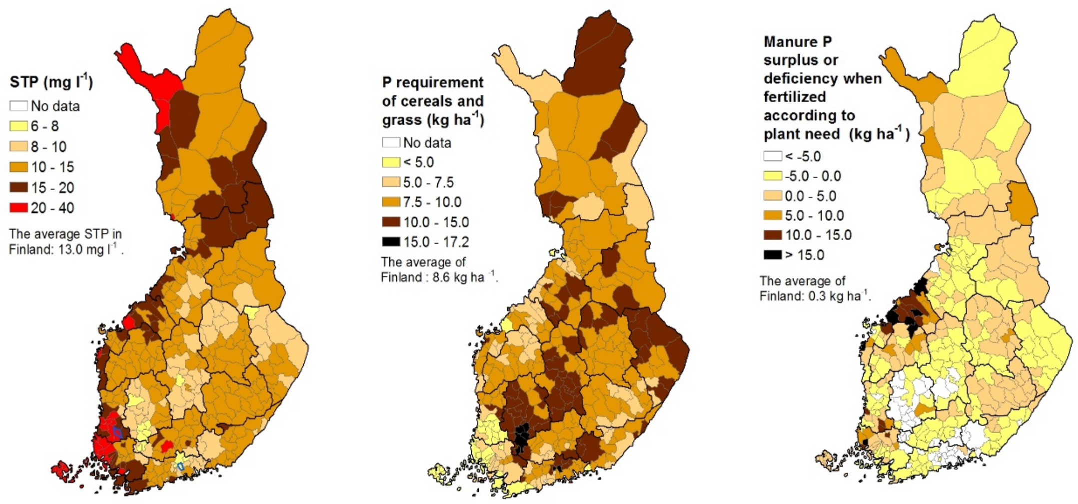

Figure 2. Soil phosphorus content (left), need for phosphorus fertilization for cereals and grass (middle) and the resulting regional surplus or deficiency of manure phosphorus in Finland (right) (Ylivainio et al. 2014).

The status of available recyclable nutrients is estimated in cooperation with Natural Resources Institute Finland Luke and Finnish Environment Institute SYKE. As a result of the project Baltic Manure, the need for more precise manure data was noticed in Finland and a national calculation tool called the Finnish Normative Manure System was developed (Luostarinen et al. 2017a). The system now provides data on national and regional manure quantities and nutrient contents for different animal categories and manure types (example of data available in Fig. 3). Later, another calculation tool for planning regional nutrient recycling was developed by the same organizations ('Nutrient Calculator', Luostarinen et al. 2020). The tool enables calculation of the quantities and nutrient contents of manure and other nutrient-rich biomasses (e.g. municipal sewage sludge and biowaste, industrial wastes and sidestreams, straw, grass biomasses) for national, regional and municipal levels. It also enables scenarios with different processing choices, calculates the needed fertilization (based on current crop production, soil characteristics and three alternative fertilization limits) and compares the availability of the resulting fertilizer products with the fertilization need. The data presented above can thus be monitored and updated, and scenarios for the future made to support decision making.

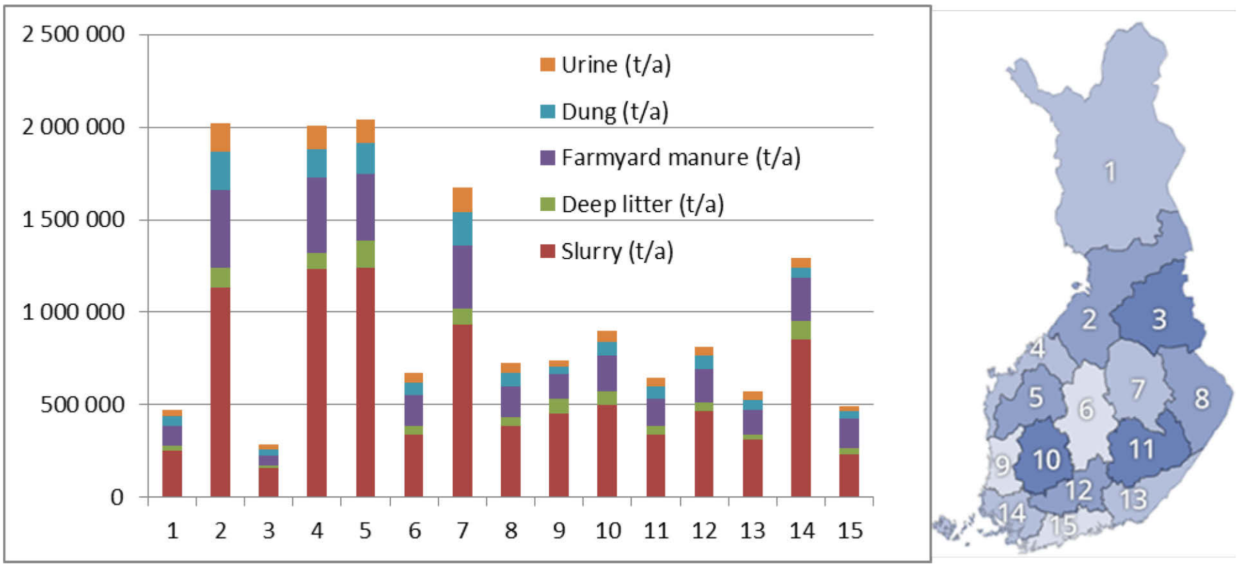

Figure 3. Manure quantity per manure type (ex storage) and per region in Finland.

2.1.2. Sweden

Since 2006, Sweden has attempted to limit phosphorus surplus in livestock production by regulating livestock density based on the amount of phosphorus in manure. The regulation limits P application from organic fertilizers to 22 kg P/ha as a five-year average for the total area used for spreading manure. This limits the amount of manure produced on a farm, establishes a link between livestock and crop production and helps distribute the manure on all farm fields, even those farthest away. The regulation works together with the Nitrate Directive so that even if manure P contents were very low, manure application cannot exceed 170 kg total N/ha in the nitrate vulnerable zones. However, it is generally the P content of manure which limits the application rates. Thus, this regulation limits the overdosage of P which would eventually lead to increased losses through runoff and leaching.

In 2016, there was 2.86 million ha of agricultural land in Sweden, including permanent grasslands. Simple field nutrient balances for this agricultural land showed generally a good balance between P addition and removal, which was on average plus and minus 12 kg P/ha respectively in 2016, 2013 and 2011 (SCB 2018). The situation has improved considerably since 1995 when there was an average surplus of 5 kg P/ha in the field balance. The balance was calculated as the difference between nutrient addition to and removal from fields. Additions included nutrients in mineral fertilizers, manure (including manure deposited on grazing land), seed, aerial deposition, biological fixation, sewage sludge and other organic amendments. The additions were gross amounts and losses (gaseous or other) were not included. Removal of nutrients included those in crops and harvested crop residues.

The field balance for nitrogen was somewhat different than for P. For N the additions accounted for approximately 119 kg N/ha and removal was only 82 kg N/ha in 2016. This suggests an average N surplus of 37 kg N/ha or a total of 112,000 t, which was accounted for as losses through ammonia (35%) and nitrous oxide emissions (22%) and as nitrate leaching (43%) (SCB 2018). The 2016 surplus was 12% greater than in previous years; however, it was 36% less than in 1995.

While the P balance on a national level looks good, regional differences were found between Sweden's eight agricultural production areas (Fig. 4). Regionally, the P balance varied from -5 kg P/ha in the Götaland Southern Plains District to almost +3 kg P/ha in the Götaland Forest District. The N balance varied from +26 kg N/ha in Norrland to +43 kg N/ha in the Götaland Southern Plains District. Negative P balances in Sweden's most productive agricultural areas indicate P mining from the soils. Maintaining production levels with a negative P balance is possible in the short-term due likely to the relic of previous years of over-fertilization which built up the soil P reserve. However, continuing production with P deficits is not sustainable in the long-term.

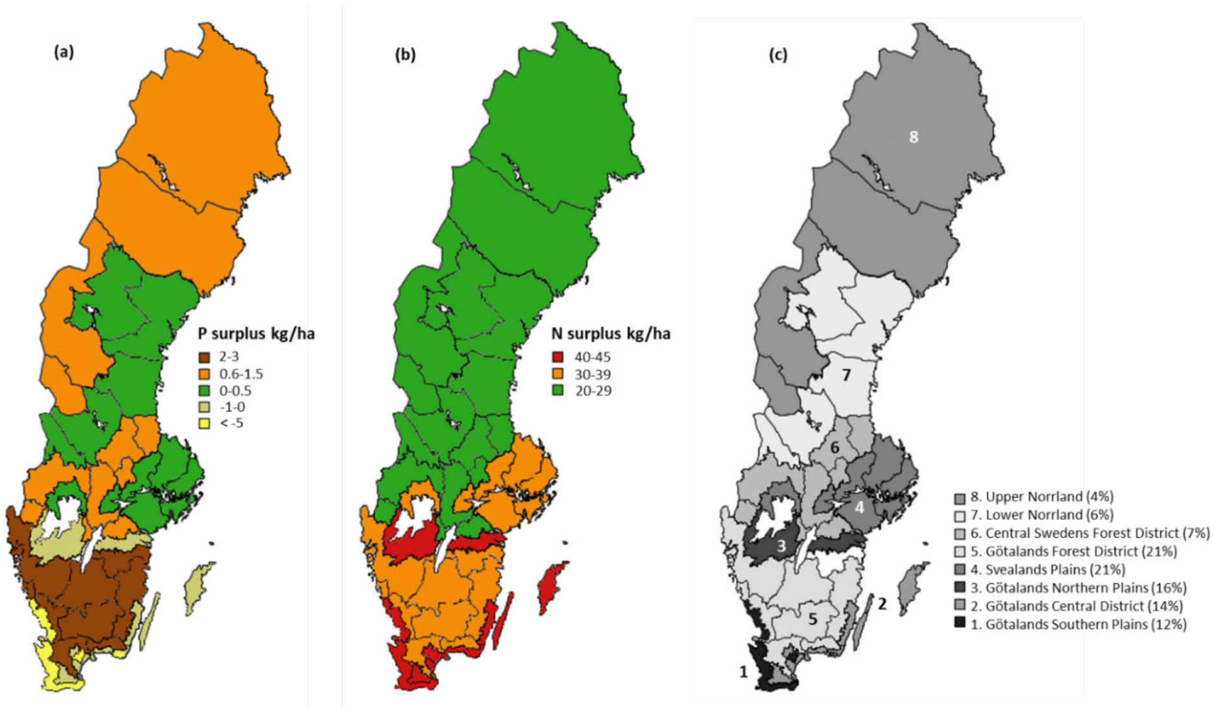

Figure 4. Field level phosphorus (a) and nitrogen (b) balances on agricultural land in Sweden in 2016 (data-from SBC 2018). See text description of balance calculations. Nutrient balance calculations were made for the 8 major agricultural production areas in Sweden shown in (c). Percentages represent the portion of the total agricultural area for that production area in 2016.

There were also differences in nutrient balances between livestock farms depending on livestock density (SCB 2018), and it seems clear that P is accumulating on livestock farms with greater animal densities (Fig. 5). The N surplus is the greatest on these farms as well. Considering that almost half of all dairy cows, sows, other pigs and hens in Sweden are on farms with large herd sizes that average over 500 livestock unit (Table 2), the regional nutrient balances shown in Figure 4 are probably missing a lot of local hotspots with greater problems of nutrient surplus.

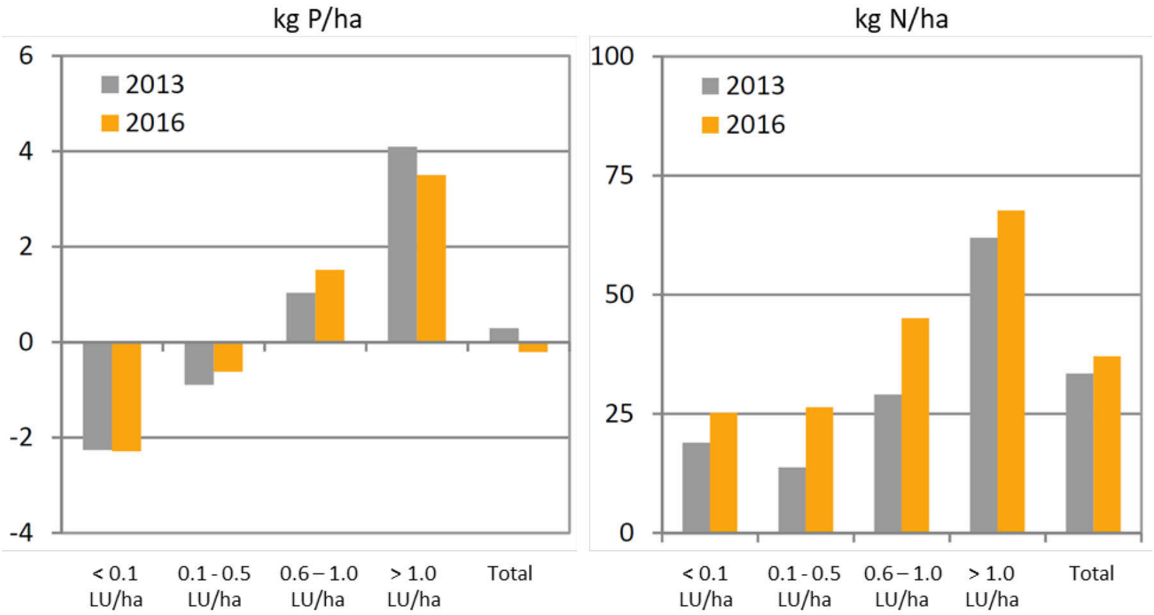

Figure 5. Nutrient balance for agricultural land (arable plus permanent grassland) in Sweden for farms with different livestock density (livestock unit, LU) during 2013 and 2016 (SCB 2018). Positive balance is a surplus and negative is a deficit.

Table 2. Total number of livestock units (LU) in Sweden for animal groups (SCB 2017). LU conversion rates are 0.5 for sows, 0.3 for pigs and 0.014 for hens. Large herds were considered > 200 dairy cows, > 500 sows, > 2000 pigs and > 5000 hens by the Swedish Board of Agriculture. Average large herd size was calculated using the number of holdings for that group.

	LU	Amount in large herds (LU)	% of total in large herds	Average large herd size (LU)
Dairy cows	330,833	90,322	27	330
Sows	69,492	37,993	55	492
Pigs	250,597	117,620	47	1032
Hens	136,488	111,799	82	545
Total	787,410	357,734	45	534

2.1.3. Germany

In Germany, around 50% of the P inputs into surface waters come from agriculture (UBA 2017). This is one of the reasons to ensure high nutrient efficiency and the minimization of nutrient losses in plant production for the production of food and feed. The P fertilization is to be determined based on the P requirement of the plant needs. This is based on the yields and qualities that can be expected under the respective site and cultivation conditions and on the P stock that is available in the soil. The P available in the soil must be analyzed as part of a crop rotation, but at least every six years (DÜV § 4). On farm level a surplus of 10 kg P_2O_5/ha/a (4364 kg P/ha/a) is permissible on average over six years. If the soil contains > 20 mg P_2O_5 / 100 g soil (> 8728 mg P_2O_5 / 100 g soil) in CAL[1] maximal

[1] CAL - Calcium chloride solution

fertilization permissible is the amount of the P uptake (DÜV § 3). In case of poor water body conditions due to P fertilizer inputs, stricter rules can be implemented by the German states.

Figure 6 shows the livestock unit density in the different districts of Germany (Häußermann et al. 2019). The highest densities with a risk of nutrient surplus are in the northwest and southeast of Germany. Around the German coastline of the Baltic Sea, the livestock unit densities in Schleswig-Holstein (west side) are higher than in Mecklenburg-Vorpommern (east side).

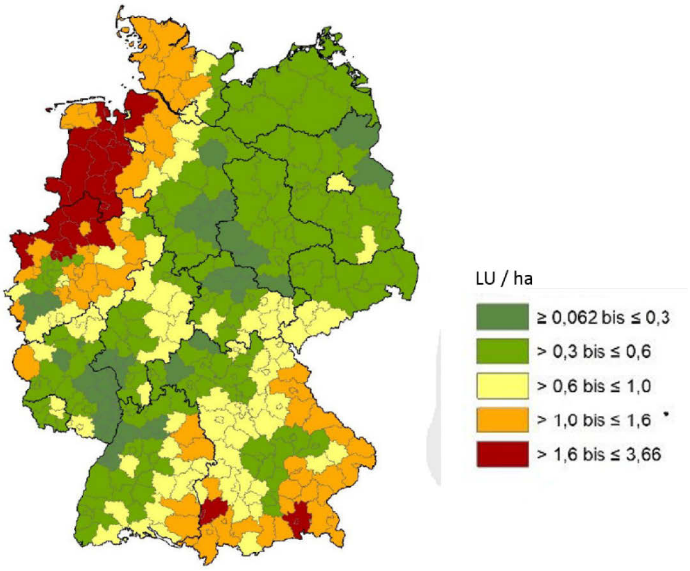

Figure 6. Livestock unit density (LU/ha) in different districts of Germany (Häußermann et al. 2019, Map basis © Geo-Basis-DE / BKG 2018.)

Figure 7 shows the partial balance for P_2O_5 in kg/ha of agricultural area (Osterburg & Techen 2012, Map A 4.2, s. 203). The amount of P produced by animal excretion (faeces and urine excreted by the livestock) was taken into relation to the P uptake of crop products. There are very high calculated P-surplus situations, especially in the livestock-intensive regions in the northwest of Lower Saxony and in the northwest of North Rhine-Westphalia. The other regions with high P surpluses, e.g. in eastern Germany, are relatively small-scale. Regions with moderate P-surplus from animal excretion can be found all over Germany. However, in many regions the amount of P from animal excretion is lower than the P-uptake of crop products. This has subsequently led in some arable regions to a gradual deterioration in the P status of the soil due to neglected P fertilization (Wiesler et al. 2016). A solution would be a better distribution of manure all over Germany, meaning especially transportation to the undersupplied arable regions.

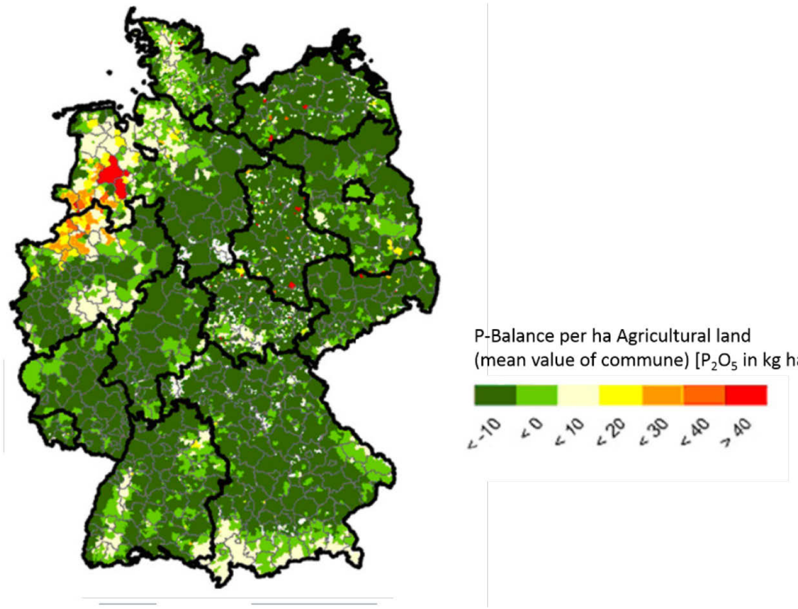

Figure 7. Partial balance for P_2O_5 in kg/ha agricultural area (Osterburg & Techen 2012, Map A 4.2, s. 203) [2].

2.1.4. Poland

Another example of a situation with uneven distribution of manure phosphorus is from Poland (presented here based on Kopinski & Jurga 2016). A general objective of P fertilization is to add an adequate (in regard to soil test P) amount of P to produce an economical yield. One of the tools for assessing the correctness of a nutrient economy is using a gross phosphorus balance calculation. Significant surpluses can increase soil fertility, but also create a risk for losses to waters. On the other hand, constant negative P balances may impair soil fertility and indicate the risk of limited productivity potential. Considering this and the Polish situation with soil P status and available P, an optimal P balance for Polish agricultural land has been estimated at 2 kg P/ha at most. A mean calculation for the P gross balance for 2014 shows an average surplus of 2.5 kg P/ha, which is relatively close to the optimum suggested.

From the regional point of view, however, the situation changes. Polish agriculture has large regional variations in production intensity, partly caused by variation in natural conditions. The soil P status varies greatly between the regions with the share of soils in low or very low P ranging from 19% to 57%.

The use of mineral fertilizers is greatest in the Western and South-Western parts of Poland. The application rates range from 41.3 kg/ha to 15.2 kg/ha mineral P. Also, the use of manure as a fertilizer varies a lot between the regions, being 12.6 kg P/ha at the highest and 2.8 kg/ha at the lowest. The use of manure is the highest in the regions where the share of high soil P status is the highest and thus the need for P fertilization the lowest.

Also, the Polish gross P balance shows great variation between the regions. Here, negative balances were found in regions with a large share of the soils being already in low or moderate soil P status. Meanwhile, the highest P surplus was found in the region with the highest share of soils already in

[2] $P_2O_5 \times 0.4364 = P$

high P status and the highest use of manure P/ha. In the same region also a relatively high use of mineral P is accounted for.

According to this data, the Polish P fertilization was not optimal in regard to the conditions for crop production, meaning to maintain the soil P in areas with low soil P status or to reduce the high P fertilization rates on areas with high soil P status. Such practices indicate an inefficient use of the valuable resource and pose a risk for P losses into the environment.

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3. An overview of manure processing

Manure processing includes the use of different technologies to somehow change manure composition and quantity with the aim of enhancing its reuse, most often as recycled fertilizer products. The technologies may be based on biological, chemical or physical methods or their combinations. They may e.g. degrade organic matter, release organically bound nutrients, reduce water content, recover or separate nutrients into more concentrated fractions and/or produce renewable energy. The different technologies may be used alone or in sequence one after another forming variable technology chains (see: chapter 4 for examples of technologies and their end-products).

The most common manure processing technologies used at the time of writing include anaerobic digestion, mechanical separation and composting. However, these technologies do not alone significantly change the nutrient content or transportability of manure and cannot alone solve the issue of needing to transport manure nutrients over longer distances. Furthermore, none of the technologies, excluding perhaps very efficient centrifuging of slurry, provide the means for separating phosphorus and nitrogen effectively into separate fertilizer products for improving their utilization. More advanced processing of manure and of manure-based digestates is therefore gaining increasing attention with the goals of effective water removal and subsequent concentration of nutrients into separate products.

3.1. Motivation for manure processing

The reasons for a farm to choose to process manure can be various. On farm-scale, it may wish to make better use of the manure via utilizing its energy content for increased energy self-sufficiency and/or for selling energy to others e.g. by investing into a farm-scale biogas plant. It may also aim at changing the N:P ratio of slurry and making better use of the nutrients on the farm or on neighboring farms or recirculating part of the slurry as a bedding material via mechanical separation.

Regulatory constraints that limit the direct use of manure as a fertilizer, meaning e.g. too much manure nutrients for the farm's cultivated area considering the fertilization limits, may push the farms to opt for a larger scale manure processing. A farm co-operative processing unit may be used to reallocate the nutrients among the participating farms and/or to produce and sell renewable energy produced at the same time. Such local cooperation may include both livestock and crop farms and even some other businesses, such as horticulture. Farmers may also wish or even need to hand over some or all of its manure to a larger centralized processing plant. This would be the case e.g. if the farm has an excess of manure for its own cultivation or its livestock production is limited due to too much manure nutrients to be used on the farm or even in the region.

While the ultimate motives for processing manure may vary between farms and regions, the most common ones are the following:

- reducing manure volume for storage, handling and transportation,
- meeting regulatory requirements (environmental permits, IED, Nitrate Directive, national regulations),
- improving fertilizer value and/or making more efficient use of manure nutrients,
- tackling limited manure storage capacity without building new structures,
- utilizing manure energy content,
- mitigating emissions,
- tackling farm-scale or regional manure surpluses via enabling transportation,
- contributing to circular economy.

All of these themes are also closely linked. The benefits and motives related processing of manure are summarized in Figure 8.

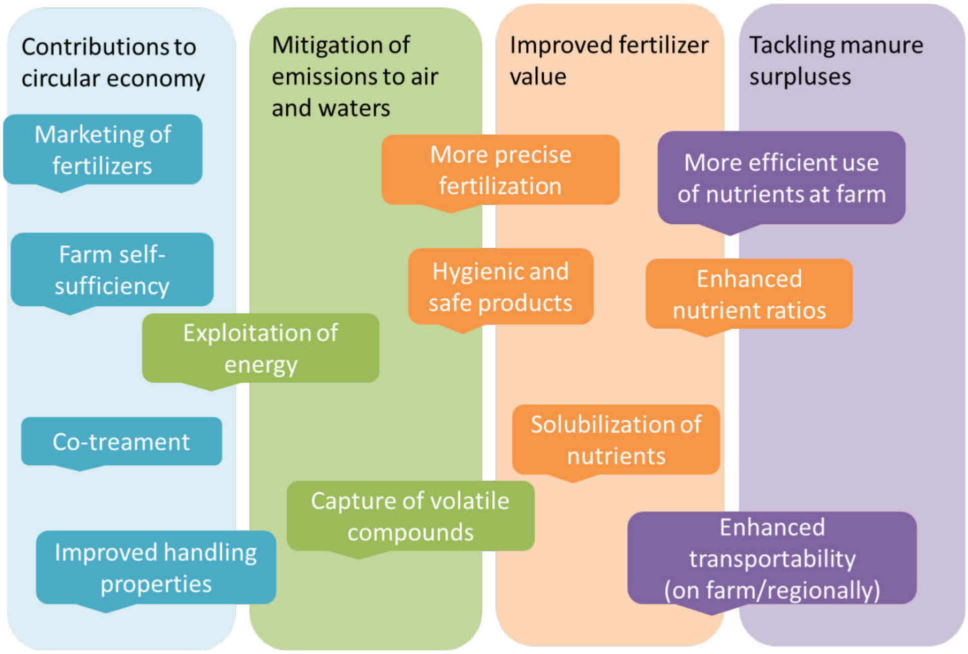

Figure 8. Benefits of manure processing divided into four interlinked themes.

An important goal in manure processing is to improve the utilization of manure nutrients often via concentrating them. Depending on the processing technology or technology chain, the nutrients may also be separated into specific products with no or very little other components. Nitrogen can also be removed through denitrification, e.g. transformation of N-compounds into molecular nitrogen and released into the atmosphere, but this is not advisable and not in line with the aim of nutrient recycling. Processing can also transform organically bound compounds into a more soluble form and thus increase the fertilizing effect of the products.

At the same time, the organic matter in manure can be concentrated into specific products. The manure-based fertilizer products with high organic matter content are valuable soil amendments. Added organic matter plays a key role in the conservation of the physical, chemical and biological properties of soil. Soil organic matter is considered a central component of sustainable soil management and maintenance of soil quality and crop productivity. Increasing organic carbon inputs into soil is also important to climate change mitigation.

Processing can also include energy production where part of the manure carbon content is transformed into energy after thermal treatments or anaerobic digestion. Depending on the technology, the energy produced can be used as heat, electricity and/or vehicle fuel. When the energy is used to replace fossil energy sources, it results in a reduced climate impact, an outcome increasingly valued.

Manure processing may also contribute to the mitigation of emissions to air and waters. A proper management practices before, during and after the processing are required for the entire chain to minimize losses. For reducing the gaseous losses due to the storage, processing is commonly carried out as soon as possible for reducing the manure storage time before the processing. During processing the nutrient ratios and their availability can potentially be transformed more optimal for crop requirement, thus reducing the risk of losses into air and waters when applied on fields. Transportability to areas in need of nutrients further reduces the risk of excess fertilization. Obviously, also sustainable management for storing and spreading the manure-based fertilizer products are essential to reduce emissions.

3.2. Economy of manure processing

The motivation to process manure is interlinked with its costs and potential revenues. The main reason for little advanced manure processing at the time of writing is the challenge of economic feasibility. While the nutrient content of the recycled fertilizer products and the versatility of their characteristics in terms of efficient use on farms are increased with more advanced processing choices, the costs also increase both as an investment and in operation and maintenance. Furthermore, the smaller the scale of the processing unit, the higher the processing costs are per ton of manure. All this is reflected in the true price of the recycled fertilizer products and currently the costs are rarely covered by the price farmers are willing to pay. There are little recycled fertilizer products available and most of them require changes in the farming practices, including either new structures and equipment or contracting services which may not be readily available. Mineral fertilizers are cheaper, and the farms have the known solutions to store and spread them. They can also often be applied with more precision and the nutrients are always readily available for the crops, which is not always the case with recycled fertilizer products.

To really introduce effective nutrient recycling with reallocation of nutrients across regions, a totally new market needs to be built. This cannot be achieved without the will and support of the society. Good practices need to be promoted to facilitate the change required. As economy is one of the largest obstacles, financial support will be needed. The support should be directed both the using the recycled fertilizer products (demand on farms) and producing them (supply from processing plants using especially manure).

Manure processing especially needs support to really get it started. For waste materials that a municipality or an industry needs to be rid of in an acceptable manner, a payment for the processing (gate fee) is available for the processing plant and this assists in reaching sufficient revenues. However, for agricultural materials and especially manure, such a fee is not usually available, or it is low. The farmer cannot pay, but finds cheaper solutions, if made possible by e.g. high fertilization limits. The processing plant cannot process as it may not receive proper revenue either as a gate fee or by selling the end-products while the market is still undeveloped.

Due to economy of scale, advanced manure processing into recycled fertilizer products would be the most economically feasible in large centralized plants. Such large plants would also be the most effective in processing sufficiently large shares of manure nutrients into recycled fertilizer products to enable regional reallocation. Still, the cost of the investment and operation of the plants is high, and revenues received may so far be low.

One partial solution to the economy challenge is the production of energy as part of the processing chain. In the case of anaerobic digestion, for example, part of the revenues is now received as income from selling the energy, while the income from the digestate is low or even negative. While potentially better income would be received from processing the digestate further into more concentrated fertilizer products with improved N:P ratios, it bears a cost and there is no guarantee for a proper price. It is often more feasible for the processing plants to transport large amounts of dilute digestate to fields than processing it into more valuable products.

This gap in the economy of manure-based biogas plants has been noticed in many countries and some already have separate support mechanisms for them. For example, Sweden offers an additional incentive for manure digestion for the years 2014–2023 (Förordning 2014:1528 om statligt stöd till produktion av biogas). The support is paid for the biogas produced from manure under certain conditions, and it has increased manure processing in biogas plants. However, the support does not really address the use of the digestate as it is not tied to compulsory rules for its use as a fertilizer. Similarly, in Germany manure is a preferable feed material for biogas production, comprising approximately 40% of all feed materials in German biogas plants (Daniel-Gromke et al. 2018). However, the larger the biogas plant, the less manure is used as the feed due to the support system focusing on energy production rather than recycling nutrients. In Finland, no separate support system is available for manure digestion, but it has been discussed as a part of a combined solution for a transfer towards less emissions, improved nutrient recycling and fossil-free traffic. Calculations for the potential financial support needed for starting up large-scale manure digestion in the livestock dense regions of Finland was made including a strong push towards tying the support to sustainable reuse of manure phosphorus (Luostarinen et al. 2019).

To enable the development of a true market for recycled fertilizer products, the farmers need support for starting to use them. The products need to be developed so that they respond to the needs and the solutions for their practical management, including e.g. contracting services for spreading, should be established. Information on their benefits should be disseminated to show them as a true alternative to mineral fertilizers. Only after the demand for the recycled fertilizer products increases, can the producers get proper revenues for their products.

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4. Processing technologies and the resulting fertilizer products

There are many different manure processing technologies available and they range from simple and robust farm-scale solutions to more high-tech solutions with more complicated processing chains (Fig. 9). Some of the technologies are mature and ready for implementation, while others are still being developed to suit manure as the substrate.

The choice of suitable technology for manure processing depends on many factors, such as

- Manure type,
- Processing of one manure type or co-processing of different manures and/or other biomasses together,
- Capacity and scale to be applied,
- Aims for the quality of the fertilizer products,
- Aims for the use of the fertilizer products,
- Interest in energy production and energy type to be produced,
- Investment and operation costs,
- Needs to reduce emissions and/or to manage other potential risks.

Different technologies can also be selected depending on the different benefits that are sought (Table 3). Often the selection of a suitable manure processing technology should start with defining the type and quality of fertilizer products, which the processing should produce. When the appropriate product characteristics (e.g. nutrient content, hygienic quality) and form (e.g. solid fertilizer, liquid fertilizer, granular fertilizer and inorganic fertilizer) are chosen, it is possible to select the technologies to produce the desired product/products. However, one technology is not necessarily enough to process manure to a high nutrient content and mineral fertilizer-like product, but the processing often requires combining two or more technologies into a technology chain.

In this chapter, selected manure processing technologies are briefly introduced including a description of their effect on the nutrient content in the end-products and environmental effects of their use. In addition, some examples of full-scale manure processing applications in farms and on industrial scale are given. This chapter concentrates especially to technologies with maximal manure nutrient recovery. Due to this, for example nitrification-denitrification technologies to remove nitrogen are not included.

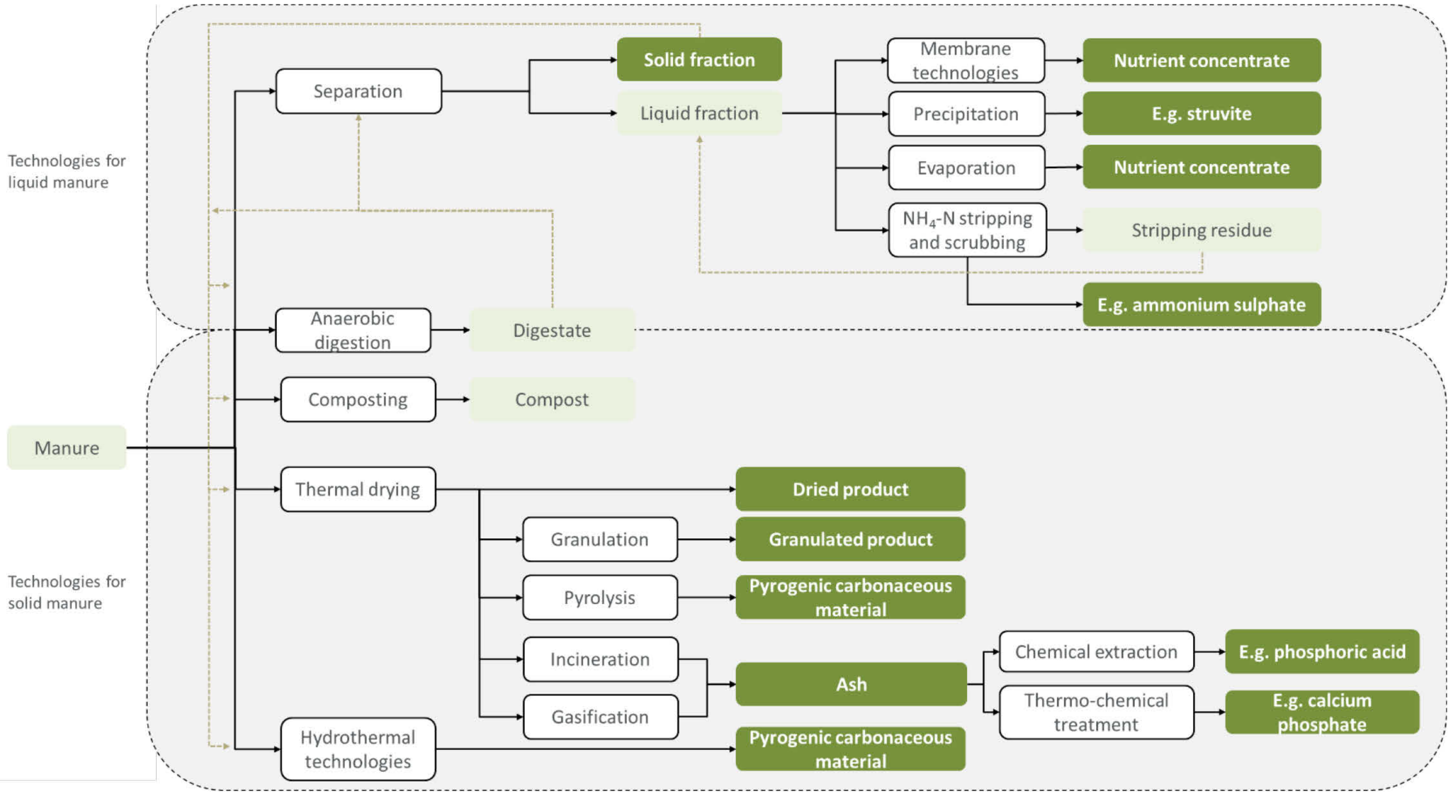
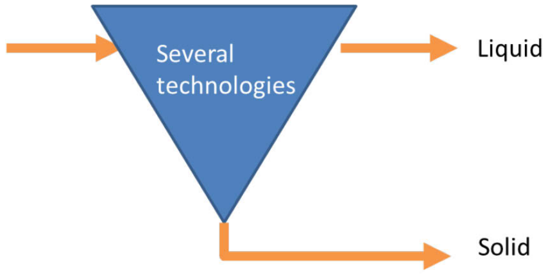


Figure 9. Examples of potential manure processing technologies and technology chains available or under development. Resulting fertilizer products are highlighted with green.

Table 3. Examples of goals associated with different manure processing technologies. It should still be noted that the technologies can be applied in processing chains in which several of the goals can be achieved simultaneously.

Goals in manure processing	Processing technologies
Improved marketability (in terms of resemblance to current mineral fertilizers)	Granulation Stripping Struvite precipitation / Membrane separation Pyrolysis
Improved farm self-sufficiency	Mechanical separation Anaerobic digestion Pyrolysis
Co-processing of several materials	Anaerobic digestion Composting Pyrolysis Gasification / Combustion
Improved handling properties	Composting Thermal drying / Granulation Pyrolysis
Production of renewable energy	Anaerobic digestion Pyrolysis Gasification / Combustion
Capture of volatile nitrogen	Manure acidification Stripping
Improved precision of fertilization	Mechanical separation Stripping Struvite / Membrane separation Thermal drying / Granulation Pyrolysis
Improved hygiene	Thermal drying Pyrolysis Gasification Anaerobic digestion
Solubilization of nutrients	Anaerobic digestion
Improved N:P ratio	Mechanical separation Thermal drying Pyrolysis Gasification Stripping / Struvite / Membrane separation / Evaporation
More efficient use of nutrients at farm	Mechanical separation Anaerobic digestion
Enhanced transportability (on farm / regionally)	Mechanical separation (on farm) Thermal drying (and granulation/pelletization) Pyrolysis Gasification Stripping / Struvite / Membrane separation / Evaporation

4.1. Mechanical separation

Objective	To separate solid and liquid fraction from slurry (or digestate). To concentrate macronutrients; P to the solid fraction and N, K to the liquid fraction. To optimize nutrient contents for fertilizing purposes. Efficiency of separation depends on the chosen technology.
Matrices	Slurry, semi-solid manure
Outputs	Solid fraction, liquid fraction
Scale	Farm, medium, large
Level of complexity	Low or medium
Innovation stage	Mature (industrial/commercial)
General diagram	
Contribution to nutrient recycling	Farm-level

Mechanical separation aims to separate solid and liquid fractions of the slurry and can consist of different technologies, typically involving a screw press, a centrifuge or a screen (Table 4). Separators are efficient in producing a solid fraction with high dry matter content on a relatively cost-effective basis. Separation can increase the efficiency and flexibility of manure handling and transport and assist in more precise management of manure nutrients.

End-products as fertilizers

Mechanical separation can reduce the volume of the liquid fraction up to 40% as compared to the volume of raw slurry. Still, it usually contains the majority of the original slurry volume. Most of the soluble nutrients end up in the liquid fraction, meaning that its P content is usually low. This may allow its application rates be based on nitrogen without exceeding P limits. However, this is dependent on the P separation efficiency, which in turn is dependent on the chosen technology and the slurry to be separated.

The solid matter often contains most of the phosphorus of the original slurry (0.5–7 g P/kg) since P is mostly bound to organic matter ending up in the solids. Organic N (0.5–12 g N/kg) is also mostly found in the solid fraction. Due to its high dry matter content (typically 20–30%) the solid fraction can be more easily transported to fields farther away from the farm reducing transportation costs and allowing manure nutrients to be used in a wider range than as slurry. It can be stored and spread similarly to solid manures.

Phosphorus in the separated fractions is mainly in an easily soluble form in cattle, pig and poultry manures, and they were shown to increase soil bioavailable P content to a comparable level as mineral P fertilizer, superphosphate.

Advantages of the liquid fraction during spreading are that it generally requires little or no mixing and causes less contamination of crop leaves on grassland. Owing to its lower dry matter content, it also infiltrates more quickly into the soil and thus reduces ammonia emissions compared to raw slurry. However, total ammonia emissions from both the solid and liquid fractions during storage and spreading can be higher than those from raw slurry in case the storages are not covered.

Separation does not affect pathogens or other contaminants, but they are separated to solid and liquid fractions according to their solubility.

Table 4. The most common mechanical separation technologies for manure.

	Screw press	**Centrifuge**	**Screen**
Description	Application of pressure to separate by filtration suspended solids and liquid fraction. The material to be separated enters into a cylindrical screen (0.5–1 mm). The liquid will pass through the screen, and the dry matter rich fraction will be pressed against a plate.	A centrifugal force is generated to cause the separation of solids from the liquid. The centrifuge uses a closed cylinder with a continuous turning motion (3000–4000 rpm). The fractions are separated at the wall into an inner layer with a high dry matter concentration and an outer layer consisting of a liquid.	Screen separators (static or vibrant) involve a screen of a specified pore size. The liquid flows through the screen and solid fraction is retained on the screen. Low TS (<2%) in the slurry is recommended. There is a compromise between sieve size, separation performance, and risk of clogging.
Conversion efficiencies	Volume 5–20%; TS 15–30%; N 5–20%; P 5–30% in the solid fraction	Volume 5–20%; TS 40–70%; TN 15–30%; NH_4-N 10–20%; TP 50–95% in the solid fraction.	Volume 30–40%; TS 50–80%, TN 40–80%; TP 30–80% in the solid fraction.
Energy consumption	0.1–1 kWh/m^3	3–6 kWh/m^3	0.1–1.3 kWh/m^3
Reagents	Not usual.	Coagulating or flocculation agents can be applied to slurry to enhance solids and phosphorus separation.	Coagulating or flocculation agents can be applied to slurry to enhance solids and phosphorus separation.
Investment costs	17,000–28,000 €	40,000–60,000 € (1.5–2 m^3/h), 100,000 € (25 m^3/h)	3,500–15,000 € (sieve), 15,000 € (vibrant)
Operational costs	0.5–1.05 €/m^3 of input	0.6–2.3 €/m^3 of input	
Labour	Low labor required.		
Site	Requires small area, but storages for solids and liquids.		

Costs reviewed from “Manure Processing Activities in Europe” (Flotats et al. 2011) and http://agro-technology-atlas.eu/

Environmental effects

Solid fraction can be exported at lower costs to areas with low livestock density, reducing problems derived from nutrient surplus, whereas liquid fractions can be used closer or further processed in situ.

Separation can reduce GHG and ammonia emissions during manure storage and after field application when compared to manure handling without processing. Methane emissions from liquid manure storage are reduced since the compounds responsible for these emissions (volatile solids) are separated along with the solids. If solids are stored, the aerated conditions limit the emissions of methane. Separation process also removes the fibrous and large pieces of organic material from the manure liquid fraction, which prevents a natural crust forming. A crust can create anaerobic conditions that promote nitrous oxide production near the surface. However, the lack of a natural crust can increase ammonia emissions from storage of the liquids. Despite the increase during storage, total ammonia emissions from manure management in separation system remain approximately the same as in systems without separation since the ammonia emissions after application are reduced. This is attributed to a more effective infiltration of inorganic nitrogen into the soil since the organic material in the liquid manure is decreased during separation.

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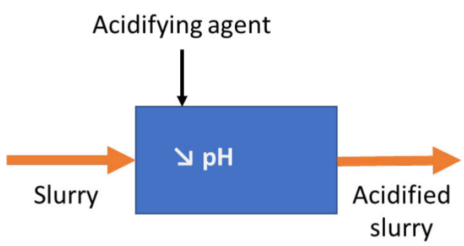
4.2. Slurry acidification

Objective	**Acidification of slurry is a method to reduce the loss of ammonia nitrogen from animal manure**
Matrices	Animal slurry, liquid manure, digestate, separated liquid fraction
Outputs	Acidified slurry
Scale	Farm, contractor
Level of complexity	Low
Innovation stage	Commercially available
General diagram	
Contribution to nutrient recycling	Farm-level

Nitrogen in manure exists largely as organic nitrogen and ammoniacal nitrogen. Ammoniacal nitrogen is the total sum of both ammonia (NH_3) and ammonium (NH_4^+) nitrogen. In liquid solution, there is equilibrium between ammonia and ammonium that is largely pH dependent. Ammonia is a colorless gas that is easily vaporized whereas ammonium readily forms salts that are soluble and stable in solution. Addition of acids aids the protonation of ammonia, shifting the equilibrium towards ammonium and thereby reducing the potential for nitrogen loss through ammonia vaporization.

There are commercially available technologies to acidify slurry in the animal house, before slurry is pumped to storage, or just before or during spreading. All systems use sulfuric acid for the acidification.

Slurry acidification is primarily a processing technology for mitigating against ammonia emissions from manure. In doing so, acidification increases the nitrogen amount in slurry that is available for plant growth after spreading, so it essentially increases the nutrient-use efficiency of liquid manure on farms and thus can increase on farm nutrient recycling.

Acidification may be used as a processing step in a technology chain to produce various recycled fertilizer products, since it could, for instance, be used to help decrease ammonia losses during drying or other subsequent processing steps.

End-products as fertilizers

The end product is acidified slurry or digestate. Acidification increases the nitrogen content of slurry by reducing losses through ammonia emissions. When sulfuric acid is used for acidification, then the sulfur content of the slurry is also increased. Acidified slurry is stored or spread with normal equipment.

Environmental effects

Acidification decreases ammonia emissions from manure and digestate by 50–70%. If slurry is acidified during the storage period, it will also reduce methane emissions by +90% during storage. Some studies suggest that acidification can reduce nitrous oxide emissions but there is not consensus on this in scientific literature.

Real scale references

There are approximately 150 in-house slurry acidification systems in Denmark, about 50% of which on cattle farms and 50% on swine farms. There is also a modified in-house system installed on a pig farm in Poland where the separated liquid fraction is acidified before it is sent to a storage lagoon.

There are approximately 75 in-storage systems in Denmark and one in Poland.

There are approximately 175 in-field slurry acidification systems in Denmark, one in Germany, one in Sweden, one in Latvia and one in Lithuania.

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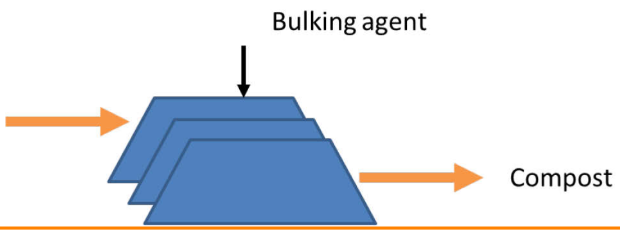
4.3. Composting

Objective	**To obtain mineralization and partial humification of the organic matter leading to a stable product with most of initial nutrients and free of pathogens and seeds.**
Matrices	Solid manure, solid fraction of slurry
Outputs	Compost, CO_2, H_2O
Scale	Farm, medium, full
Level of complexity	Low or medium
Innovation stage	Mature (industrial/commercial)
General diagram	
Contribution to nutrient recycling	Farm and regional level

Composting is a spontaneous, aerobic and thermophilic (40–65°C) process involving the mineralization and partial humification of the organic matter, leading to a more stabilized final product called compost. Composting process is most suitable for solid manure although wet composting technologies exist.

The composting process starts with decomposition where exothermic reactions produce an increase of temperature of the composting matrix above 50°C. Aerobic conditions must be assured in order to enable the reaction. In a second stage, curing is produced. Organic compounds are degraded and humic and fulvic acids are produced. Temperature slowly decreases. The whole process lasts between 8 to 16 weeks. Optimal conditions in the composting matrix are moisture content of 40–65% and C/N ratio of 25–35. Solid manures usually need the addition of bulking agent (e.g. well-chopped straw) in order to have appropriate C/N ratio, structure and porosity.

End-products as fertilizers

The main purpose of composting manure or separated solids is to reduce transport costs of nutrients by mass reduction and to stabilize the material, producing a low-odour, weed-free and low-pathogen soil amendment.

The composting process decreases the organic carbon content in the material due to decomposition of organic matter. This loss reduces mass and decreases the C/N ratio. Total mass loss is commonly recorded at about 55% consisting both of lost moisture and dry matter and serves to concentrate nutrients. Composts can have a dry matter content of around 20–60% depending on the original material, process technology and bulking agents used. Phosphorus content remains unchanged in the process although some decrease in water-soluble P can be observed. Nitrogen preservation can be difficult because aeration and high temperatures volatilize NH_3 during the nitrification cycle. Total N loss from the composting process is commonly 10–30%. The mineralization of the organic compounds produces NH_4-N. However, nitrification, detected by the formation of NO_3-N, leads to a low NH_4-N/NO_3-N ratio in mature compost.

Bioavailability of P in poultry manure has shown to decrease as the stockpiling period advanced, whereas in a pot trial composted dairy manure had better P fertilization effect than mineral P fertilizer.

Environmental effects

Composting stabilizes organic matter but produces GHG that reduces also the agronomic value of the final compost. The carbon lost is in the forms of CO_2 and CH_4. Actively turned windrow produces higher CO_2 emissions and lower CH_4 than passive aeration (no turning). Emission of N_2O is relatively low.

In-vessel composting has numerous advantages over windrow composting, since it occurs in more controlled conditions. They also hold the potential to capture gases (primarily NH_3, NO_x and N_2O) generated during the composting process and to clean the outlet air before it is released to the environment. Temperature control can be a good method for lowering N-losses through NH_3-volatilization and hence for producing an N-rich compost. As composting progresses, stable N compounds are formed, which are less susceptible to volatilization, denitrification and leaching. Therefore, stabilized materials such as composts seem to constitute a better source of organic matter and N for the soil, from an agricultural point of view.

In manure composting, trace element concentrations increase in relation to the mass loss of substrate. Composting may partially degrade antibiotics, but it depends on the compound and the circumstances of the composting. To get hygienized end-products, windrow composting batches should be kept at 55 °C for at least 4 hours between each turning (min. 3 turnings), and compost should be matured to complete the composting process. In an aerated pile and in-vessel composting, batches should be kept at least 40 °C for at least 5 days during which batch should be kept for 4 hours at a minimum of 55 °C, and compost should be maturated to complete the composting process. Compost should also be aerated well to ensure proper hygienization.

Table 5. Manure composting technologies.

	Passive windrow	Active windrow	Aerated static windrow	In-vessel channel
Description	Composting in piles or windrows by natural aeration over long periods of time. Low-tech, quality problems.	Composting in windrows using mechanical aeration by a front-end loader or a specially designed windrow turner. Most common on farms.	Composting in piles or windrows with mechanical aeration and an air source. Forcing or drawing air through the compost pile. In farm and municipal use.	Composting in drums, silos or channels using a high-rate controlled aeration system to provide optimal conditions. Rapid decomposition process year-round. Large-scale systems for commercial applications.
Conversion efficiencies	Volume reduction 40–50%; ammonia to NO_3 and organic N 40–70%; concentration of P, K; organic matter stabilization			
Energy consumption	-	-	-	Container-type (11 d) 10 kWh_el/t
Bulking Agent	Less flexible, must be porous.	Flexible.	Less flexible, must be porous.	Flexible.
Process duration	6–24 months	21–40 days	21–40 days	21–35 days
Curing	Not applicable.	30+ days	30+ days	30+ days
Process control	Initial mix only.	Initial mix and turning.	Initial mix, aeration, temperature and/or time control.	Initial mix, aeration, temperature and/or time control, and turning.
Aeration system	Natural convection only.	Mechanical turning and natural convection.	Forced airflow through pile.	Extensive mechanical turning and aeration.
Odour	Odour will occur. The larger the windrow, the greater the odours.	From surface area of windrow. Turning can create odours during initial weeks.	Odour can occur but can be controlled with e.g. insulation and air filters.	Odour can occur. Often due to equipment failure or system design limitations.
Investment costs	-	Full plant (2000 t/y manure + 1360 t/y sawdust) 35,000–100,000€.	-	Drum composter incl. containers, mixing, conceyors etc. 320,000 €.
Operational costs	-	20 €/t	-	-
Labour	Low labour required.	Increases with aeration frequency and poor planning.	System design and planning important. Monitoring needed.	Requires consistent level of management/product flow to be cost efficient.
Site	Requires large land areas.	Can require large land areas.	Less land (faster rates and effective pile volumes).	Very limited land due to rapid rates and continuous operations.

Costs are reviewed from Flotats et al. (2011) and http://agro-technology-atlas.eu/

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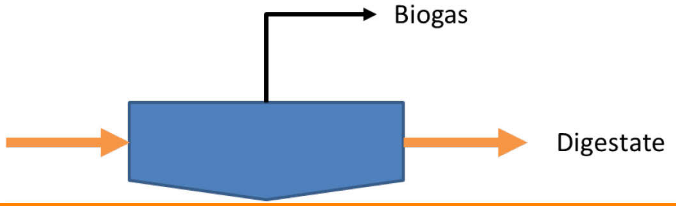
4.4. Anaerobic Digestion

Objective	**To valorize manure energy potential through microbiological anaerobic degradation. Other objectives are reduction of emissions during manure storage, increase of the share of soluble-N in the end-product, possibility to recirculate other organic materials on farms (co-digestion with manure).**
Matrices	Slurry, solid manure (plus additional feed materials)
Outputs	Digestate, biogas
Scale	Farm, medium, full
Level of complexity	Medium
Innovation stage	Mature (industrial/commercial)
General diagram	
Contribution to nutrient recycling	Farm-level or regional level (regional nutrient reallocation may be significantly enhanced if the digestate is post-processed into more concentrated products)

Anaerobic digestion (AD) means microbiological biomass degradation in anaerobic conditions. It is a widely used technique for processing various organic side-streams such as manure. AD recovers energy in the form of biogas (50–70% methane, 30–50% carbon dioxide, traces of other gases) for direct use in combined heat and power plants and/or in vehicles and industry gas after purification (CO_2 removal) and replacing natural gas. It also enables recycling of nutrients and residual organic matter via reuse of digestate as a fertilizer product.

AD is usually operated at a mesophilic (35–40°C) or a thermophilic (50–55°C) temperature range. Mesophilic digestion is conceived to be more resistant towards process disturbances, such as temperature changes, while thermophilic digestion proceeds somewhat faster and can produce higher biogas yields but is more vulnerable to process inhibition. AD can be applied in either wet conditions (totals solids, TS, content <15%) or as dry digestion (TS content over 15%). Wet digestion is suitable for biomasses with initially high water content, for example slurry and sludge. Also feedstocks with a high dry matter content can be added into wet digestion with other, more dilute materials so that the overall dry matter content in the process stays below 15%. Dry materials can also be digested in solid-state processes (also known as high-solids digestion or dry digestion) without additional water or with minor dilution depending on the needs of the reactor type applied. Dry digesters can be operated both in batch and continuous mode (plug-flow).

Table 6. Technologies for anaerobic digestion of manure.

	Wet digestion	High solids (batch)	High solids (continuous)
Description	Cylindrical, continuously mixed reactors, TS <15%.	Windrow- or garage-type reactors, TS >25%.	Drum-type, plug-flow reactors, TS 15–25%.
	Well-known and reliable process.	Higher organic loading rate and thus smaller reactor volume due to higher TS in feedstock. More tolerant towards inerts, such as sand and stones, compared to wet digesters. No problems related to stratification and floating of fibrous material, but challenging to mix and produce heterogeneously stabilized digestate.	
Conversion efficiencies	Around 30% substrate organic matter is transformed into CH_4 and CO_2. Mass change negligible. Total content of nutrients is not affected during the process. Organic nitrogen is partially mineralized into NH_4-N during digestion.		
Energy consumption	10–30% of produced energy is needed for reactor heating, 4–10% of electricity production to mixing and pumping	Less energy used for heating due to smaller reactor volume. Less electricity use if no mixing is applied.	Less energy used for heating due to smaller reactor volume, more electricity is needed for stirring.
Process duration	Continuous, retention time 14–100 d depending on biomass degradability	Batch process, duration around 30–60 d	Continuous, retention time 20–100 d
Process control	Continuous mixing	No mixing. Recirculation of percolation liquid possible.	Continuous mixing
Odour	Odour is reduced in all process types if the process works well. Mixing may be a problem in solid digestion and cause partial degradation and thus foul odours.		
Investment cost	Dependent on the reactor capacity, feedstocks and integration with digestate processing technologies. Costs for digesters treating 50% manure and 50% plant biomass can vary from 0.42 to 0.59 €/kWh for small scale plants, 0.36–0.62 €/kwh for farm cooperative scale and 0.38–0.41 €/kWh for large scale. Investment cost 50 €/ton.		
Operational cost	2.1 €/ton.		
Labour	Medium labour needed, dependent on scale.		
Site	Cylindrical reactors	In batch mode several windrow- or garage-type reactors working in parallel	Drum-type reactors with lower footprint compared to wet-type digesters

Investment costs are estimated according to Gebrezgabher et al. 2012 and http://agro-technology-atlas.eu/

End-products as fertilizers

The organic matter of manure partially degrades during the microbiological digestion process, but all nutrients are conserved. Phosphorus and potassium may be partly solubilized, but the change is more significant with mineralization of organic nitrogen into ammonium nitrogen. The nutrient content of the digestate is dependent on the nutrient content and degradability of the feedstocks.

Availability of P in digested dairy cattle slurry has been noted to be at the same level as in undigested slurry. P availability of both slurry and its digestate was better than in mineral P fertilizer, superphosphate. With the same total P application rates, slurry and its digestate produced higher barley yield as compared to superphosphate.

During digestion easily degradable organic matter is transformed to biogas, but around 20–50% of the feedstock's organic matter is still in the digestate and acts as a soil amendment. Compared to the manure feedstock, pH in digestate is usually higher (pH 7.5–8). Digestate from wet-type digester has a TS content of 2–7%, which is similar to slurries and can thus be stored and spread with similar equipment. In addition, nutrient content can be very similar to slurries (0.5–6 g P/kg, 3–10 g N/kg), only the ammonium concentration is higher in digestates (0.5–5 g NH_4-N/kg). Digestate from solid digestion has higher solids content and can preferably be stored and spread same way as solid manures. It may also resemble semi-solid manure which is difficult to manage due to not being pumpable or stackable. In this case, the dagestate needs to be mechanically separated to enable its practical management.

Environmental effects

The energy use of renewable biogas can replace fossil fuels and the use of digestate nutrients replaces mineral fertilizers. Nitrogen may be more readily available for crops as part of the organic nitrogen is released into a soluble form during the digestion process. However, nitrogen mineralization may also increase the risk for NH_3 emissions and good solutions for digestate storage and spreading are needed. Covered storage is recommended and spreading should be performed with injection (sludge-like digestate or separated liquid fraction from digestate) or direct mulching (in case of solid digestate or separated solid fraction from digestate).

Anaerobic digestion may decrease GHG emissions from manure management if the retention time in the reactor is sufficient, and/or post-digestion is applied and the solutions for manure storage include covering. Furthermore, possible methane emission from the biogas plant due to leakages should be minimized.

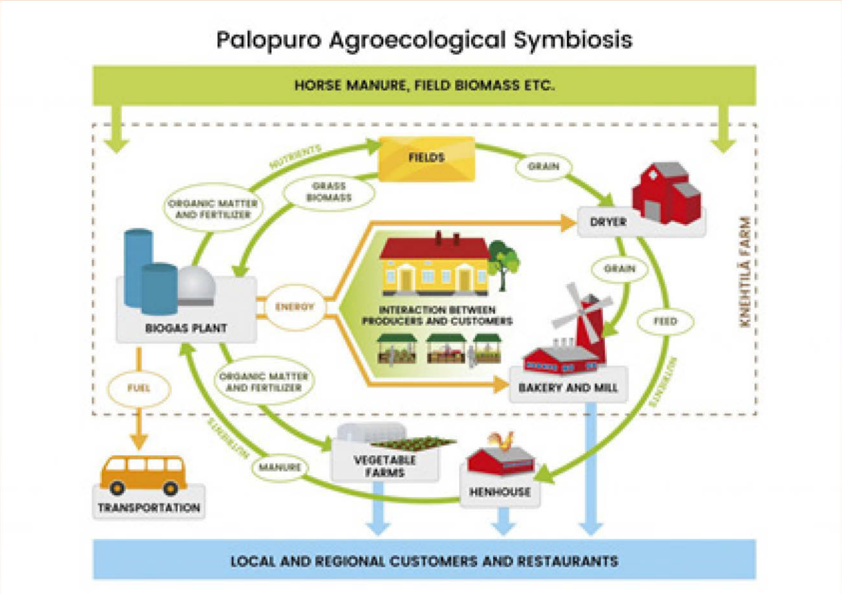
There is a need to post-process the digestate especially in large-scale biogas plants to improve logistics and to enhance nutrient recycling to areas in need of the nutrients. Digestate can be post-processed with various technologies (see: other technologies presented in chapter 4), e.g. solid liquid separation and further refinement of digestate solid and liquid fractions.

Hygienization during AD depends on process parameters; higher temperature and longer retention time increase pathogen removal. Thermophilic digestion can ensure effective pathogen reduction, but at mesophilic temperature range separate hygienization may be needed. To achieve safe end-products in terms of the most relevant zoonotic pathogens (with the exception of spore-forming bacteria), mesophilic AD should be combined with pasteurization (70°C for 60 min) as a pre- or post-treatment, and it would also increase the safety of thermophilic digestates. In addition, thermal hydrolysis as a pre-treatment or thermal drying (see section 4.5.1) as a post-treatment can be used for hygienization, and they are more effective than pasteurization against spore-forming bacteria. Dry digestates can also be composted for further hygienization, but due to nitrogen loss this is not usually recommendable (see section 4.3).

The effect of AD to organic contaminants is still unclear although it is known for some compounds to be biotransformed during the process. However, some compounds are known to be unaffected by the degradation and their fate in the digestate is dependent on their physicochemical nature. AD does not decrease trace element concentrations but slightly increases them in relation to the mass loss of the substrate. Antibiotics may be partially degraded, but different antibiotics can be found in digestates in significant concentrations depending on their concentrations in the feedstuffs.

Case example: Palopuro agroecological symbiosis, Finland

Knehtilä farm in Finland is an organic farm producing mainly cereals. Together with other local enterprises the farm has developed an agroecological symbiosis, which promotes cooperative food production, energy and nutrient self-sufficiency. The feedstocks are green manure leys grown on the farm as part of its crop rotation (2000 t/a) and poultry and horse manure (500–1100 t/a) from neighboring farm and stables. The process used is a batch solid-state digester. The produced energy (2.5 GWh/a) is utilized mainly as vehicle fuel, with the gas upgrading and distribution operated by a local energy company. Digestate is used as an organic fertilizer on the farm.



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Case example: Jepuan Biokaasu Ltd, Finland

In Finland, a large-scale biogas plant (Jepuan Biokaasu) is currently operating with capacity of 90,000 t/a (increases to 150,000 t/a in 2020–2021). The main substrate is pig slurry (around 40,000 t/a), but also cattle slurry and different side-streams from industry and crop production are used. Pig slurry is transported to the plant in pipes from the nearby (distance <5 km) farms. At the time of writing the plant consists of three 4000 m^3 reactors for slurry digestion, but an additional solid-state digestion system is under construction. The solid-state batch process will digest solid manures, straw and industrial side-streams as substrates. Produced biogas (30 GWh/a from the wet digestion alone) is used for plant's own operations, sold as vehicle fuel on-site and sold to industrial use.

The produced digestate is used not post-processed, but used as such as a fertilizer at the time of writing. Digestate is transported to nearby farms through pipes or to longer distances (up to 100 km) by trucks. The biogas plant pays for the transportation. The digestate is a desired product among farmers due to its suitability to organic farming. The plant is also testing digestate separation and processing of the liquid fraction to more concentrated fertilizer products.

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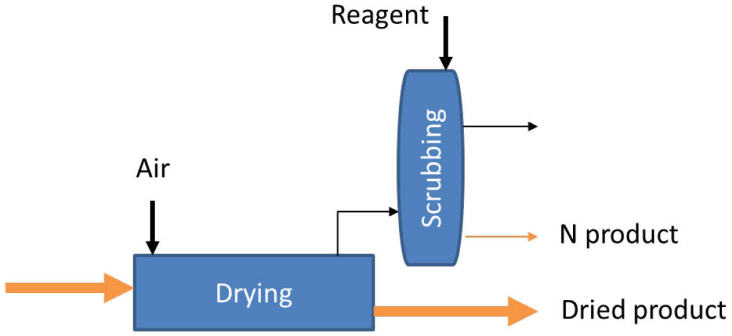
4.5. Technologies for solid manure

4.5.1. Thermal drying

Objective	**Drying the material to >90%TS to reduce mass, conserve nutrients, hygienize and stabilize the material for handling and transport.**
Matrices	Solid manure, separated solid fraction
Outputs	Dried product, gas
Scale	Full (commercial/industrial)
Level of complexity	Complex
Innovation stage	Mature
General diagram	
Contribution to nutrient recycling	Regional level

Thermal drying of solid manure or separated solid fraction from slurry/digestate aims at stabilizing the fertilizer product, reducing its total mass and increasing its nutrient concentration. The total solids content of the final product can reach 95%. The benefits of the technology are reduced volume for transport and storage, improved marketability and effective pathogen kill. Challenges include high investment cost, high energy requirement and nitrogen loss. Drying also produces secondary products, such as a gas fraction (containing dust, ammonia and volatile substances) and reject water (containing ammonia) that require proper management.

To catch volatilized nitrogen, the drying system can be equipped with a nitrogen scrubbing unit producing a nitrogen-rich product, e.g. ammonium sulphate. Another option is to acidify manure prior to drying to retain nitrogen during the process. Drying can be followed by a pelletizing process, which involves molding the dried manure into pellets of a certain size range, to obtain a product that is easier to transport and spread on field. The following techniques can be applied for drying: contact/convection technologies, such as belt, drum and flash dryers; conductive technologies, such as disc, paddle and thin film dryers. In addition, solar and freeze-drying as well as superheated steam drying have been implemented with sewage sludge. Also infrared drying has been developed.

Table 7. Technologies for thermal drying of manure.

	Disc dryer (contact /convective drying)	**Drum/belt dryer (convection drying)**	**Flash dryer (convective drying)**
Description	Heating the dryer surface delivers heat to the material. Less exhaust gas formed. Overheating and uneven heating of the material possible.	Drying with direct contact with hot air (60–150°C) for approx. 2 h on conveyor belts or drums. In drum-type systems material is in contact with hot air through rotation in a drum. High dry matter content achieved. Can utilize heat exchangers and flue gases. High dust formation. Long drying time. To enhance evaporation of water, large contact surface is needed.	Less space needed and simple construction.
Conversion efficiencies	5–20% of mass and 100% of P remains in the dried product. P recovery is dependent on the treatment of flue gas/condensate.		
Energy consumption	800–900 kWh/t of evaporated water	700–1100 kWh/t of evaporated water	1200–1400 kWh/t of evaporated water
Reagents	E.g. sulphuric acid can be used to control ammonia emissions.		
Process rate	7–35 kg/m^2/h	30 kg/m^2/h	0.2 kg/m^2/h
Odour	Steam and odours confined	Odorous	Odorous
Investment cost	300,000 € for dryer treating 30 m^3 of digestate per day		Higher compared to belt and disc systems
Operating cost	5.81 €/m^3		

Costs estimated based on Bolzonella et al. 2018.

End-products as fertilizers

Dried manures have a solid powder-like form with a TS content of 60–95% and can be stored in silos. The content of P is high (4–35 g P/kg depending on feedstock). N content can be very similar to that of P, but its solubility is negligible due to volatilization of ammonia and retainment of only organic nitrogen. Dried manures may need post-processing with granulation or pelletization to produce marketable and more easily manageable and spreadable product. The fertilizer use of a dust-like product requires special machinery.

Depending on the drying temperature, solubilization of P may increase. In a pelletized form, dried manures have shown equal fertilizer value as mineral P fertilizers in field tests.

Environmental effects

As the exhaust of the dryers contains dust, ammonia and other volatile substances (e.g. volatile acids), exhaust gas cleaning systems have to be applied to reduce emissions. Such systems contain a dust filter as well as washer/scrubber units. To recover volatile nitrogen, the exhaust gas is to be scrubbed.

Thermal drying enables effective hygienization and partial organic contaminant removal (depending on temperature). To be effective against pathogens, temperature should be raised to at least 80 °C for 10 min and the moisture content reduced to less than 10%. Non-volatile trace elements are concentrated into the end-product due to decreasing water content.

Case example: Fertilex, Finland

Fertilex is a company processing poultry manure in Mynämäki, Finland. The processing plant is located at a poultry farm with 300,000 laying hens and manure production of around 12,000 t/a. In Fertilex's manure processing system, solid manure from the animal houses is dried with a belt dryer, pelletized and hygienized. The product formed is then packed and sold as a fertilizer. The processing equipment is delivered by the Dutch Dorset Group.

The estimated annual production of pelletized product is around 4000 t. The drying process utilizes the excess heat from the animal houses and, if needed, energy from wood-based heat production. The aim of the manure processing is to decrease the need for manure transportation, to ease manure handling and to decrease ammonia emissions.

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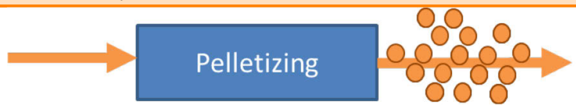
4.5.2. Pelletizing / granulation

Objective	**To increase product density and produce marketable and easily handled product from dried manure**
Matrices	Solid manure, dried solid manure, dried solid fraction, ash
Outputs	Pellets/granules
Scale	Large
Level of complexity	Complex
Innovation stage	Industrial/commercial
General diagram	
Contribution to nutrient recycling	Farm and regional level

Prior to pelletizing or granulation, manure needs to be either dewatered with solid-liquid separation (slurry, see: 4.1) or thermally dried (solid manure, see: 4.5.1).

The granulation process usually consists of size agglomeration, drying and screening, which ensure the production of even-sized granules. In pelletizing, the material is pressed through a die with holes of the desired shape and size. Pellet compression and temperature are the major factors affecting the process and end-product quality.

End-products as fertilizers

The TS and nutrient content of pelletized or granulated manure are similar to dried manure product, while the density is increased. Pelletized/granulated products are suitable for spread with similar equipment as mineral fertilizers.

Phosphorus fertilizing effect of pelletized fox manure has been noted slightly better than that of composted fox manure. This may be partly due to the concentrated P batches in the soil, improving P availability compared to the situation where compost is more diluted in the soil volume.

Environmental effects

During the process there is a risk for dust emissions if exhaust gases are not recovered or filtered. Dust can be recirculated in the process.

Table 8. Technologies for pelletizing and granulation of manure.

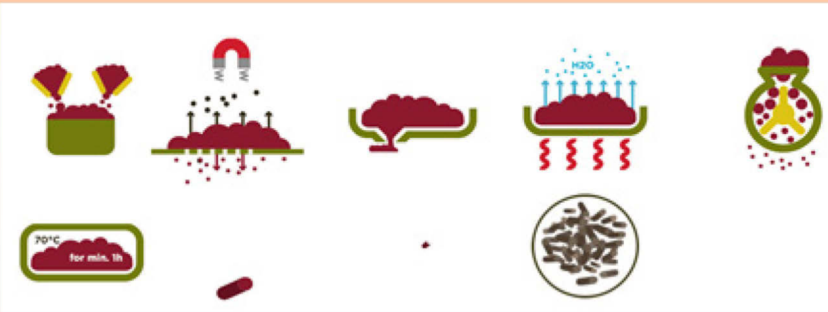
	Pelletizing	Granulation (disc/drum)
Description	Pre-dried manure is pushed or pressed through dies under high pressure. Due to high temperature, the surface of pellets melts and forms shiny coating.	Manure solid fraction (TS 20–40%) is mixed, screened and granulated. In disc granulator, an inclined rotating pan facilitates nucleation and formation of even-sized spherical granules. Granule size can be affected with pan rotation and manure feed-in rate. After granulation, granules are thermally dried and screened.
Conversion efficiencies	Increases bulk density of drier material from 250–350 kg/m^3 to over 700 kg/m^3.	If drying is included, reduction of water content. Otherwise manure mass and nutrients are conserved within the granulated product.
Energy consumption	30–50 kWh$_{el}$/t	
Reagents	Water can be used to bind material. Possibility to add also nutrients to balance NPK ratios of the product.	Binders can be used. Possibility to add also nutrients to balance NPK ratios of the product.
Process control	Pellet/granule quality needs to be monitored to produce uniform products.	
Odour factors	Dust and gas fractions are recovered to reduce odours.	
Investment cost	-	1.0–1.3 M USD for the treatment on manure from 21,000–23,000 cows (cost excluding manure separation equipment cost) (890,000–1,160,000 €,~45 € per cow)
Site	When connected with manure drying unit, the plant size can be optimized.	

Costs estimated based on Shahara et al. 2018.

Case example: Fertikal, Antwerp, Belgium

Fertikal, in the Belgian port of Antwerp, collects organic materials from up to 150 km, including 18,000 tonnes of digestates from biogas plants, 200,000 tonnes of different manure types (poultry, solid fractions of cattle and pig manure), 60,000 tonnes of other secondary raw materials (by-products from food and animal feed industries) and secondary raw minerals (e.g. struvite). Fertikal produces 200,000 tonnes of compost mixing the feedstocks to obtain an optimal NPK-ratio for different crop demands. The final products, pellets and crumbs, are produced using extrusion at 75,000 tonnes per year. The pellets (3–5 mm width, 10 mm length) are suitable for arable and horticultural crops. The crumbs (1–3 mm) are broken and sieved pellets that are ideal for precision farming, mixing in substrates, potting or fertilizing lawns. The products are nearly all exported.

Pelletizing process by Fertikal [www.fertikal.nu]



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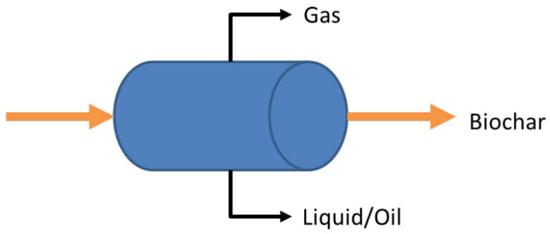
4.5.3. Pyrolysis

Objective	**To produce solid, hygienized, carbon-enriched biochars (C content >50% DM) or chars (C content <50%). To reduce manure volume and to concentrate P. Higher added value by the use of by-products.**
Matrices	Dried solid manure, dried solid fraction
Outputs	Char fraction and pyrolysis gases and liquids
Scale	Different stages of development (also depending on raw material) from demonstration/pilot plant to industrial plants.
Level of complexity	From medium to high.
Innovation stage	Different stages of development, from demonstration or pilot plant to industrial plants.
General diagram	
Contribution to nutrient recycling	Regional level

Pyrolysis (carbonization, thermochemical decomposition) is a technology under development for manure management. It is a process in which biomass is thermally decomposed into gas (pyrolysis gas), liquid (pyrolysis liquid) and solid (biochar or char) fractions in low-oxygen conditions or in absence of oxygen at a temperature range of 350–700 °C in a relatively short time. Up to 50% of the raw material mass can end up in the gas and liquid fractions, thus cutting the need for manure storage and transport capacity significantly. Pyrolysis concentrates non-volatile compounds, such as phosphorus and potassium, in the char fraction, whereas volatile compounds, such as nitrogen, end up in gas and liquid fractions. Thus, most of the phosphorus is recovered in the solid char fraction.

End-products as fertilizers

Properties of the char fraction depend strongly on the initial substrates and the process conditions (e.g. temperature, heating rate). Thus, pyrolyzed manures differ from those of e.g. plant-based biochars being often more alkaline and rich in phosphorus and ash. The ash content is often over 50% which is the limiting value for using the term biochar according to European Biochar Certificate. P solubility in pyrolyzed manures seems to be lower than in raw manure. Therefore, the crop availability of P in different pyrolyzed manures, especially in longer term, needs to be assessed. Nitrogen in pyrolyzed manure tends to be in an unavailable form. The most suitable spreading technology for pyrolyzed manures and the possible needs for post-processing require more research and development (e.g. pelletizing or granulation). At the moment, pyrolyzed manures are not included in the new EU Fertilising Products Regulation (EU/2019/1009).

Table 9. Technologies for pyrolysis of manure.

	Slow pyrolysis	Fast pyrolysis
Description	Heating rate 1–100 °C/s and the temperature range 350–700 °C.	Heating rate >1000 °C/s and the temperature range 450–550 °C.
General	Suitable for relatively dry materials; otherwise pre-drying needed. Maximizes yield of char fraction.	Suitable for relatively dry materials; otherwise pre-drying needed. Maximizes yield of liquid fraction.
Conversion efficiencies	Produces 15–40% char, 20–55% liquid and 20–60% gas fraction from original feedstock mass.	Produces 10–30% char, 50–70% liquid and 5–15% gas fraction from original feedstock mass.
Energy consumption	Energy required in pre-drying and in increasing and maintaining pyrolysis temperature. Energy from produced gas can be used, but it is not always sufficient.	
Reagents	Non-biomass materials may be added to catalyze the process or to modify the ration of the different products.	
Process duration	Residency time of biomass hours.	Residency time <1 min.
Odour	Char fraction more or less odourless.	
Investment cost	No data	

Environmental effects

To increase the sustainability of pyrolysis, nitrogen should be recovered and the liquid fraction utilized. Feasible usages for the liquid fraction are under research. The energy from pyrolysis gases and liquids could also be recovered at the pyrolysis plant for pre-drying the input material or for heating the pyrolysis reactor. In conclusion, the benefits from manure pyrolysis must be weighed against the emissions resulting from the pyrolysis.

Due to the mass and volume reduction of the original biomass, the transportation and storage of pyrolyzed manure become more economical. Related to contaminants, nonvolatile persistent pollutants, such as trace elements, concentrate to the char fraction, whereas pathogens are destroyed. Pyrolysis with severe time-temperature profiles is, in general, more effective against organic contaminants, although some of them are more persistent. Organic contaminants, such polycyclic aromatic hydrocarbons (PAHs), dioxins and furans (PCDD/F) and dioxin-like polychlorinated biphenyls (dl-PCB) can be formed, although their levels can be restricted during the pyrolysis process.

Case examples

At the moment pyrolysis industry comprises of enterprises with relatively small volumes. The current markets in Europe are relatively small and production is focused on the plant-based materials with low P-content. For example, companies operating in Germany are Pyreg GmbH, Terra Preta e.K., Carbon Terra SPRL and Swiss Biochar GmbH.

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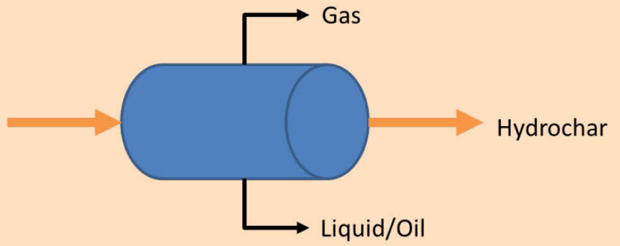
4.5.4. Hydrothermal carbonization (HTC)

Objective	**To produce a hygienized, carbon-enriched end-product and to reduce manure volume from slurries without the need to pre-dry.**
Matrices	Slurry, semi-solid manure
Outputs	Hydrochar and pyrolysis gases and liquids. Without dewatering the moisture content of hydrochar (10–40%) is much higher than that of char from pyrolysis (0–5%).
Level of complexity	From medium to high.
Innovation stage	Ongoing research for HTC of manures and slurries.
General diagram	
Contribution to nutrient recycling	Local level (regional level in case of post-drying)

In hydrothermal carbonization (HTC) the processed biomass can have a lower total solids content compared to pyrolysis as water is used as the reaction media. In temperatures between 125–350°C and a heating rate of 5–10 °C/min, the water is in subcritical conditions and acts as a mild acid and base. In HTC, pressures between 0.5 and 20 MPa are applied to avoid evaporation of water. Either O_2 or H_2O_2 can be added as an oxidizing agent. The end-products are gas, liquid and carbon-containing solid fraction (hydrochar), the characteristics and distribution of which are dependent on the processing conditions (temperature and pressure). There is still very limited information on the investment and operational costs related to HTC of manure as the first commercial-scale processing plants have just started operation co-processing manure with other biomasses, such as sewage sludge.

End-products as fertilizers

From the original feedstock mass HTC transforms 5–40% to solid hydrochar, 20–40% to liquid fraction and 2–10% to gas fraction. As with pyrolysis, process conditions such as temperature, pressure, residence time and the ratio of water to biomass affect the characteristics of the end-products. Generally, hydrochars have lower C and ash content and slightly lower pH compared to biochars. Most of the P from manure ends up in hydrochars as precipitated phosphate salts, whereas N goes to the aqueous solution. The solubility of P in manure-based hydrochar can vary depending on process temperature. However, reduced P solubility in HTC treated cattle manure has been noted. Knowledge on plant-availability of P in manure-based hydrochars is still limited.

Hydrochars still need post-processing (e.g. thermal drying) to be transportable over longer distances. As with pyrolyzed manure, the most suitable spreading technology must be assessed as well as possible needs for post-processing. Very little information is available regarding agricultural use of manure-based hydrochar. At the moment, hydrochars are not included in the new EU Fertilising Products Regulation (EU/2019/1009).

Environmental effects

In general, HTC-process has a potential to degrade organic contaminants, although HTC in low temperatures can have lower contaminant removal rates than pyrolysis and its more severe conditions. Chlorinated aromatics seem to be recalcitrant in HTC-treatment. Trace elements can accumulate in hydrochar.

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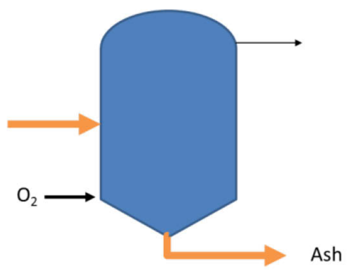
4.5.5. Combustion/Incineration

Objective	**Energy production. Effective reduction of feedstock mass.**
Matrices	Solid manure, solid fractions, dried manures
Outputs	Ash, heat
Scale	Full (scalable)
Level of complexity	Complex
Innovation stage	Mature technology for municipal waste and sewage sludge-processing. Used for processing solid manures.
General diagram	
Contribution to nutrient recycling	Regional level

During combustion, biomass is oxidized in the presence of oxygen to produce energy and to greatly reduce the mass of the processed biomass. Combustion temperatures are conventionally above 900°C. Produced thermal energy can be converted to electricity with a steam generator and turbine. The feedstocks need to be relatively dry (TS >70%) to achieve sufficient energy efficiency, and usually pretreatment with thermal drying is needed. There are several combustion technologies available, e.g. grilled bed and rotatory drum of fluidized bed reactors. Efficient flue gas treatment must be applied in all combustion plants. Several technologies are available to recover phosphorus from the incineration ash. These technologies are not yet used with manures, but with ashes from combustion of sewage sludge.

The technology is most suitable for centralized, large-scale processing. Reported equipment costs for a power plant combusting poultry manure were 6.27 M€ for a 21.5 MW plant with a capacity of 2 t/h and 20.7 M€ for 6 MW plant with capacity of 6 t/h.

End-products as fertilizers

Over 70% mass reduction is achieved during combustion, and the end-product has a TS of >80%. Nitrogen is fully evaporated during the process, but phosphorus remains in the ash (50–110 g P/kg). Higher energy efficiency is achieved with dry feedstocks, but also materials with higher water content can be used. The solubility of P is reduced decreasing the fertilizer value of ash which is also not recommended as a starter P fertilizer. Ash can be used as such in fertilization or processed into pellets or granules. Product needs to be stored in dry conditions to prevent moisture effects on the ash quality.

Environmental effects

There is an emission risk from flue gases. During combustion nitrogen in converted mainly to N_2, but to ensure its recovery, subsequent N recovery steps needs to be applied.

Combustion does not decrease non-volatile trace element concentrations but increases them in relation to the mass loss of substrate. The remaining ash needs most likely to be processed further. Antibiotics and most other organic contaminants are eliminated. It is assumed that thermal treatment of organic materials at high temperatures (850–950 °C) destroys organic contaminants to a large extent. Due to severe process conditions, pathogens are destroyed.

Case example: Fortum Horse Power, Finland

A Nordic energy company Fortum has developed a concept for utilization and management of horse manure via co-combustion. Fortum offers both bedding and manure management services for horse stables in both Finland and Sweden (at the time of writing in total 4300 horses in 260 stables). The bedding consists of wood-industry side-streams, which are delivered to the stables. Manure together with the used bedding material is transported from the stables to Fortum's co-combustion power plant to produce electricity and heat. The concept started as a pilot project in Järvenpää, Finland but has since spread to other Fortum's co-combustion plants around Finland. According to Fortum's calculations, horse manure has an energy content of around 0.6 MWh/m^3 and two horses produce manure sufficiently heat to one family house for a year under Nordic conditions.

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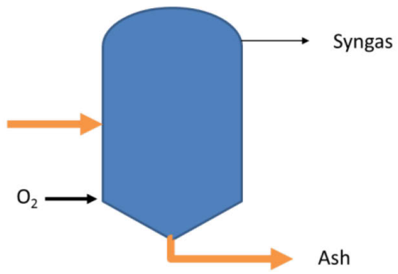
4.5.6. Gasification

Objective	**Syngas production through partial oxidation.**
Matrices	Solid manure, solid fractions, dried manures
Outputs	Ash, gas, liquid
Scale	Full (scalable)
Level of complexity	Complex
Innovation stage	Mature technology for municipal waste and sewage sludge treatment. Little demonstrations with manures.
General diagram	
Contribution to nutrient recycling	Regional level

Gasification is a thermal process which in low-oxygen conditions converts biomass into carbon monoxide, carbon dioxide and methane, i.e. syngas. Process temperature is high, >700 °C. Oxygen, air or steam is injected to the combustion chamber to enable partial oxidation. High feedstock solid content is needed (TS>70%). Feedstock composition affects process conditions and thus feedstock quality should be constant.

For processing poultry manure in a gasification plant with a capacity of 100 t/day, the investment cost was 2.7 M€, equipment cost 900,000 € and operational costs 1.76 M€.

End-products as fertilizers

The ash produced has very low mass compared to the original manure feedstock. The manure phosphorus is retained in the ash, while nitrogen is evaporated unless it is recovered in a subsequent drying step. Ash is a P fertilizer, but gasification reduces the solubility of P and thus decreases its value as a fertilizer. Ash can be used as such in fertilization or processed into pellets or granules. The product needs to be stored in dry conditions to prevent moisture affecting the ash quality.

Environmental effects

Emission risks from gasification are lower compared to traditional combustion. During gasification, there is a risk of formation of PAH compounds.

Nitrogen management and recovery during the processing chain needs to be taken into account.

Process efficiently sanitized manure and removed harmful organic compounds, but it may concentrate trace elements into ash.

Case example: Agro America, the Netherlands

Agro America in the Netherlands has developed pig slurry processing to decrease regional manure surpluses. The first step in the process chain is to separate slurry into solid and liquid fraction. The phosphorus is recovered from the solid fraction through gasification. The phosphate rich, solid, char-like material can be used as a soil amendment in areas where phosphates are truly needed. In addition, the process also includes purification of the liquid fraction with membranes and evaporation to clean the water and recover nitrogen and potassium.

Photo: www.rvomagazines.nl/miavamil/2017/01/taj-willems-agro-america-bv

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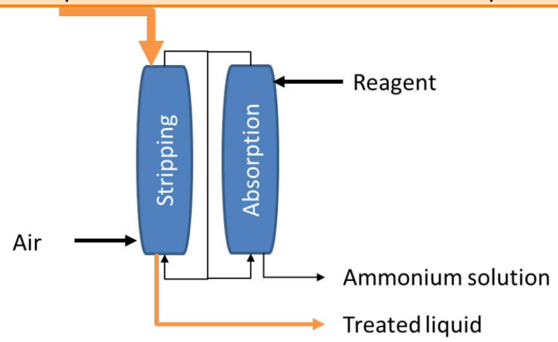
4.6. Nutrient recovery technologies for liquid fractions

4.6.1. Ammonia stripping

Objective	**Recovery of ammonium nitrogen in the form of ammonia from liquid fractions and production of an inorganic fertilizer**
Matrices	Liquid fraction (digestate, air)
Outputs	E.g. ammonium sulphate, treated liquid/reject water
Scale	Full
Level of complexity	Complex
Innovation stage	Mature technology for wastewater treatment, some full-scale processes in connection to manure processing
General diagram	
Contribution to nutrient recycling	Farm and regional level

During ammonia stripping, the ammonium nitrogen is stripped to gaseous ammonia by blowing air through the liquid flow in a stripping column. The volatility of ammonia is increased by increasing temperature (up to 80°C) and pH (up to 10). Gaseous ammonia is then absorbed into an acidic solution in a scrubber unit to produce an ammonium-rich end-product. Usually used acidic reagents are sulphuric acid forming ammonium sulphate, but also nitric acid can be used to produce ammonium nitrate. Another method for ammonia stripping is the use of higher temperatures to produce vapor. In this process, ammonia is directly condensed together with the water vapor to produce ammonia-water, and no scrubber column is needed. Ammonia stripping can also be used to lower the ammonium concentration of biogas plant digestate and to capture ammonia from animal housing.

The heat needed for the stripping process can potentially be taken from the excess heat of a biogas plant, and the pH decrease can be achieved also with CO_2 stripping before the process to lower the buffer capacity needed. Stripping columns are usually filled with a packing material to ensure sufficient mass transfer between gas and liquid.

To ensure the function of the stripper, the liquid fraction processed should be free from solid material to prevent clogging of the packed column. The cleaning of the column requires chemicals and labor.

Table 10. Technologies for ammonia stripping in manure-based liquid fractions.

	Air stripping	Vapor/steam stripping
Description	Use of air to strip ammonia from the liquid at 40–80°C. Use of a scrubber to recover ammonia e.g. as ammonium sulphate.	Use of air vapor (>100°C) to strip ammonia from the liquid. Ammonia is recovered with the vapor condensate as ammonia-water.
Conversion efficiencies	70–99 % of NH_4-N in product	
Energy consumption	Lower energy consumption compared to vapor/steam stripping.	More heat need due to higher process temperature compared to air stripping.
	Power: 2–10 kWh/m^3 input Heat: 45–100 kWh/m^3 input	
Reagents	Use of reagents for pH decrease and ammonia scrubbing. Increased need for pH decrease compared to vapor/steam stripping.	Reagent for pH decrease. No scrubbing reagents used.
	95–97% sulphuric acid 7–10 kg/m^3 and NaOH 6–6.5 kg/m^3 (for a digestate liquid fraction).	
Process duration	Batch/Continuous	Batch/Continuous
Process control	Both technologies need active control and maintenance.	
Investment cost	750,000 € for a system treating 100 m^3/d of digestate.	-
Total cost	5.44–8 €/m^3	-
Labour	Need of regular maintenance and cleaning. Stripping columns are prone to fouling due to particles in the stripped liquid stream.	
Site	Possible CO_2 stripping column + ammonia stripping column + ammonia scrubber.	Lower space requirement as no scrubber column needed.

Costs estimated based on Bolzonella et al. 2012 and Vaneeckhaute et al. 2017.

End-products as fertilizers

End-products from ammonia stripping are dependent on the scrubbing solution used. If water is used, a mild ammonium solution is formed. With sulphuric acid, a liquid ammonium sulphate fertilizer is formed with around 2–11% of N. With nitric acid scrubbing, ammonium nitrate solution is formed with 13–20% N. Due to the safety risk with ammonium nitrate handling, nitric acid is not very commonly used as the scrubbing reagent.

Both ammonium sulphate and ammonium nitrate can be used in fertilization as mineral fertilizers. All nitrogen is in a mineralized form and no P or K is present. The use of nitric acid increases the N content in the final product, while sulphuric acid adds sulphur, which can also serve as a micronutrient. The low pH of ammonium sulphate can cause corrosion in spreading equipment and also negative effects on crops, but it reduces ammonia volatilization during storage and spreading. The storage and spread of ammonia-water solution requires prevention of ammonia volatilization. The storage of these fertilizers requires safe handling.

The secondary product from ammonia stripping is the dilute reject water with no organic N, P and K. This liquid can be used locally in fertilization or it can be further processed.

Environmental effects

Ammonia stripping poses a risk for ammonia volatilization and release during processing and maintenance of the system. Depending on the end-products, there is also a risk for ammonia emissions during storage and spreading (mainly ammonia-water).

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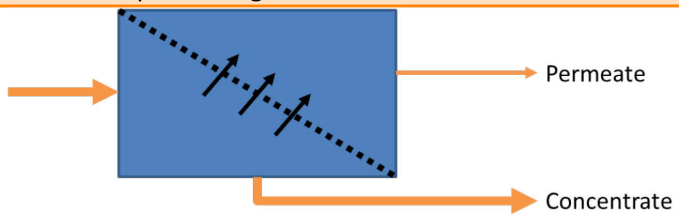
4.6.2. Membrane separation

Objective	**To remove water and concentrate nutrients.**
Matrices	Liquid fractions
Outputs	Concentrate, permeate
Scale	Scalable
Level of complexity	Moderate
Innovation stage	Applied in wastewater treatment, only few full-scale solutions in manure processing.
General diagram	
Contribution to nutrient recycling	Regional level

In pressure-driven membrane separation, liquid is passed through a membrane, where the separation is based on the pore size and the pressure applied or the dissolution to the membrane and the diffusion velocity. Particles retained by the membrane form a concentrate, while water and ions passing the membrane form a permeate. Membranes consist of either polymers or ceramics, of which ceramic membranes are known to withstand also harsh chemical cleaning. The membrane modules can be hollow fiber, flat sheet, tubular, or spiral wound.

Membrane technologies are divided into four categories depending on their pore size. Especially microfiltration (MF) but also ultrafiltration (UF) is mainly used as a pretreatment to remove solids from the liquid flow. Efficient recovery of nutrients is possible with nanofiltration (NF) and reverse osmosis (RO). RO is able to recover ammonium nitrogen, and the recovery can be aided with adjusting pH lower. With membrane filtration, the increase of pressure increases the separation capacity. With increasing temperature, the flux of the processed water is increased leading to decreasing the size of the processing plant. However, increasing temperature can also lead to loss of ammonia.

Membranes are usually applied in series, e.g. NF + RO, where RO can have several steps. Pretreatment of the input liquid fraction is needed as UF, NF and RO are very sensitive to solids. Particulate matter leads to clogging and fouling of the membranes and increases water, energy and chemical consumption.

End-products as fertilizers

The concentrates produced are liquid with a TS content up to 15%. Nitrogen concentrations can be relatively high (2–20 g N/kg), depending on the characteristics of the liquid feedstock and preceding process steps, but phosphorus content is usually lower (up to 1 g P/kg) due to the exhaustion of P during preceding solid-liquid separation. Storage of these materials should be executed in airtight containers to prevent ammonia emissions. Membranes are able to remove even viruses from the water flow, but they are usually aimed at recovering the nutrients. There may be other harmful compounds and salts concentrating into the product.

The secondary product, permeate, has very low nutrient concentrations and does not usually have any value as a fertilizer. Permeate is usually used as process water required in the processing plant or purified with e.g. RO to produce clean water dischargable to the environment.

Table 11. Technologies for membrane separation of manure.

	Microfiltration	Ultrafiltration	Nanofiltration	Reverse Osmosis
Description	Pore size 0.05–10 µm to retain particles, suspended solids and bacteria. Pressure 0.1–2 bar. Used as a pretreatment to remove solids and organic matter.	Pore size 0.01–0.05 µm to retain suspended solids, colloids, oil emulsions, enzymes and viruses. Pressure 1–5 bar.	Pore size 0.001–0.01 µm to retain colloids, enzymes, tensides, metal ions and dissolved salts. Pressure 5–20 bar.	Pore size 0.0005–0.005 µm to retain metal ions and dissolved salts (e.g. NH_4). Pressure 10–100 bar.
Conversion efficiencies	Efficient solid separation.	-	-	90–100% TS, 96–100% N, 70–95% P
Energy consumption		From 0.2–1 up to 8.8 kWh/m^3	0.7–2 kWh/m^3	1.5–10 kWh/m^3
Reagents	Yes, for cleaning (acids, alkali).		Yes, for cleaning (acids, alkali) and pH control. Ammonia recovery is enhanced by decrease in pH.	
Process duration	Continuous, several stages can be applied.			
Process control	Slightly less cleaning needed compared to NF and RO.		Needs maintenance and cleaning.	
Investment cost	Over 1 M€ for a UF + RO system with a capacity of m^3/day.			
Operation cost	1–13 €/m^3			

Costs estimated based on Bolzonella et al. 2012, Vaneeckhaute et al. 2017 and http://agro-technology-atlas.eu/

Environmental effects

No emissions from the process. Treatment and management of the permeate needs to be acknowledged.

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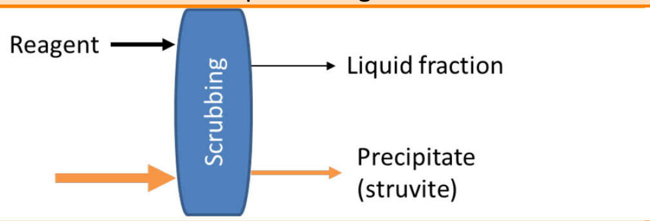
4.6.3. Struvite precipitation

Objective	**Recovery of phosphorus and ammonium nitrogen as a solid fertilizer (magnesium ammonium phosphate)**
Matrices	Slurry, digestate, liquid fraction
Outputs	Struvite, reject water
Scale	Full (usually in industrial scale only)
Level of complexity	Moderate
Innovation stage	Mature technology for wastewater treatment, few full-scale processes in manure processing.
General diagram	
Contribution to nutrient recycling	Regional level

The precipitation and crystallization of struvite (MAP, magnesium ammonium phosphate) from manure-based liquid fraction or slurries can be executed in stirred-tank vessels or fluidized bed reactors. The process pH is maintained in the range of 8.3–10 with addition of NaOH. Mg and in some cases even P is added to maintain nutrient ratios of 1.3:1:0.9 for Mg:N:P, if ammonia is in excess. The separation of struvite crystals can be continuous from the bottom of the reactor or separated with centrifuge after the reactor. Struvite precipitation can remove 80–90% of soluble P in the processed liquid fraction and 10–40% of NH_4-N. With struvite precipitation from manures, adequate size of the crystals for separation may be difficult to achieve. Electricity consumption of struvite precipitation has been estimated to be 0.8 kWh/m^3 input.

Another option is to precipitate P as other crystals, such as K-struvite or calcium phosphates, such as hydroxyapatite or brushite. There is a need for CO_2 stripping to avoid calcium carbonate formation and precipitation. P removal efficiencies with calcium phosphate production can be as high as 100%, but 50–60% is more common. The precipitation of calcium or other phosphates can also be a non-wanted phenomenon during struvite precipitation.

There are noted challenges with chemical use and maintaining a stable process and a stable product quality with precipitation of nutrients. The process is very site specific due to the varying characteristics of input liquids. Inappropriate nutrient rations may affect the precipitation of struvite and decrease process yields. High costs are related to chemical use (Mg, NaOH) and initial investment. Struvite production plant in a wastewater treatment plant can cost 1.4 M€ and operation cost be 0.2–0.3 €/m^3 of digestate. For a pilot plant for manure processing, an estimated cost of crystallization reactor has been reported as 4.85–7.25 €/m^3 (simplified reactor 2.41–3.62 €/m^3).

End-products as fertilizers

Struvite is a good fertilizer with higher NH_4-N and P content compared to solid manures and slurries (TS 60–100%, P 60–130 g/kg, N 30–60 g/kg) and providing also Mg as a micronutrient. Its solid, crystalline form enables storage and spread similarly to mineral fertilizers. Particle size of the final product can be 0.5–5 mm depending on process design and desired end-use.

Struvite releases both nitrogen and phosphorus slowly. P availability to crops has been estimated to be comparable to superphosphate.

The residual liquid flow is dilute and may contain organic and soluble nitrogen, phosphorus and potassium and its management and processing must be taken into consideration when planning struvite precipitation from manure-based liquid fractions.

Environmental effects

There are no emissions from the reactors, but there is a risk of ammonia volatilization when pH is increased.

Struvite precipitated after dewatering has low trace element concentrations. It has also been noted to have low concentrations of antibiotics. Generally, the contamination of struvite with organic contaminants is low because more than 98% of them stay in solution when the process is optimized.

As with stripping, organic contaminants and other harmful compounds are not chemically bound to the main nutrient product (struvite) but remain in the reject flow. Depending on the previous processing steps, produced struvite crystals may also need hygienization.

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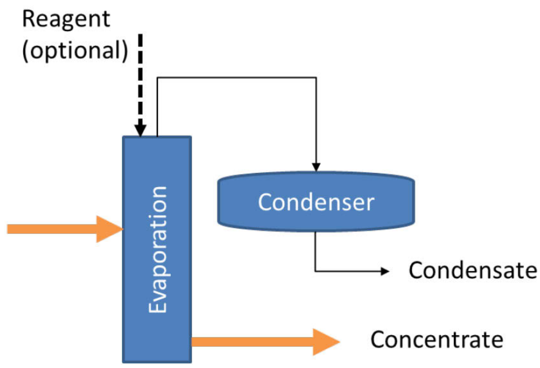
4.6.4. Vacuum evaporation

Objective	**To remove water and concentrate nutrients within the concentrate.**
Matrices	Liquid fraction
Outputs	Concentrate, condensate/reject water)
Scale	Industrial (scalable)
Level of complexity	Complex
Innovation stage	Mature
	
Contribution to nutrient recycling	Regional level

In vacuum evaporation liquid fraction is concentrated under negative pressure in a closed vessel to form nutrient-rich concentrate that also contains all residual solid matter from the liquid. The processed liquid is dispersed on the inner surface of the evaporator, which is heated. The vacuum conditions reduce the boiling point of water to 40–75 °C.

The TS content of the concentrate is around 15%. The condensate is received after condensation of the evaporated water vapor. If the pH of the liquid fraction is not reduced prior to vacuum evaporation, ammonia is volatilized and recovered within the condensate. Vacuum evaporation is usually connected with an ammonia scrubber to recover ammonia with sulphuric acid. If pH is reduced (typically to a level of 4.5 with sulphuric acid), also ammonia is recovered within the concentrate along with P and K.

The energy requirements of the single-stage vacuum process are 10–13 kWh/m^3 of material processed for power and 600–1000 kWh/m^3 of evaporated H_2O. However, to recycle heat and reduce energy inputs, evaporation is usually performed in series in several units, e.g. in a 4-stage process the power requirement is 5 kWh/m^3 and the heat demand only 250–350 kWh/m^3 of evaporated H_2O. Due to the relatively high energy, especially heat consumption evaporation is conventionally applied after anaerobic digestion and biogas upgrading in a CHP, where excess heat energy is available.

End-products as fertilizers

Evaporation can recover 80–99% of N and 85–100% of P from the treated liquid fraction. Concentrates have higher nutrient content compared to manures and slurries due to separation of excess water during the treatment (2–7 g P/kg, 5–40 g N/kg). In addition, the reduced volume requires less storage capacity. The concentrate can be used as a liquid NPK fertilizer, with relatively high nutrient concentrations compared to manure slurries. The secondary product, condensate can be used as process water or be treated with RO to produce clean water.

Environmental effects

No emissions from the process, but there is a risk of concentration of salts and harmful compounds to nutrient concentrate.

During evaporation high temperatures can further hygienize treated liquids, but for example metals and salts are concentrated to the products. Also, volatile organic compounds may be transferred to the condensate.

Case example: Gasum, Vehmaa, Finland

Gasum Vehmaa is a biogas plant, commissioned originally in 2005 by Biovakka Finland Ltd. The plant processes around 90,000 t/a enzyme and food industry wastes and pig slurry (total capacity 120,000 t/y, 32 GWh/y). The plant produces electricity, which is partly used onsite and partly fed to the grid (~6700 MWh/year). The heat produced is used both onsite and in a nearby greenhouse. The digestate is solid/liquid separated by centrifuges. The solid fraction is mainly used locally as a fertilizer, while the liquid fraction is concentrated in a vacuum evaporator. The nutrient-rich concentrate is used as a fertilizer but also sold to paper industry needing especially nitrogen in their wastewater treatment plants. The condensate from the evaporator, which contains trace nutrients but near zero carbon and solids, is purified by reverse osmosis before discharge.

Photo: Gasum Ltd

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4.7. Technology chains for manure processing

One unit process is usually not enough to process manure into fertilizer products that can be transported longer distances to areas where e.g. phosphorus is needed, and are truly desirable fertilizers among farmers. To achieve this, several processing technologies may be implemented in a sequence. However, the most suitable manure processing technologies and technology chains are always site-specific and are dependent on the economics of the total processing chain.

Here we demonstrate two manure processing chains, which can be applied for cattle or pig slurries. In the first example (Fig. 10), slurry is separated by screw-press. The liquid fraction is treated with struvite precipitation to capture phosphorus and the reject water is further processed with ammonia stripping to recover residual ammonia. The remaining liquid water thus still contains e.g. potassium. The solid fraction from the screw-press is thermally dried. In this first technology chain, 77% of P in the original slurry can be recovered in struvite and 78% of ammonium nitrogen as ammonium sulphate. Mass of these fertilizer products is decreased and corresponds to 1% and 9% of the original slurry mass, which emphasizes the effect of mass reduction during manure processing.

In the second chain (Fig. 11), pig slurry is first anaerobically digested and the digestate then separated into solid and liquid fractions with a centrifuge. Ammonium nitrogen from the liquid fraction is recovered with ammonia stripping and the residual nutrient flow is concentrated with membranes, while the solid fraction is thermally dried and pyrolyzed. The main advantage of the introduction of anaerobic digestion to the technology chain is the production of energy, which can be utilized in the subsequent processing steps. If biogas is upgraded to vehicle fuel, the income from the fuel production can be used to balance the economics of the processing chain. AD also enables co-digestion of slurries with other organic feedstocks at once to produce both energy and fertilizer products. In the second processing chain, 68% of pig slurry phosphorus is recovered as the char from the pyrolysis process and 97% of ammonium nitrogen as ammonium sulphate from the stripping. Organic nitrogen fractions are recovered with the membrane process.

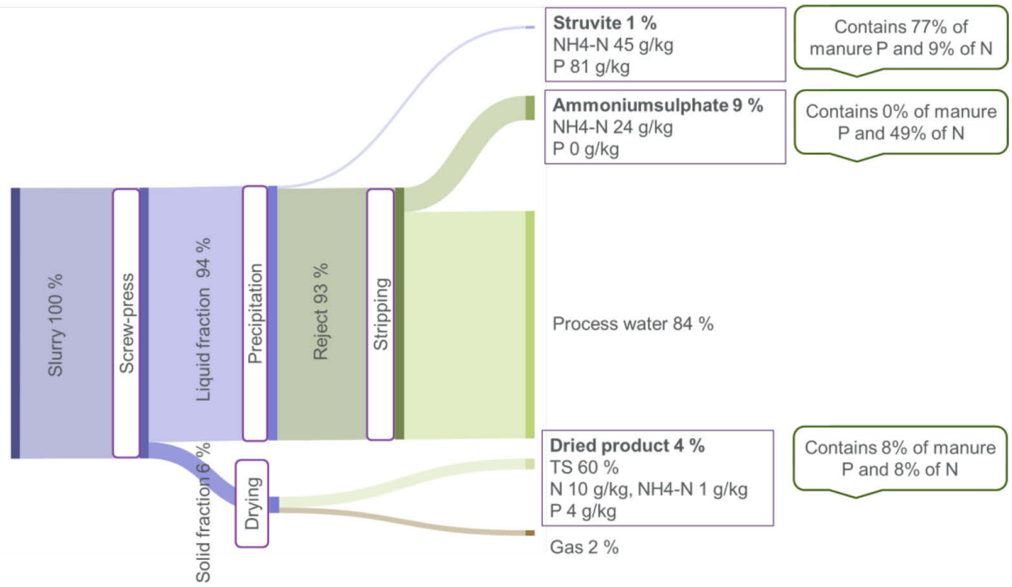

Figure 10. Technology chain for pig slurry treatment including screw-press, struvite precipitation, ammonia stripping and thermal drying. All numbers represent the percentage of mass/P/N/NH_4-N from the original pig slurry.

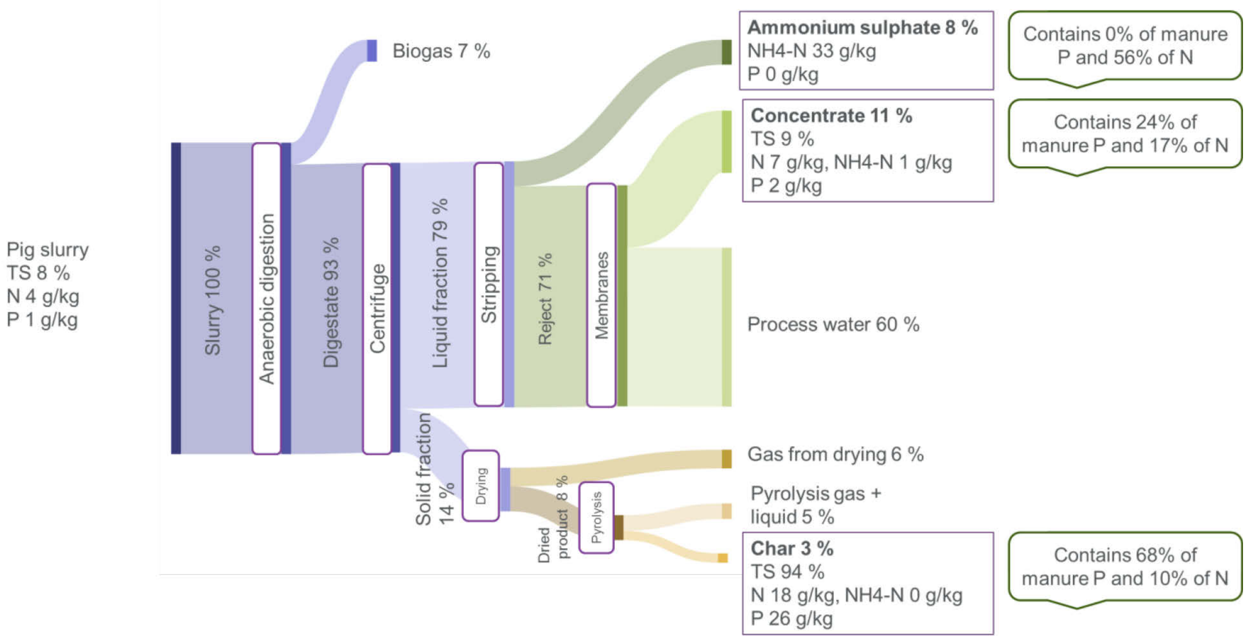

Figure 11. Technology chain for pig slurry treatment including anaerobic digestion, centrifuge, ammonia stripping, membrane separation, thermal drying and pyrolysis. All numbers represent the percentage of mass/P/N/NH_4-N from the original pig slurry.

4.8. Summary of manure processing technologies and their end-products

The end-products from manure processing, which are aimed for fertilizer use, have different nutrient content dependent on the original manure quality and the chosen processing technology. The following table (Table 12) summarizes manure processing technologies and presents the range of characteristics for each end-product obtained as reported in literature. It should be noted that the wide range of e.g. TS concentration within each technology is due to the variety of input materials used as well as the process parameters chosen. P availability estimations are based on Ylivainio et al. (2008, 2018) and Ylivainio et al. (2017).

Table 12. Summary of manure processing technologies and the nutrient content of the manure-based end-products produced.

Process	Product	P availability (%)	Total solids (%)	P (g/kg)	N (g/kg)	Soluble-N (g/kg)	Ref.
Solid-liquid separation	Liquid fraction	100	1–10	0.05–1	1–4	0.5–3	1–6
Solid-liquid separation	Solid fraction	100	20–35	0.5–7	0,5–12	0.01–5	1–6
Anaerobic digestion	Digestate	100	2–25	0.5–6	3–10	0.5–5	4, 7–9
Composting	Compost	100	20–60	0.2–6	0,2–6	0–0.5	7, 10–13
Drying	Dried manure	100	60–96	4–35	2–36	0.5–4	1, 7, 14
Pyrolysis	Biochar	20–90	>95	10–100	4–50	~0	15–18
Combustion	Ash	40–80	>80	50–110	0	0	1, 19–20
NH_4-N stripping	Ammonium-sulphate	-	10–30	0	20–110	20–110	14, 21–22
Evaporation	Concentrate	100	10–30	2–7	5–40	0.1–20	23–24
Membranes	Concentrate	100	2–15	0.01–1	2–20	2–20	1, 6, 9, 14, 25
Struvite precipitation	Struvite	100	60–100	60–130	30–60	30–60	14, 26–29

[1]Lebuf et al. 2013, [2]Gilkinson & Frost 2007, [3]Paavola et al. 2016, [4]Virkajärvi et al. 2016,[5]Hjorth et al. 2010, [6]Velthof 2015, [7]Evira 2017, [8]Luostarinen et al. 2013, [9]Shi et al. 2018, [10]Keskinen et al. 2017, [11]Karjalainen et al. 2014, [12]Michel et al. 2004, [13]Rizzo et al. 2015, [14]Systemic-project 2018, [15]Professional estimation, [16]Subedi et al. 2016, [17]Al-Wabel et al. 2017, [18]Qambrani et al. 2017, [19]Masiá et al. 2007, [20]Bloem et al. 2017, [21]Ervasti et al. 2018, [22]Laureni et al. 2013, [23]Bonmatí & Flotats 2003, [24]Chiumenti et al. 2013, [25]Vaneechaute et al. 2012, [26]Ackerman et al. 2015, [27]Katanda ym. 2016, [28]Vaneechaute et al. 2015, [29]Schoumans et al. 2017

The effect of manure processing on the nutrient content of the end-products is primarily dependent on water separation efficiency. The lower the amount of original manure mass, the higher nutrient concentrations can usually be achieved. Some technologies are very efficient in concentrating phosphorus, while other are more focused on concentrating nitrogen. In Figure 12, the mass, P and N separation efficiencies of different manure processing technologies are presented. Each figure shows the average range of mass, P or N separation efficiency based on previous studies with manure as a substrate. Most efficient processes regarding mass are those on the right hand side, where most of manure liquid fraction or water is removed. With P and N separation the more efficient nutrient concentration is achieved with technologies that are concentrated on the right-hand side.

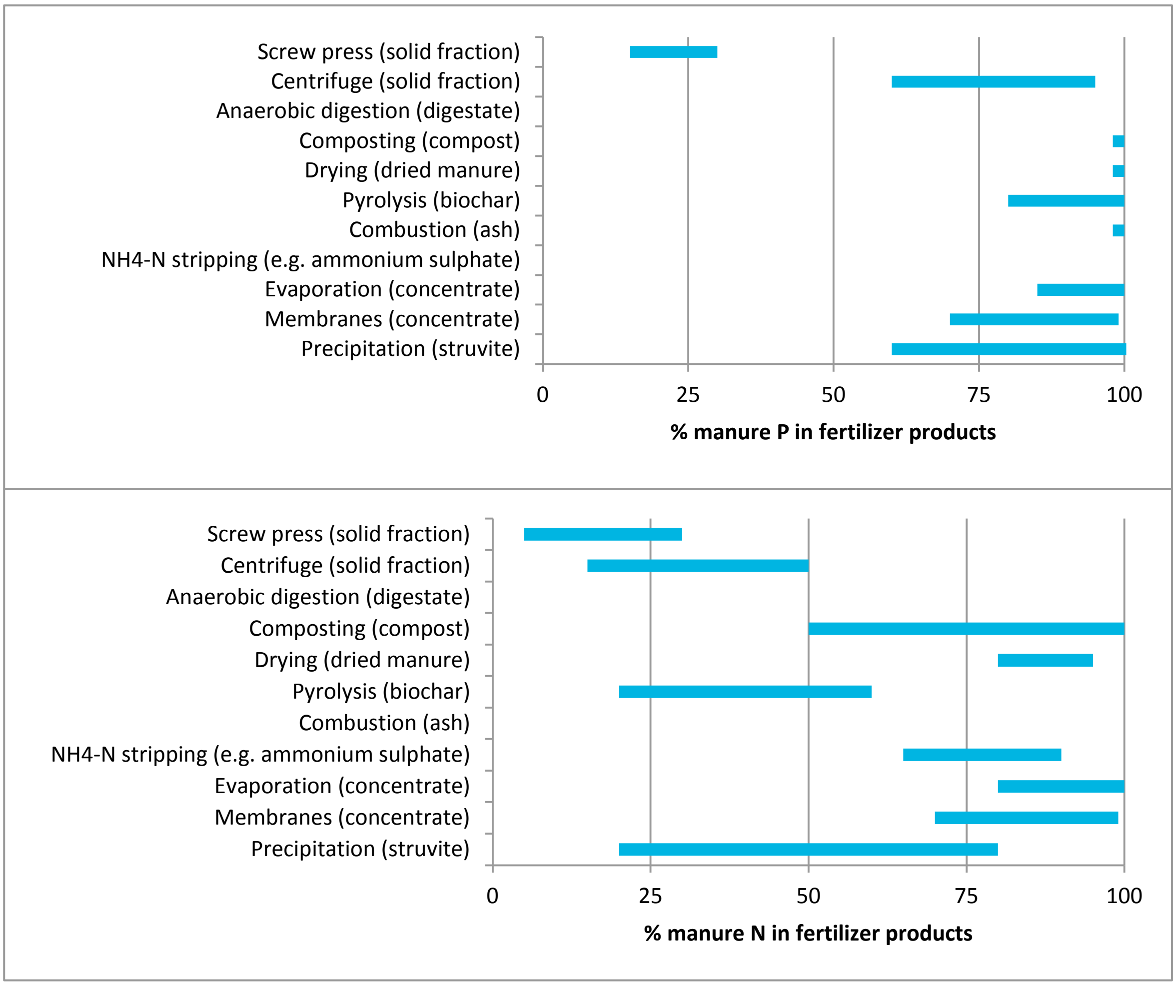

Figure 12. Separation efficiency of mass, P and N in processed fertilizer products as compared to original manure with different processing technologies.

Another important aspect of manure-based fertilizer products is the availability of nutrients and organic matter in them. The traditional fertilizer products in the markets are inorganic, meaning that the products contain no organic matter, whereas recycled fertilizer products are often referred to as organic fertilizers. Most of the recycled fertilizer products in the market are in fact organic fertilizers, which by definition include organic matter in addition to nutrients. However, some of the processing technologies introduced in this report, result in end-products with no organic matter. It would therefore be advisable to refer to recycled fertilizer products as fertilizers of organic origin, or manure-based fertilizers, which then may include both organic and inorganic fertilizer products.

The organic fertilizer products, by definition, include both nutrients and organic matter. When used as a fertilizer, it is important to note that part of the nutrients bound in the organic matter are not readily available to crops. Part of the organic matter and nutrients are released during mineralization in soil and thus eventually become available to crops. This is important to note especially in the case of nitrogen. In the most of the common mineral fertilizer products, all nitrogen is readily available to crops, but in organic fertilizer products, only part of the nitrogen will be directly available after spread, the rest being available only later during the growing period, or even during the following year.

The nitrogen release from the organic matter depends on site-specific conditions, e.g. temperature and humidity of the soil. This may lead to lower nutrient value and nutrient use efficiency of the organic fertilizer products e.g. with grains, which need most of the nitrogen quite early in the growing period. Crops with a longer growing period or several yields can more effectively make use of the nutrients released later. On the other hand, if there is no vegetation in active growing stage at the time of nitrogen release, there is a risk of emissions. This makes the use of organic fertilizer products somewhat more complicated than the use of common mineral fertilizers.

In case of mineral fertilizers, the calculation of the fertilizer value is simple as all nutrients are readily available for crops. The fertilizer value of organic fertilizer products is more complicated due to the slower nutrient release. On the other hand, also the organic matter in the organic fertilizer products has a value as a soil amendment. The organic matter content in the products varies significantly.

The total nutrient content also varies between different types of fertilizer products of organic origin. One of the aims of processing the manure or other organic feedstock is to remove water and/or air and/or organic matter, thus having a higher nutrient concentration in the end-product.

Thus, it would be very important for the end-users to have access to proper product information of the fertilizer products of organic origin. Also interpreting the product information needs attention. Choosing the right product for the right crop and production circumstances is essential when striving for high nutrient use efficiency. Many of the products also require special arrangements for storage, and spreading might not be possible with the machinery used for mineral fertilizers, but more with machinery usually used for manure spreading. Farmers with little or no previous knowledge on the use of these products might thus need special advisory on the best practices.

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5. How to control potential risks related to hygiene and contaminants

5.1. Trace elements

Although trace element concentrations (As, Cd, Cr, Cu, Ni, Pb, Zn) in manures do not usually restrict their agricultural use (Sarvi et al. 2017), the concentrations are commonly higher than in agricultural soils causing accumulation in soils after repeated applications (Bloem et al. 2017). In some cases, concentrations of specific trace elements (As, Cu, Zn) in manures can be high due to feed additives (Bolan et al. 2015). Cu and Zn are used as feed additives in pig and As in pig and poultry production. According to Bloem et al. (2017), the highest Cu and Zn concentrations within manures are found in pig manures and As concentrations in pig and poultry manures. Thus, using trace elements in feed additives increases their concentrations in manure and after manure spreading to the fields, they can circulate back to animal feed (Li et al. 2005). In sewage sludge, trace element concentrations can be higher than in manures (Bloem et al. 2017), but the annual input can be higher from livestock manures depending on application rates (Nicholson et al. 2003).

Although current trace element concentrations in manures are low or moderate, it would be advisable to minimize the use of trace elements in animal diets to minimize the accumulation risk in agricultural fields where manure is spread regularly. Liming decreases the solubility of most trace elements and thus reduces possible plant uptake and leaching of trace elements from agricultural soils (Adriano 2001).

5.2. Organic contaminants

In general, more than 1500 different organic compounds have been registered and some of them can end up in manure, sewage sludge and other fertilizer products in different ways. In manure, organic contaminants originate from e.g. medicines, feeds and washing waters. Antibiotics, such as several other pharmaceuticals, are excreted in great proportions (up to 90%) in urine and feces (Sarmah et al. 2006). According to the review by Bloem et al. (2017), antibiotic concentrations in manure can be at the same level than in sewage sludge, but higher peak values can be found in manures. Among manures, frequencies and concentrations of veterinary antibiotics are higher in pig and chicken than in cattle manures (Bloem et al. 2017). This was also observed in the study by Bloem and Lehmann (2016), where input and output materials from 29 biogas plants were studied for antibiotic concentrations. In the study, sewage sludge was always contaminated with antibiotics regardless of its processing, and among the manures pig slurry and poultry manure were most often contaminated. The highest maximum concentrations of tetracyclines and fluoroquinolones were found in poultry manure, pig slurry and poultry digestate.

It should, however, be noted that the concentration of antibiotics in manure is highly dependent on their use in animal production which varies significantly between different countries (European Medicines Agency 2018).

In Finland, Marttinen et al. (2014) analyzed several groups of organic compounds (polychlorinated dibenzo-p-dioxins and -furans (PCDD/F), polychlorinated bifenyls (PCB), polyaromatic hydrocarbons (PAH), bis(2 ethylhexyl)phtlalate (DEHP), perfluorinated compounds (PFC), linear alkylbenzene sulfonate (LAS), nonylphenol and nonylphenol ethoxylate (NP+NPEO), and brominated flame retardants including polybrominated diphenylethers (PBDE), hexabromocyclododecane (HBCD), tetrabromobisphenol A (TBBPA) and 25 different pharmaceuticals) from the digestates of Finnish centralized biogas plants that co-digest manure, by-products from food industry, municipal biowaste and sewage sludge in different ratios. None of the plants digested solely manure and two plants digested almost solely sewage sludge. According to the study, a calculated median soil burden of studied compounds after a single addition (15 t/ha) of the digestate was at the same level to the annual atmospheric deposition in Finland or other Nordic countries with the exception of PBDEs, which burden was 400–1,000 times higher. The soil burden of separated solid fraction (10 t/ha) were at the same level or higher than that of digestate. However, solid fraction is often applied to fields e.g. at five-year interval, whereas digestate might be applied annually, which decreases the soil burden difference between digestate and solid fraction. The soil burden of liquid fraction (30 t/ha) was estimated to be lower or at the same level with that of digestate or solid fraction. The conclusion for most of the studied compounds were, that it is unlikely that the agricultural use of end-products would cause significant risk for food safety in Finland, but further research is needed especially for PBDEs, PFCs, HBCD and pharmaceuticals. Soil burden of the end-products can also vary due to the large variation in concentrations.

Although many factors (e.g. chemical structure of the antibiotic, soil properties and plant species) have an effect on the behavior of antibiotics in soil, it can be concluded that low concentrations of antibiotics and their metabolites enter the food chain via grazing or applying e.g. manures or their digestates to the fields (Bloem et al. 2017). This poses a risk for proliferation and creation of antibiotic resistance genes and finally generation of resistant pathogens and bacteria, which can have an effect on humans (Bloem et al. 2017). Antibiotic resistence genes have been found in manure and their amounts have been noticed to decline soon after soil application (Muurinen 2017). It has been suggested that to control the risks related to antibiotics in manure, their use in animal production should be minimized, because repeated exposure to low doses pose a risk of development and spread of antibiotic resistant bacteria in livestock animals (You & Silbergeld 2014).

Different processing technologies affect organic contaminants differently (see section 4). They can also degrade to intermediate or transformation products that can be found in even higher concentration and toxicity than the parent compounds (Huerta-Fontela et al. 2010). A review by Verlicchi & Zambello (2015) on the influence of different sewage sludge treatment processes on the concentrations of 152 pharmaceuticals and 17 personal care products revealed that most compounds were reduced or attenuated during sludge processing (digestion, composting, conditioning, drying etc.), but some groups of compounds (analgesics, antibiotics, hormones, antiseptics) were even enriched in comparison to the primary sludge.

5.3. Hygiene

Like with other organic nutrient sources, different kinds of bacteria (e.g. *Salmonella* spp., *Campylobacter* spp., *Listeria monocytogenes*, EHEC, *Yersinia* spp.), viruses and parasites (e.g. *Cryptosporidium* spp., *Giardia* spp.) can also be found in manure. Some of them can be either species-specific or zoonotic (Bloem et al. 2017). However, possible presence of pathogens in manure does not inevitably mean a risk for humans or animals, because the health risk is dependent on several issues, such as their transport and survival in the environment and infectious dosage and virulence of the pathogen. In general, with the exception of spore-forming bacteria (e.g. *Clostridium spp*.), bacteria are more sensitive to different environmental factors and processes than viruses and parasites.

To control the potential risks related to pathogens, proper processing conditions need to be taken care of (see section 4) and recontamination from e.g. equipment, machines and animals during storage and handling need to be avoided.

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6. Conclusions

Nutrient recycling is an integral part of circular economy, and measures to enhance it are needed across the world. In the Baltic Sea Region, nutrient recycling may serve as a significant solution to reduce nutrient losses from agriculture to the sea.

As animal manure is the most important recyclable nutrient-rich material, enhancing its use as a fertilizer product could significantly reduce the dependency on mineral fertilizers and the risk for nutrient emissions from food production. Especially in regions of dense animal production, manure nutrients may be available in excess to the actual need of the crop production in the same area. The regional segregation of animal and crop production, also notable in many Baltic Sea countries, increases this discrepancy.

Manure nutrients should thus be reallocated via processing them into more concentrated and thus transportable recycled fertilizer products. These products could then be transported to regions in need of nutrients, relieving the original region of the excess and reducing the overall need for mineral fertilizers in food production. Simultaneously the emissions into the environment could be minimized and the safety with regard to hazardous compounds and hygiene ensured. Depending on the technology chosen, renewable energy can also be produced.

Several processing technologies are available and under development. They can be put into use in various different technology chains depending on the scale of the processing and the outcome desired. To implement sustainable manure processing, also the practical management solutions including storage and spreading should be developed and optimized.

The profitability of manure processing is still a challenge with the investment cost being high and the market for the end-products just starting to develop. Thus, incentives to kick-start both the processing and the markets are needed from the society.

To create a truly functioning market, the manure-based fertilizer products should meet the needs of the end-users, in this context mainly farmers. As the products often differ from traditional mineral fertilizers, development of services to facilitate the transfer to using recycled fertilizer products should also be supported.

Thus, incentives for the use of manure-based fertilizer products are of vital importance in boosting the transfer towards circular agriculture and the future possibility for a market-based nutrient recycling.

SuMaNu in brief

Eutrophication of the Baltic Sea is still a major problem caused by the excess nutrient loading mainly from agriculture. Thus, more efficient manure and nutrient management in agriculture is required to minimize nutrient losses and close the nutrient loops. The situation calls for transnational measures both at the farm and regional level throughout the catchment area. Several previous projects have been tackling this challenge during the recent years from different perspectives, but more holistic recommendations are still needed.

To boost development towards more sustainable agriculture SuMaNu (Sustainable Manure and Nutrient Management for reduction of nutrient loss in the Baltic Sea Region), as an Interreg Baltic Sea Region funded platform project, synthesizes sustainable manure and nutrient management practices both at the farm and regional level (work package 2) promoted by four international projects; Interreg Baltic Sea Region funded Baltic Slurry Acidification and Manure Standards, Interreg Central Baltic funded GreenAgri, and BONUS Programme funded BONUS PROMISE. In addition, the results from previous Interreg Baltic Sea Region funded projects such as Baltic Manure, Baltic Deal, Baltic Compass and Baltic Compact are utilized. This synthesis is a basis for jointly formulated policy recommendations for environmentally and economically sustainable manure management (work package 3). All the recommendations are prepared in cooperation with different target groups to enhance their implementation.

Via the broad partnership (Natural Resources Institute Finland (Luke) as a coordinator, Research Institute of Sweden (RISE), HELCOM, BSAG, Estonian Crop Research Institute (ECRI), Union Farmers Parliament (ZSA, Latvia), Agricultural Advisory Center in Brwinów (CDR, Poland), Organe Institute ApS (Denmark) and Julius Kühn Institute (JKI, Germany)) the recommendations are communicated to various target groups, such as policy makers, advisors and via farmers' unions to farmers (work package 4). The policy recommendations are also utilized in the process of HELCOM Nutrient Recycling Strategy and in the revision of the Baltic Sea Action Plan.

More information at www.balticsumanu.eu

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