Nutri2Cycle

Nurturing the Circular Economy

Nutri2Cycle

D.1.4 Effects of current techniques and management systems on CNP flows in Europe

Deliverable: Effects of current techniques and management systems on CNP flows in Europe

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Abbreviations

AD	Anaerobic digestion
C	Carbon
CH_4	Methane
CO_2	Carbon dioxide
FADN	Farm Accountancy Data Network
GHG	Greenhouse gas
GPS	Global Position System
K	Potassium
LF	Liquid fraction
N	Nitrogen
NDN	Nitrification-denitrification
N_2O	Nitrous oxide
NH_3	Ammonia
NO_3	Nitrate
OC	Organic Carbon
OM	Organic Matter
P	Phosphorus
TRL	Technology readiness level
VOC	Volatile organic solids

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Glossary

Ammonia stripping/scrubbing: A physical-chemical process used to recover volatile NH_3 from different waste sources, e.g. anaerobic digestate and animal manure.

Anaerobic digestion: The breakdown of animal manure and other organic material in the absence of oxygen. The organic material is decomposed by acid formers into fatty acids and then into biogas by methane formers or methanogens.

Bio-based fertilisers: Organic fertilisers produced from organic residues following some treatment. This would suggest that animal manure is a bio-based fertiliser only following a treatment of the raw manure. Furthermore, bio-based fertilisers may also comprise inorganic materials, e.g. after thermal treatment of organic waste leading to a carbon free ash product.

Biogas: A mixture of carbon dioxide (CO_2) and hydrocarbons, primarily methane (CH_4) gas, from the biological decomposition of organic materials.

Digestate: The material remaining after the anaerobic digestion of a biodegradable feedstock. Anaerobic digestion produces two main products: digestate and biogas.

Life cycle assessment: Life cycle assessment or LCA is a methodology for assessing environmental impacts associated with all the stages of the life cycle of a commercial product, process, or service.

Mixed farming systems: Systems including at least one type of cash crop and one type of livestock production, considered both at farm and at regional level, as a combination of specialized farms exchanging resources between them.

Nutrient cycling: The continued movement and use (with possible temporary accumulations) of nutrients between different compartments (soil, plants, animals, humans, water, air) and trophic levels in the biosphere.

Nutrient use efficiency: The ratio of the nutrient in desired output (e.g. crop product) divided by the total nutrient input of a system (field, farm, technological unit, region), expressed in kg kg^{-1} or in %.

Precision fertilisation: A strategy to adapt the fertiliser use based on the crop nutrient requirement. It combines GPS, proximal or remote sensors, and computers on agricultural machinery and tractors in order to observe, measure and respond to spatial and temporal variation in crop nutrient requirements.

Technology readiness level: Technology readiness levels are a method for estimating the maturity of technologies during the acquisition phase of a program.

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Executive summary

This report provides a literature review on current (management) techniques to improve nutrient cycling and their effects on CNP flows. This review of techniques contributes to the establishment of the baseline of the Nutri2Cycle project against which the solutions from Nutri2Cycle will be assessed. The literature review focusses on current techniques and systems that improve the cycling of CNP flows in agriculture. This review focuses on four main aspects: 1) emission reduction in animal production, 2) manure processing techniques, 3) precision fertilisation, and 4) mixed farming systems. The assessment of the impacts of these existing practices and techniques on CNP flows, provides insight in the current state of the art and environmental performance, which contributes to the first objective of the Nutri2Cycle project to map and comprehensively present the current flows and gaps in C, N and P cycles. The main observations from this review are summarised below.

Livestock farmers already apply several mitigation techniques to decrease gaseous emissions from agriculture, so far mainly focussing on reduction in ammonia emissions. Current techniques and practices comprise N and P feeding strategies, stable adaptations, manure treatment, and use of effective manure application techniques. Air scrubbers in animal stables, low protein feeding strategy and manure injection techniques are commonly used to reduce ammonia emissions. Phytate is commonly used as additive to improve the uptake of phosphorus. Manure acidification is only applied at larger scale in Denmark, whereas in the Netherlands and Belgium several manure processing techniques are already used in practice.

Depending on the working principle of manure processing technologies, it is possible to generate energy (e.g. anaerobic digestion, incineration), up-concentrate nutrients (e.g. mechanical separation, stripping/scrubbing) or even to destroy the nutrients (e.g. nitrification/denitrification) from animal manure. This suggests that manure processing technologies can have various effects (i.e. positive and negative) on CNP flows in the European agriculture, which are not always fully documented. Nowadays, anaerobic digestion and composting are one of the most commonly used manure processing technologies in the EU Member states. On the other hand, mechanical separation, incineration, nitrification/denitrification and stripping/scrubbing technology are more typical for regions with animal manure surplus.

For precision fertilisation, the variable rate fertiliser application technology is most relevant for improving the cycling of CNP flows. This technique is able to equalize the soil nutrient availability and the crop nutrient requirement, which can increase nitrogen use efficiency (over 15% increases have been observed), by increasing crop yield and reducing N losses. Precision fertilisation offers potential for reducing ammonia and GHG emissions. The technique is used in practice, but not yet widely applied, due to the required investments in machinery. Most studies on variable rate application focus on the reduction in mineral fertilisers, only limited research has been carried out on the effect of variable rate application of C-rich products (e.g., solid manure, compost, carbon-rich digestate) and the effects on soil carbon.

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The literature review on mixed farming systems shows that the environmental benefits on farm-level might be limited, but that mixing and cooperation at a regional scale can improve the efficient and circular use of resources. Mixing of crop- and livestock farms on a regional level can favour the efficient use of manure and decrease the use of primary resource P and fossil energy use can be reduced if more feed is produced locally. No quantitative evidence was found that N and GHG emissions to the environment were reduced by mixed farming. No quantitative evidence was found that mixed farming on a farm- or regional level would overall increase soil organic matter.

To synthesise this literature review, the different practices and techniques have been qualitatively assessed on their potential i) to reduce the use of primary resources, i.e. rock phosphate and fossil energy (related to energy use and production of mineral N fertilizers), ii) reduce emissions to air and water, which refers to ammonia and GHG emissions and nitrate leaching and iii) increase soil organic matter, which contributes to climate change mitigation and improves soil quality. Based on the literature review each of the current practices and techniques has been assessed in terms of positive effect (+), negative effect (-) or no effect (0), see Table S.1.

Table S.1. Summary table of effect of practices/techniques to improve CNP cycling on five main indicators

Practice/technique	Reduce primary resource P	Reduce fossil energy	Reduce N emissions to air and water	Reduce GHG emissions	Increase soil organic matter
Emission reduction in animal production					
Low N and P feeding strategies	0/+	0/+	+	0/+	0
Stable adaptations	0	0/+	+	0	0
Manure acidification	0	+	+	+	0
Manure application techniques	0	0/+	+	-	0
Manure processing					
Anaerobic digestion	0	+	+/-	+	0
Mechanical separation	0/+	0	0	0	0/+
Membrane filtration	0/+	-/+	0	0	0/+
Composting	-/0	-/0	-/0	0	+
Incineration	0	-/+	0/+	0	-
Nitrification – denitrification	0	-	-/+	0	0
Stripping/scrubbing	0	-/+	+	0	0
Precision fertilisation	0/+	+	+	+	0
Mixed farming	+	0	0/+	0	-/+

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The table shows that there is no practice/technique that scores positive on all five indicators. To reach optimal circularity of CNP a combination of practices and techniques will be required, which address the different components of the manure management chain, i.e. animal feeding, animal housing, manure storage and manure and fertilizer application. Overall, we can conclude that already a wide range of techniques and practices to improve nutrient cycling are available and to different extent used in European farming.

In regions with high livestock densities and manure surpluses the use of manure separation, where possible in combination with anaerobic digestion, can be useful to provide a better balance between demand and supply of nutrients, and reduce the volume of exported manure. Incineration and nitrification-denitrification of manure cannot be considered as techniques that fit in circular agriculture. Other regions that are more relying on inputs from mineral fertilizers, should try to increase the input of organic matter to the soils and make use of precision fertilization, which currently is mainly used for mineral fertilizer application. The environmental benefits of mixed farming systems are limited at farm level, but on regional level the cooperation between livestock and arable farmers can be a good alternative towards improved nutrient cycling, with a more local exchange of feed and manure. The solutions developed in Nutri2Cycle should enhance such a collaboration.

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Introduction

1.1 Background

Nutri2Cycle is a H2020 EU project and aims to enable the transition from the current (suboptimal) nutrient management in European agriculture to the next-generation of agronomic practices, characterized by an improved upcycling of nutrients and organic carbon. This will help to decrease greenhouse gas (GHG) emissions, reduce soil degradation, improve water quality, and reduce the EU dependence on imported nutrients (especially phosphorus).

In the Nutri2Cycle project a range of solutions are developed among five research lines: 1) innovative soil, fertilisation and crop management systems and practices for enhances N, P efficiency and increased soil OC content, 2) substituting primary resources by biobased products, 3) novel animal feeds produced from agro-residues, 4) innovative management systems, tools and practices for optimized nutrient and GHG management in animal husbandry, and 5) tools, techniques and systems for higher-precision fertilisation. The shortlisted solutions have been selected and described in Deliverables 2.1 and 2.2 of the Nutri2Cycle project and are currently further elaborated in WP2. The effectiveness of these solutions in reducing emissions and improve nutrient cycling will be assessed in WP3 using emission models and life cycle assessment approaches and emission models.

Some of the shortlisted solutions in Nutri2Cycle are still at low technology readiness level (TRL) and not applied in practice yet, but other solutions have a higher TRL and are already applied in practice in some EU countries. Besides there are existing practices that contribute to improved CNP cycling, which are in some countries already widely applied, and not specifically investigated in Nutri2Cycle, but should be taken into account for an integrated analysis on the potential for closing CNP cycles. Therefore the impact of existing management practices and techniques on CNP flows should be known. For the assessment of the impact at larger scale, the degree of implementation of these solutions should also be estimated. Therefore it is required to know where these solutions could be effective, to what extent these or similar practices already are applied, and how current nutrient management techniques and practices effect CNP flows.

Techniques and systems that stimulate sustainable agricultural practices developed rapidly over recent decades. This literature review gives an overview of current techniques and systems that are being used to improve cycling of CNP flows within Europe. Taking the nutrient flow chain (Figure 0.1) as a starting point, nutrient losses, in terms of GHG and ammonia emissions, and leaching, can be reduced at the source. Animal production can become more sustainable through, for example, low emission feeding and filtered housing systems. Losses can also be reduced at the manure storage and processing side, for example, improving the recycling of nutrients through manure processing plants. A third way of reducing CNP losses is through the use of best management practices during the application of carbon (C), N and P to arable land. This report focusses on the techniques and systems that are currently being used and the implementation of it within Europe, and the (potential) effect of these techniques and systems on CNP flows and nutrient use efficiency, and the level of implementation.

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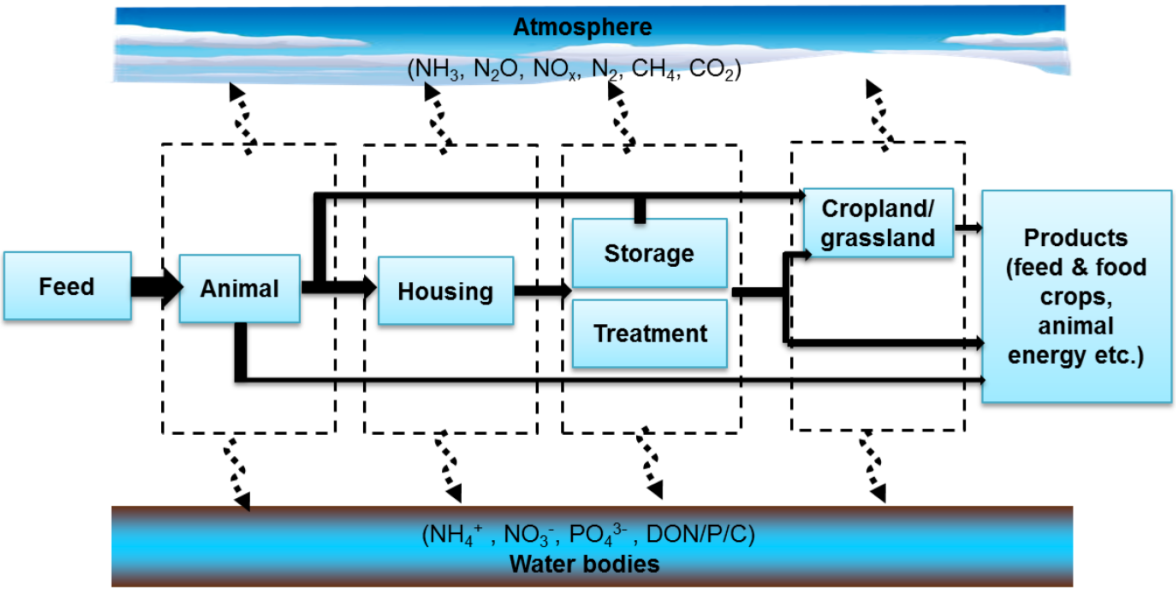

Figure 0.1 Schematic representation of the nutrient flow chain (Hou, 2016). Solid arrows show the main nutrient flows and the dashed arrows show possible losses of nutrients to the atmosphere and to groundwater and surface waters.

1.2 Overview EU farming systems

In Europe a large diversity exists in the farming systems and their distribution. Their distribution can be partly explained by environmental conditions, such as climate and soil types. For example the wet areas in Ireland and the peat meadow soils in The Netherlands are not suitable for arable crops, but can be used for grassland. Therefore these regions have a high share in dairy and/or beef production. In the Mediterranean areas, where low rainfall limits arable crops and grassland, perennial crops often can be grown. Also economic or logistic reasons can explain the distribution of certain farming types. For example, pig production is often concentrated in regions close to urban consumers to safeguard supply of fresh meat and close to ports to facilitate trade of feed and meat. Examples of these regions are Bretagne, serving the Paris area, the south of the Netherlands serving the Amsterdam-Rotterdam area and the Ruhr area in Germany, and Cataluña serving the Barcelona area (van Grinsven et al., 2018).

In the Nutri2Cycle project six main farming systems are distinguished, which are arable crop farms, permanent crop farms, cattle farms, pig farms, poultry farms and mixed crop livestock farms, see also N2C Deliverable 1.2. Figure 0.2 shows the distribution of these main farming systems, based on Eurostat data from the 2010 Farm System Survey.

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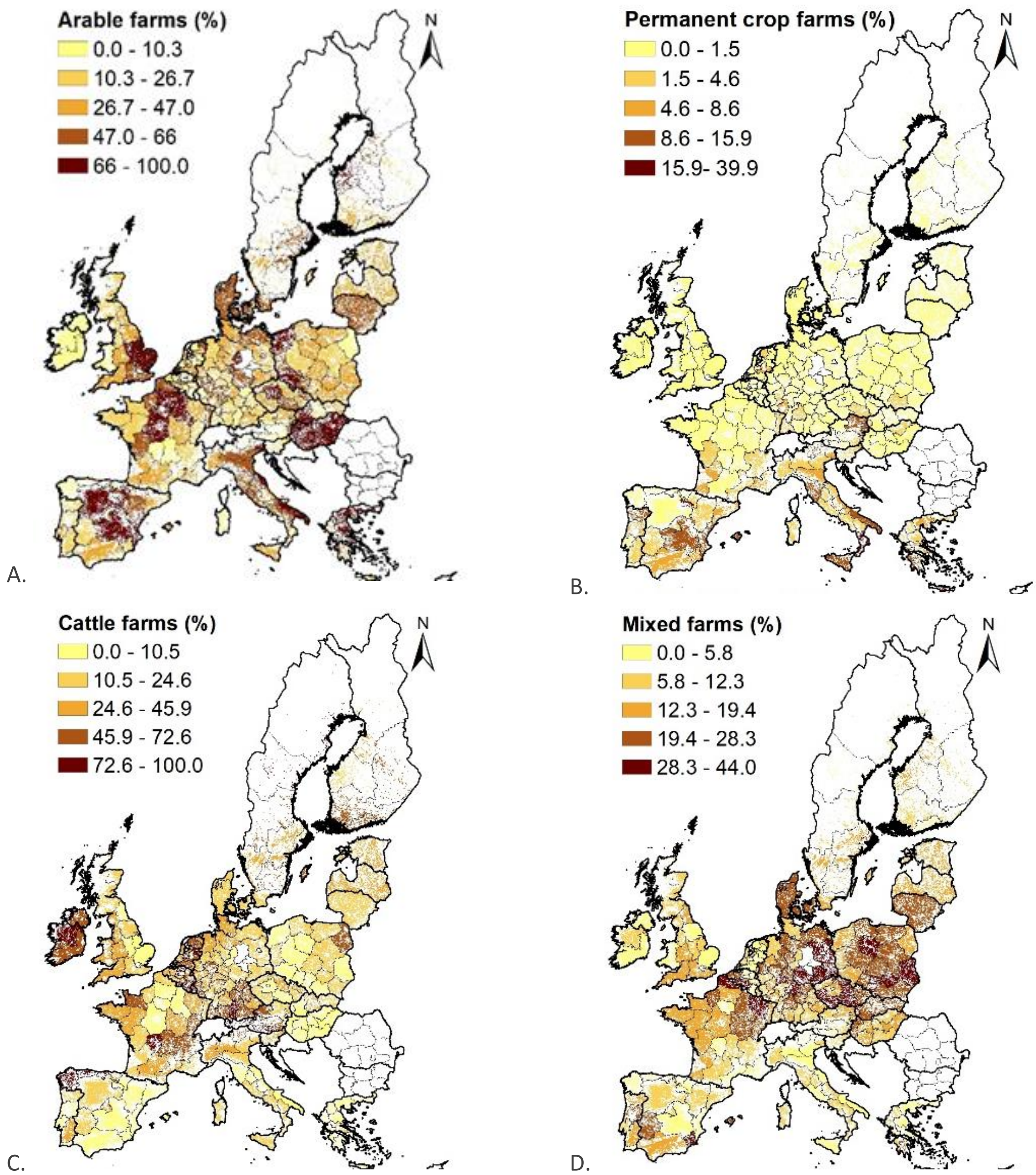

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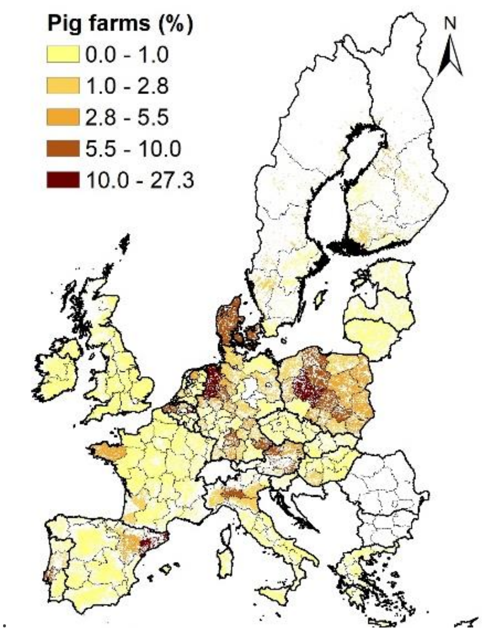

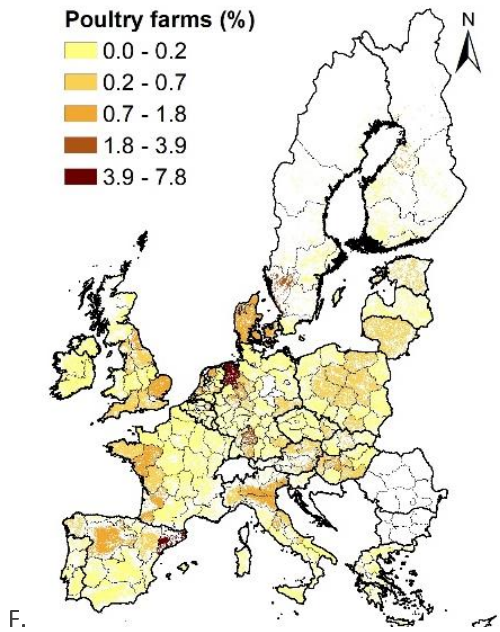

Figure 0.2. Share of farming systems expressed as percentage of the total agricultural land, for arable crop farms (A), permanent crop farms (B), cattle farms (C), mixed farms (D), pig farms (E) and poultry farms (F). Data is derived from the Eurostat 2010 Farm System Survey. Data for Bulgaria, Romania and Croatia were missing in the available data set. Note that some of the intensive pig and poultry regions (e.g. South of the Netherlands) are not well shown, as the distribution is expressed as the share of land, which do not cover the landless farms

1.3 Objective

The objective of this report is to provide a literature review on the effects on CNP flows of these existing(management) techniques that improve CNP cycling. This objective contributes to the establishment of the baseline of the Nutri2Cycle project against which the solutions from Nutri2Cycle will be assessed. In this review the impacts of existing practices and techniques on CNP flows are assessed, which contributes to the following objectives of the Nutri2Cycle project: i) to map and comprehensively present the current flows and gaps in C, N and P cycles and ii) further development and testing of minimal 1-2 prototype per farm typology taking into account the different agro-climatological and socio-economic aspects.

1.4 Outline of the report

The literature review on current techniques and systems that improve the cycling of CNP flows in agriculture is dived in four sections. Section 2 focusses on emission reduction techniques in animal production, Section 3 on the different manure processing techniques, Section 4 on precision agriculture and precision fertilisation, and Section 5 on the existing mixed farming systems. Given the range of practices and techniques and the wide range of scientific papers and reports that are already published on these topics, we have made a comprehensive review with the main focus on the effects on CNP flows of these different practices and techniques. Section 6 provides a short synthesis of the

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overview of current management practices and techniques in EU agriculture and the implications for the Nutri2Cycle project.

Besides the literature review, a small survey was performed to obtain a first overview of current practices and management techniques. This survey was based on a questionnaire among the partners in the Nutri2Cycle project. The recipients were asked to provide a brief description of the farming systems, respond to several specified questions on regular farming practices and fill in a table that featured several management practices to improve nutrient cycling. The results of this limited survey shows that farming systems and their practices differ vastly among and within countries, and these differences depend on location, climate, soil types, historical legacy, laws and regulations, and other factors. Many common practices or measures used to reduce N, P, and C losses and close the nutrient cycles are already applied, but there is also scope for further uptake of these existing practices. Given the limited number of respondents and the differences that might also occur within countries, we decided to not include this survey in the main report, but still report them as an Annex to this Deliverable.

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Emission reduction in animal production

The increasing production of livestock products in some regions has led to an overproduction of manure and the necessity of transporting manure to other areas, where nutrients are necessary. Unfortunately, there are several issues related to the use of untreated animal manure, like the nitrate (NO_3^-) or P leaching, presence of pathogens and medicines, and increased greenhouse gases (GHG) and ammonia (NH_3) emissions (Birkmose and Vestergaard, 2012; Hassouna et al., 2017; Piveteau et al., 2017; Regueiro et al., 2016a). These issues reduce the manure fertilizer value and make it difficult or unappealing for farmers to use. Gaseous emissions from animal production are a major concern, as emission of NH_3, CH_4 and N_2O and NO_x, may affect both human and animal health, as well as the environment. Farmers need to implement mitigation techniques to decrease gaseous emissions from agriculture. These techniques and practices comprise N and P feeding strategies, stable adaptations, manure treatment, and use of effective manure application techniques.

Even though several effective techniques and practices to reduce gaseous emissions, such as slurry injection, are currently used by farmers, further mitigation of emissions warrants more efforts throughout the entire farm cycle (Hassouna et al., 2017). For example, during storage the mitigation of NH_3 emissions should be based on the following principles: i) decreasing the contact area of manure and air, for example by covering or crusting, ii) lowering the manure pH, and iii) minimizing disturbances like aeration (Economic and Social Council, 2014). Another approach to minimise the environmental impact of slurry applications is to first treat the manure before soil application (Fangueiro et al., 2017), either to increase its nutrient efficiency or to create separate products with different nutrient contents.

Some of the techniques are easier to implement than others, a simple change in airflow or bedding materials in animal housing, for example, can effectively reduce the NH_3 emissions. During the storage phase, a variety of solutions can be implemented, such as slurry acidification, anaerobic digestion, the use of nitrification inhibitors or air scrubber, which, in some cases, can reduce both the NH_3 and GHG losses. These treatments aim to reduce environmental problems associated with the use of manures, which avoid human and animals health problems (He et al., 2016). However, even though all of these techniques are available, only a few of them are implemented at farm scale and there is still some reluctance to use some of these solutions (Fangueiro et al., 2011).

1.5 Low N and P feeding strategies

Adaptation of feeding strategies can lead to lower N and P excretion and decrease CH_4 emissions, and therefore contribute to reduction of CNP losses to the environment. The application of these strategies is often feasible for farmers and the strategies can be adapted to different situations, by focusing on various aspects of the animal's diet (e.g., crude protein content, dietary fibre, feed additives) (Philippe and Nicks, 2015).

There are plenty of research studies that focus on feed adaptations an their effect on nutrient (N and P) excretion and GHG emissions for a variety of animals (i.e., ruminants and non-ruminants) (Adegbeye

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et al., 2019; Ferket et al., 2002; Graña et al., 2013; Mathot et al., 2020; Niu et al., 2017; Philippe and Nicks, 2015; Prasai et al., 2018). Table 0.1 presents some of the strategies and their effect on nutrient excretion. The feeding strategies for reducing N and P emissions might fit in three categories, namely: management techniques, nutrient technologies and additive strategies.

Table 0.1 Potential impact of nutritional strategies on excretion of nitrogen and phosphorus (Source: Ferket et al., 2002; van Heugten and van Kempen, 2000)

Strategy	Reduction in nutrient excretion
Improve feed efficiency	3% for every 0.1 unit in improvement
Minimize feed wastage	1.5% for all nutrients for every 1% reduction
Match nutrient requirements	6-15% for N and P
Phase feeding	5-10% for N and P
Split-sex feeding	5-8% for N
Phytase	2-5% for N; 20-50% for P
Formulate on nutrient availability	10% for N and P
Replace protein with amino acids	9% for N for every 1% reduction in crude protein
Highly digestible feed ingredients	5% for N and P
Pellet the ration	5% for N and P
700-1000 micron particle size	5% for N and P
Enzymes: cellulases, xylanases, etc.	5% for N and P for appropriate diet
Growth promoting feed additives	5% for all nutrients
Low-phytate corn	25-50% for P

Management strategies

Animal feeding management involves a series of strategies that aim to fine-tuning the diet to the animal needs (e.g. phase feeding, improvement efficiency, reducing feed wastage, closely match nutrient requirements, and splitting diet per sex). Both phase feeding and matching nutrient requirements can use low N and P strategies to emission reduction. Phase feeding is a type of management that delivers more precision to nutrient requirements of animals diet needs, resulting in better nutrient efficiency and lower excretion amounts of potential excess of nutrients in effluents which can cause environment pollution and economical losses. Besides, phase feeding is a technique to study new forms of diets (Ferket et al., 2002; Graña et al., 2013; van Heugten and van Kempen, 2000). In the same way, matching nutrient requirements may result in emission reduction. Sex separation in diets has the advantage of being able to meet the nutrient requirements of the animals more accurately and can thus contribute to lowering GHG emissions (Ferket et al., 2002).

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Nutrient technology feeding strategies

Nutrient technology feeding modifies the feed rations beyond merely selecting the type of feed or balancing the diet. Instead, these strategies transform physical, chemical, or biological properties of the feed products to achieve better results, and may thus reduce gaseous losses. An example is the palletisation of grains (e.g. soybean pellet) (Van Amburgh et al., 2019), which can minimize waste and improve feed animal conversion rate (Ferket et al., 2002). Modelling and formulating provides prediction on N and P excretion in slurry and dung due to nutrient availability needs. However, to generate the outcome for the N and P excretion the information on feed availability is needed. Van Amburgh et al. (2019) showed that a reduction by 14% of the N excretion can be obtained.

Low protein diets (input) lead to a significant decrease of N released (output) and consequently to lower emissions from manure and dung. Every percent (absolute value) reduction in the protein content of the animal diet can lead to a 5% to 15% reduction in NH_3 emissions from animal housing, dung storage, and land spreading. Animal production systems that use low protein rations consequently also reduce N_2O emissions, and increase nitrogen use efficiency (Santonja et al., 2017).

Research on feeding diets with the ideal protein concept (IP) in combination with feed additions of phytase and minerals (IP+PHY+MIN) showed a reduction of 13% in N excretion. It also lowered phosphorus, calcium and manganese release, and enhanced phosphorus maintenance (Graña et al., 2013).

Additives strategies

Additives are more often used in many forms such as minerals, enzymes, fibres, hormones, acids, antibiotics, probiotics, plants extracts. These techniques have long since been around, and may now be employed to reduce N and P excretion, as well as GHG emissions, either by themselves or in combinations.

<u>Mineral additives</u>

Several mineral additives with impact on emission are used with different effects. Examples of these are Cu sulphate, Fe sulphate, Ca iodate, Mn sulphate, Na selenide, Zn sulphate, organic Cu, organic Mn, organic Zn, organic Mn, organic Zn, limestone, biochar, zeolite, bentonite, $NaHCO_3$, NaCl (Graña et al., 2013; Niu et al., 2017; Prasai et al., 2018). Mineral additives are commonly used in animal production (Niu et al., 2017). Poultry manure from birds fed with rations that included biochar, bentonite, and zeolite had moisture retention and granulation properties (Prasai et al., 2018). A study compared manure from conventionally-raised layer and broiler poultry and found differences in nitrogen, carbon, and water content in manure when diets were supplemented with three different concentrations (1, 2, 4%) of biochar, bentonite, and zeolite. The increase in manure pH might lead to ammonia loss in the manure after 35 days considerably elevated for biochar and zeolite ~5% N in the biochar and zeolite samples related to control and bentonite samples. Future fertilization can benefit from biochar due to capability of produce the highest bulk sized granules (2-4 mm) even though this benefits and reduction of costs, the use of organic biochar is just economically feasible for pastured poultry production in high-quality markets (Rothrock et al., 2019).

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Enzymes, hormones and growth promoters additives

The enzyme phytase can be added to the diet of monogastric animals to break down P from phytic acid (phytate), one of the most common organic P forms. As a result this can significantly increase P uptake and utilization and reduce P depletion in the animals (Santonja et al., 2017). Alternatively, low phytate feed can provide an alternative route to reduce P excretion, by selecting for plants with lower phytate content (Ferket et al., 2002; van Heugten and van Kempen, 2000).

Commonly in animal production hormones are used and excreted into the environment. During the application of manure those hormones can be released into the production system, the air and water. Endocrine waster might affect local fauna by interfering with population diversity indicators (AMEC, 2014). In contrast with this, plant hormones show potential to reduce nitrous oxide emission (Di et al., 2016).

Plant additives

Plant additives, also known as phytogenic feed additives, resemble plant components and are capable of enhancing effectiveness in various animals, acting in their microflora, e.g. *Oreganum vulgare*, *Piper Nigrum*, *Syzygium aromaticum*, *Thymus vulgaris*, *Yucca schidigera* and *Quillaja saponaria* (Santonja et al., 2017). These plant additives have been used in the animal production for a long time and strategies have appeared for solving old and new problems such as reducing emissions in animal production (Adegbeye et al., 2019; Ferket et al., 2002; Philippe and Nicks, 2015; Snapp et al., 2005).

A study in poultry production showed that *Achyranthes japonica* extract supplementation led to mitigation of gas emissions (Park and Kim, 2019). A promising plant additive is *Yucca schidigera*, which reduces CH_4 and N_2O emissions, as well as N excretion in urine and dung. Demonstrated benefits were a lower concentration of total ammonia nitrogen and nitrate, which led to improved water quality in fresh and marine aquaculture water. On the one hand, this study indicated that *Yucca* could be included with conclusive results in the nutrition strategies of sheep, cattle, horses, goat, fishes, rabbit, and shrimps. On the other hand, this review indicates gaps to in vivo studies of Yucca in swine rabbit, horses and even poultry (Adegbeye et al., 2019; Philippe and Nicks, 2015; Santonja et al., 2017). The evidence for *Yucca* is inconclusive however. As stated in a review, *Yucca* had no significant effect on GHG emissions. Still, the study suggests that novel nutritional options should be tried in the future, as they apparently can reduce emissions successfully (Philippe and Nicks, 2015). Several other studies with a wide range of animal production systems found emission reductions after using *Yucca* as an additive (Adegbeye et al., 2019).

Conclusion

The overall effect of precision fertilisation on CNP flows can be summarized as:

- *Effect on C*: most feeding strategies are aimed at reducing N and P excretion, and have no effect on C in manure. However, there are now also feed additives that can reduce the

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methane emission from enteric fermentation (e.g. Honan et al., 2021), and methane emissions are also affected by the composition of the feed basket.

- *Effect on N*: precision fertilization can better match the N application with the crop demand and reduce therefore the N emissions to water and air. Emission reduction is rather context specific but on average a reduction of about 10% is possible.
- *Effect on P*: Feeding strategies and feed additives can increase the P use efficiency and reduce the amount of P in animal excreta. Especially phytase is an important enzyme that can improve the uptake of P by monogastric animals, and increase the efficiency.

In the context of CNP flows, advantages (+) and disadvantages (-) of feeding stratgies have been summarized as follows:

(+) Many different feeding strategies and feed additives are available that can improve the nutrient use efficiency

(+) Additives and feeding strategies can also reduce GHG emissions, either directly (CH_4) or indirectly (N_2O)

(+) Feed additives can reduce the cost for feed or increase productivity

(-) Some additives could have negative consequences on the environment

(-) Not all additives are widely accepted by farmers

1.6 Stable adaptations

Ventilation

Ventilation is one of the parameters considered and can not only aid in increasing animal welfare, but also in reducing NH_3 emissions (Economic and Social Council, 2014). For example, the use of automatically controlled natural ventilation can decrease the emissions by 20% as the result of the lower temperature and air velocities (Bittman et al., 2014). If air velocity and temperature of the housing are controlled emissions, especially NH_3, can be reduced. Nevertheless, this is easy to implement at pig or poultry farms since the air circulation is forced, but in cattle housing, the airflow is usually natural and does not have an air control system (Bittman et al., 2014).

Air scrubber to reduce ammonia emissions

Air scrubbing is a technique used to remove the NH_3 from the air through forced ventilation in animal housing. There are two methods of air scrubbing, the chemical and biological scrubbers, which have different removal efficiencies. The chemical scrubber can remove up to 70-90% of the NH_3 present in the air, whereas the biological scrubber has a maximum efficiency of 70%. Van der Heyden (2017) extensively reviewed the implementation of air scrubbers at animal housing systems, reporting numerous examples of air scrubbers at pig and poultry housing facilities. The authors reported NH_3 recovery efficiencies at poultry and pig farms in the range of 40%-100% (Van der Heyden, 2017). Air scrubbers can be very effective, but the cost associated with its implementation is one of the disadvantages, and the main reason why it is not that instigated (Bittman et al., 2014). In conclusion,

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air scrubbers have a direct effect on N removal from air (up to 100%). No effects are reported on C and P flows.

Bedding

Animal housing is one of the greatest sources of NH_3 emissions from agriculture, contributing 35% of the total NH_3 emissions in Europe (Gilhespy et al., 2009). Previous studies indicate that the bedding material has an effect on the NH_3 emissions, but there is still little information available concerning this subject. The different bedding materials may influence the emissions in diverse ways. One parameter that may be important is the physical characteristic (urine absorbance capacity, bulk density), which results in a distinct way the urine drains through the bedding. This aspect is important since there is a direct relationship between the emissions and the urine, the emissions will be reduced when the urine is kept under the bed material, protecting it from air contact and consequently decreasing the emission of NH_3. Even though the physical characteristics are more determined on the NH_3 emissions we can discard the chemical characteristics (pH, cation exchange capacity, carbon to nitrogen ratio), and indeed some more explanatory essays should be conducted concerning the influence of the bedding materials (Bittman et al., 2014).

In some studies, at lab scale, different materials were tested to evaluate the effect on NH_3 emissions from dairy cattle urine, in which it was concluded that the presence of bedding material can indeed reduce the NH_3 emissions in cattle housing. In a study by Chambers et al. (2003) a 30% reduction on the NH_3 was reported when straw-bedding was used comparatively to slurry without straw in cattle housing. However, manure storage systems based on solid manure have often higher N_2O emissions compared to liquid manure systems (Pardo et al., 2015).

Conclusion

The overall effect of precision fertilisation on CNP flows can be summarized as:

- Effect on C: The stable adaptations discussed were mainly aimed at reducing NH_3 emissions, however, also methane emissions can be reduced if stables are adapted in such a way that manure is quickly transported to the digester, as fresh manure can produce more biogas and CH_4 emissions to the atmosphere are prevented.
- Effect on N: stable adaptations such as air scrubbers can reduce NH_3 emissions by more than 70%. These scrubbers can be easily applied in more closed pig and poultry systems
- Effect on P: most stable adaptations will not affect P flows.

In the context of CNP flows, advantages (+) and disadvantages (-) of stable adaptations have been summarized as follows:

(+) Ammonia emissions in pig and poultry systems can be significantly reduced with air scrubbers
(+) In combination with anaerobic digestions stable adaptations can also reduce CH_4 emissions
(-) Stable adaptations require often significant investments
(-) Energy use increases by using air scrubbers
(-) A trade-off might exist between ammonia reduction and animal welfare

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1.7 Manure acidification

Slurry acidification appears a solution to reduce ammonia emissions, by strongly increasing the NH_4^+: NH_3 ratio (Fangueiro et al., 2015b; Owusu-Twum et al., 2017). This method uses a number of additives, the most common is sulphuric acid, to reduce the pH of manure to 3.8-5.5 (Pedersen et al., 2017). The use of sulphuric acid may lead to problems regarding the safety of the handler, so some other additives have been considered, but none have achieved the efficiency of sulphuric acid.

The slurry acidification can lead to 1) reduction of the GHG and ammonia emissions (Hjorth et al., 2015; Wang et al., 2014) and 2) reduction of pH of slurry which inhibits activity of bacteria responsible for the nitrification of NH_4^+ (pH that maximizes the nitrification is 7.5-8) and keeps N longer available for crops and less susceptible to leaching (Fangueiro et al., 2015a; Park et al., 2018). Even though the delay on N nitrification can be beneficial since plants have N available for a longer period due to the slow release of this nutrient, it can also lead to N immobilization (Fangueiro et al., 2015b). The acidification can increase the solubility of P, but it does not mean it will be more available to plants (Pedersen et al., 2017; Piveteau et al., 2017). In terms of inorganic carbon, most of it is lost during the process of acidification (Fangueiro et al., 2015b).

This treatment seems a good solution to restore the slurry fertilizer value and slurry can be applied without posterior incorporation. For example, Pedersen et al. (2017) observed an increase in the dry matter (DM) yield in sandy soil with slurry acidification with pH 3.8, compared to the control treatment. Another study showed that when using acidified slurry as a fertilizer, more than 40% of the present NH_4^+-N was taken up by the crop (ryegrass) (Pantelopoulos et al., 2017). This technique may therefore solve two problems: i) the delay on the nitrification that will valorise the slurry fertilizer value while reducing the ammonia emissions; and ii) reduction of the GHG emissions (Petersen et al., 2014; Wang et al., 2014). Concerning NH_3, Wang et al. (2014) found a maximum efficiency reduction of 92% and Petersen et al. (2012) reported a decrease of 96 to 99% of the emissions using slurry acidification with sulphuric acid. For CH_4, reduction in emissions from slurry acidification during storage the efficiency obtained was between 67 to 87%, due to inhibition of bacteria *methanogens* activities (Petersen et al., 2014, 2012; Regueiro et al., 2016b; Wang et al., 2014).

Currently, this is a technique applied at farm scale in Denmark and in some countries of North and Eastern Europe. The lower implementation rate may be due to the handling of concentrated acids, which requires more careful handling of the slurry, but also in additional training of employees. It is still unclear what the long term effect of the application of acidified slurry is on the soil.

Conclusion

The overall effect of precision fertilisation on CNP flows can be summarized as:

- *Effect on C*: Manure acidification can reduce methane emissions from liquid manure storage systems by more than 70%
- *Effect on N*: Acidification of manure can strongly reduce NH_3 emissions from manure storage systems and also during field application. There is a potential risk on increased N leaching.
- *Effect on P*: Manure acidification has no effect on P flows.

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In the context of CNP flows, advantages (+) and disadvantages (-) of manure acidification have been summarized as follows:

(+) NH_3 emissions can be strongly reduced, not only during storage, but also during application of the manure

(+) Methane emissions from manure storage are reduced due to the lower pH

(+) Manure acidification increases the fertilizer value of manure

(-) The use of strong acids poses some risks to farmers

(-) Lowering the pH of manure might require additional liming to prevent soil acidification

1.8 Manure application techniques

Best practice in manure spreading techniques points out that low-emission manure applications follow at least one of the next fundaments: (i) diminishing the area of the contact of soil and manure where emissions occur, i.e. through band application, injection, incorporation; (ii) diminishing the period between application and a reducing solution, i.e. through rapid incorporation of manure into the soil or immediate irrigation; (iii) diminishing the cause power of the emitting surface, i.e. by reducing the pH and NH_4+ concentration (through diluting). This literature review shows some of the best available practices to reduce N losses to air and water through changes in manure storage and spreading techniques (including equipment) (Table 0.2 and Table 0.3), as well as spreading practices including spreading quantities, area and timing. These include options for differing levels of ambition (AMEC, 2014).

Table 0.2 Summary of best practices under different ambition levels (A-C) (Source: AMEC Environment & Infrastructure UK limited (2014)

Element	A (high)	B (moderate)	C (low)
Manure spreading technique and incorporation	Target NH_3 emission reduction of >60% (slurry application) and >30% (solid manure application). Techniques: Slurry: injection (grassland, arable)/ band spreading with incorporation within 2h (arable) Solid: direct incorporation (within 4h), where feasible (applicable on arable land only)	Target NH_3 emission reduction of >30% (slurry) and >30% (solid). Techniques: Slurry: band spreading (trailing hose or trailing shoe) (grassland)/ with incorporation within 4h (arable) Solid: direct incorporation (within 12h), where feasible (applicable on arable land only)	Target NH_3 emission reduction of >30% (slurry) and >30% (solid). Techniques: Slurry: band spreading (trailing hose or trailing shoe) (grassland)/ dilution / management systems with incorporation within 12h Solid: direct incorporation (within 24h), where feasible (applicable on arable land only

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Table 0.3 Best Available Techniques (BAT) on land-spreading equipment land

Land use	BAT	Emission reduction	Type of manure	Applicability
Grassland and land with crop height below 30cm	Trailing hose (bandspreading) Trailing	30% this may be less if applied on grass height >10cm	Slurry	Slope (<15% for tankers; <25% for umbilical systems); not for slurry that is viscous or has a high straw content, size and shape of the field are important
Mainly grassland	Trailing shoe (bandspreading)	40%	Slurry	Slope (<20% for tankers; <30% for umbilical systems); not viscous slurry, size and shape of the field are important
Grassland	Shallow injection (open slot)	60%	Slurry	Slope <12%, greater limitations for soil type and conditions, not viscous slurry
Mainly grassland, arable land	Deep injection (closed slot)	80%	Slurry	Slope <12%, greater limitations for soil type and conditions, not viscous slurry
Arable land	Bandspreading and incorporation within 4 hours	80%	Slurry	Incorporation is only applicable for land that can be easily cultivated, in other situations BAT is bandspreading without incorporation
Arable land	Incorporation as soon as possible but at least within 12 hours	Within 4 hours: 80% 12 hours: 60-70%	Solid pig manure	Only for land that can be easily cultivated

Source: Best Available Technology Reference Document [BREF] (2003). It should be noted that two Member States did not support the conclusion that bandspreading of pig slurry on arable land followed by incorporation is BAT and expressed a view that applying bandspreading on its own is a BAT. Furthermore, in their view, incorporation within 24 hours is Best Available Techniques.

References developed in the name of the European Union are released and actualized along the time in regard of manure application e.g.: Best Available Techniques (BAT) Reference Document for the Intensive Rearing of Poultry or Pigs. Industrial Emissions Directive 2010/75/EU (Integrated Pollution Prevention and Control) it has information in regard of techniques for the reduction of emissions from manure land spreading (BREF, 2003; BREF, 2015; Santonja et al., 2017).

Application methods that lead to greater contact between the manure and the soil, such as direct injection, band-spreading, and broadcasting ultimately affect the distribution of critical spots of manure. Mainly the methods of manure distribution were described for methods of injection and

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surface application (Petersen, 2018). The type of fertilizer, the rate at which it is applied, and the technique used all influence the amount of NH_3 originating organic fertilizers (i.e. slurry and manure, digestate, poultry manure). Emissions also depend on temperature and on the time between application and incorporation (Peter et al., 2017).

Conclusion

The overall effect of precision fertilisation on CNP flows can be summarized as:

- *Effect on C*: Manure application techniques have no direct effect on C.
- *Effect on N*: Low emission manure application techniques can reduce NH_3 emissions by more than 50%.
- *Effect on P*: Manure application techniques have no direct effect on P.

In the context of CNP flows, advantages (+) and disadvantages (-) of low emission manure application techniques have been summarized as follows:

(+) NH_3 emissions are significantly reduced
(+) The N use efficiency of manure can increase
(-) Investment cost for new machinery can be high
(-) N_2O emissions might increase
(-) Effects on soil quality and soil biota are debated

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Manure processing

Manure treatment technologies can greatly contribute to reduce greenhouse gas (GHG) emission and improve the cycling of carbon (C), nitrogen (N) and phosphorus (P) flows (Awasthi *et al.*, 2019; Weiland, 2010; Hou *et al.,* 2017). Hereinafter, seven most promising technologies, currently applied in Europe to process manure, are highlighted. The described technologies are analysed based on their effect on CNP flows and efficiency of nutrient recovery. Finally, a more detailed level of geographical implementation for each technology is described. The technologies are described individually, however, in practice manure processing typically entails a subsequent cascade of described technologies.

1.9 Anaerobic digestion

Description of the technology

Anaerobic digestion (AD) is a naturally occurring process during which microorganisms convert complex carbon (C) polymers into simpler inorganic molecules – methane (CH_4) and carbon dioxide (CO_2) – in the absence of oxygen. AD is capable of processing a broad range of substrates such as animal manure, sewage sludge, the organic fraction of municipal waste, different types of agricultural residues, food waste, fruit and vegetable waste, slaughterhouse waste, etc. Compared with aerobic processes, the conversion of organic substrates via AD has a low energy demand which results in energy-rich intermediate (volatile fatty acids, ethanol, H_2) and final products (CH_4) (Angelidaki *et al*., 2011).

The four key stages of AD involve hydrolysis, acidogenesis, acetogenesis and methanogenesis (Figure 0.1). A trophic chain of specific microbial flora comes into play during each of these steps converting the intermediate products from one stage to products that can be used as feedstock to microorganisms in the next stage, until the final product – biogas - is reached. During the initial stage – hydrolysis – organic macromolecules are broken down into smaller soluble molecules, which can then pass through the cellular membrane of the microorganisms and be used as a source of energy (Zeikus, 1980). Through fermentation, solubilized monomers are transformed during acidogenesis into volatile fatty acids. During acetogenesis, the intermediate metabolic products from hydrolysis and acidogenesis are converted to CH_4 precursors: CH_3-COOH (acetate), CO_2 and H_2 (Tholen and Brune, 1999). During the final phase – methanogenesis – the precursors are transformed into biogas by methanogenic archaea via 2 metabolic pathways (Thauer *et al*., 1977):

The acetotrophic pathway: $CH_3COO^- + H^+ \rightarrow CH_4 + CO_2$

The hydrogenotrophic pathway: $HCO_3^- + 4H_2 + H^+ \rightarrow CH_4 + 3H_2O$

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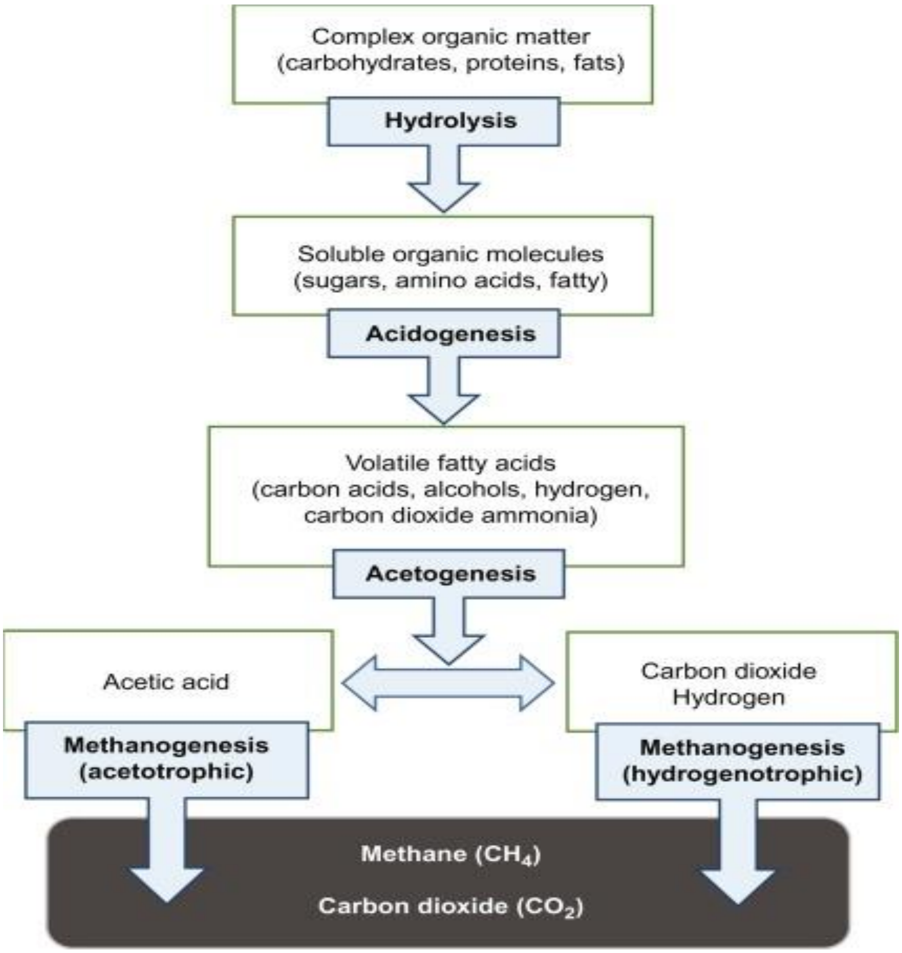

Figure 0.1 Main steps of the anaerobic digestion process (Fardin et al., 2018)

Biogas typically contains about 60-70% CH_4 and 30-40% CO_2, and can be used for the production of electricity and heat. It can also be upgraded further into biomethane for injection into the existing gas grid and for biofuel production. Optionally, the CO_2 can be recovered for use in greenhouses or the beverage industry. This constitutes an additional source of income for plant owners, and is therefore gaining more and more attention from stakeholders in the AD sector (Shin *et al*. 2019).

During AD, certain quantities of macro- (N, P, Ca, C, S) and microelements (Fe, Cu, Mg, Zn, Mo, Co, Ni, Se) are metabolized by the microorganisms. Previous studies have shown the optimal ranges of such nutrients for biogas production, usually expressed as Chemical Oxygen Demand$_{mgO2/L}$ (COD$_{mgO2/L}$) /N$_{mg/L}$/P$_{mg/L}$ and C/N ratios. Recommended COD/N/P values generally range from 600/7/1 (Mata-Alvarez, 2002) to 700/7/1 (Syaichurrozi and Sumardiono, 2013), while the C/N values range between 20 and 30 (Fricke *et al*., 2007).

Aside from the production of renewable gas in the form of biogas or biomethane, the microbial breakdown of organic feedstock during AD leads to another product of interest, namely digestate: a partly digested organo-mineral residue in liquid or solid form. Digestate retains most of the original nutrients (NPK) contained in the input materials while also increasing the mineral (plant-available)

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fraction of these nutrients (Arthurson, 2009; Insam *et al*., 2015), which makes it an interesting product for agricultural application as a fertiliser and/or soil improver. Complex organic N compounds are mineralized to NH_4^+-N during the AD reaction, which leads to a higher NH_4^+-N/total N ratio than in its undigested counterpart, and consequently to a possible higher nutrient use efficiency. In this way, up to half of the N_{org} contained in the feedstock can be mineralized (NH_4^+-N) as depicted in Figure 0.2. The same holds true for P as a significant part of Porg is converted to labile P (Grigatti et al., 2015) with reported values of up to 55% Pinorganic in digestate (Moeller et al., 2018). This positions AD as a strategic technology both for energy recovery and for converting nutrients (NPK) contained in the raw materials into more soluble forms, resulting in a higher NUE. Digestate also has a lower C/N ratio, as some C is removed in the form of biogas.

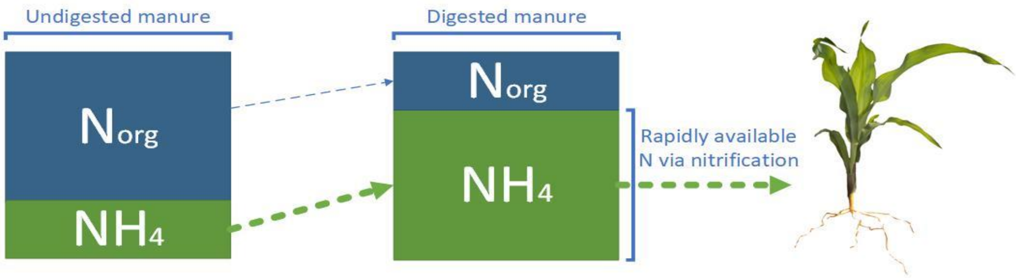

Figure 0.2 Schematic representation of the mineralization pattern of N and ensuing higher nutrient use efficiency when digested anaerobically (adapted from Valbiom, 2012)

However, owing to the wide array of feedstock used for biogas production and the process parameters of the fermentation, exact fertilising value of digestate is difficult to predict (Sogn *et al*., 2018; Zirkler *et al*., 2014). For example, even an organic manure with a similar C/N ratio is likely to be mineralized in a different rate, due to the differences observed in chemical composition of various types of manure (Möller and Müller, 2012). In general, AD converts between 20 and 95% of organic matter (OM) present in the initial feedstock into biogas (Gil *et al*., 2019). Though the exact value will depend on the type of feedstock and the presence of recalcitrant polymers (such as lignin).

Although digestate has a lower C content compared to the manure before digestion, the impact on soil carbon seems to be limited. As AD is a relatively new technique, there are not yet studies available that assessed the long-term effect of digestate on soil carbon. However, incubation studies and shorter term experiments, e.g. Barłóg et al. (2020 and Thomas et al. (2019), showed that application of digestate instead of manure no negative effect on soil organic carbon was found. A review by Möller (2015) concludes that the lower C content in digestate is compensated by the lower decomposition of the digestate and that no significant effect long-term on soil organic matter stocks is expected.

An overview of CNP flows in the technology

Figure 0.3 shows a simplified diagram of CNP flows from digested manure, which is subsequently mechanically separated (see section 3.2.2) into a liquid fraction (LF) and a solid fraction (SF). The values

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are indicative and are based on estimates from Bauer *et al*. (2009) and Gil *et al*. (2019). These studies have estimated that on average 70-80% of OM is removed in gaseous form: from this, 60-70% is converted to CH_4, and the rest to CO_2. The other 20-30% remains in the digestate and contains the recalcitrant C, out of which 60-70% goes to the SF of digestate, and 30-40% to the LF in the case of subsequent mechanical separation. For the sake of clarity, it is considered that N, P and other macro- and microelements, which were initially present in the feedstock, are all retained in the digestate.

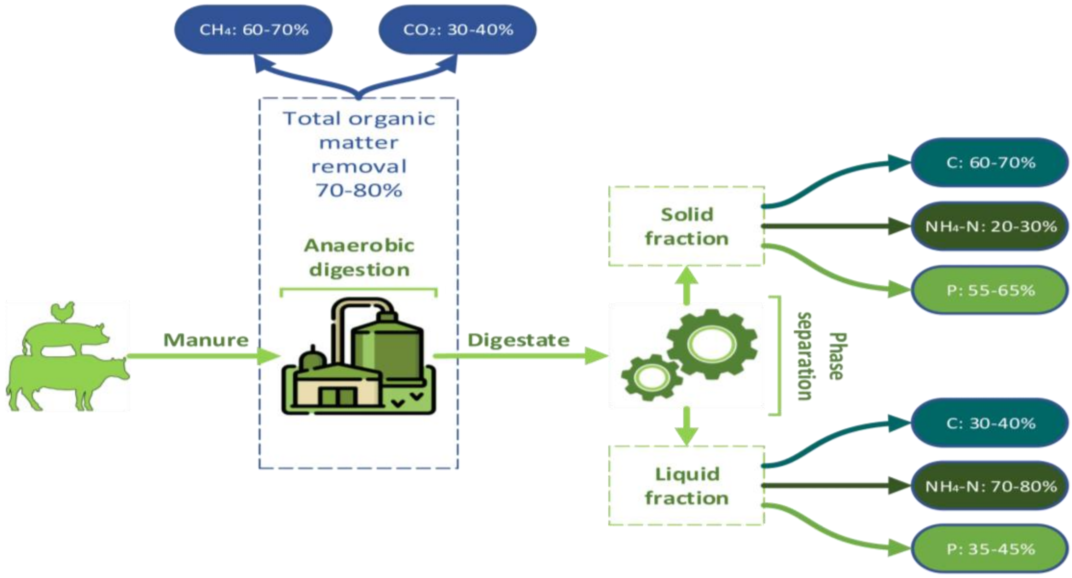

Figure 0.3 Schematic representation of CNP flows from digested manure

Geographical representation of the technology and farming systems

At the European level, "farm-fed" biogas plants represent almost 75% of the AD sector (Figure 3.4) This category encompasses all substrates related to agricultural production: manure (mostly from cattle and pigs1), straw, harvest residues, catch or cover crops but also energy crops. A closer look at the national level reveals a more contrasted picture (Figure 0.5), since the types of feedstock which are given priority by national authorities - agricultural substrates, sewage sludge from wastewater treatment plants, municipal or household waste, industrial by-products, landfill waste - can sometimes vary significantly from one country to the other.

[1] To a lesser extent also manure from sheep, goat and poultry.

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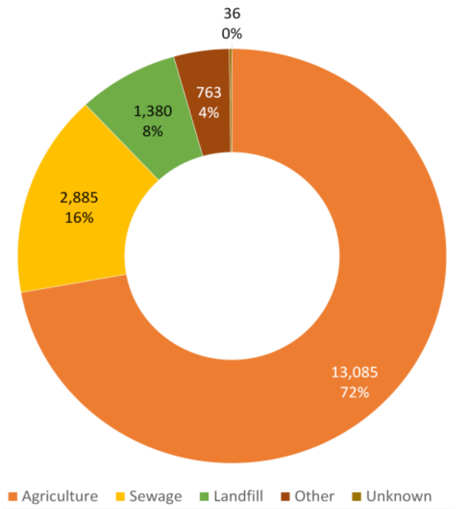

Figure 0.4 Relative use of feedstock types in Europe according to the number of biogas plants (EBA, 2020)

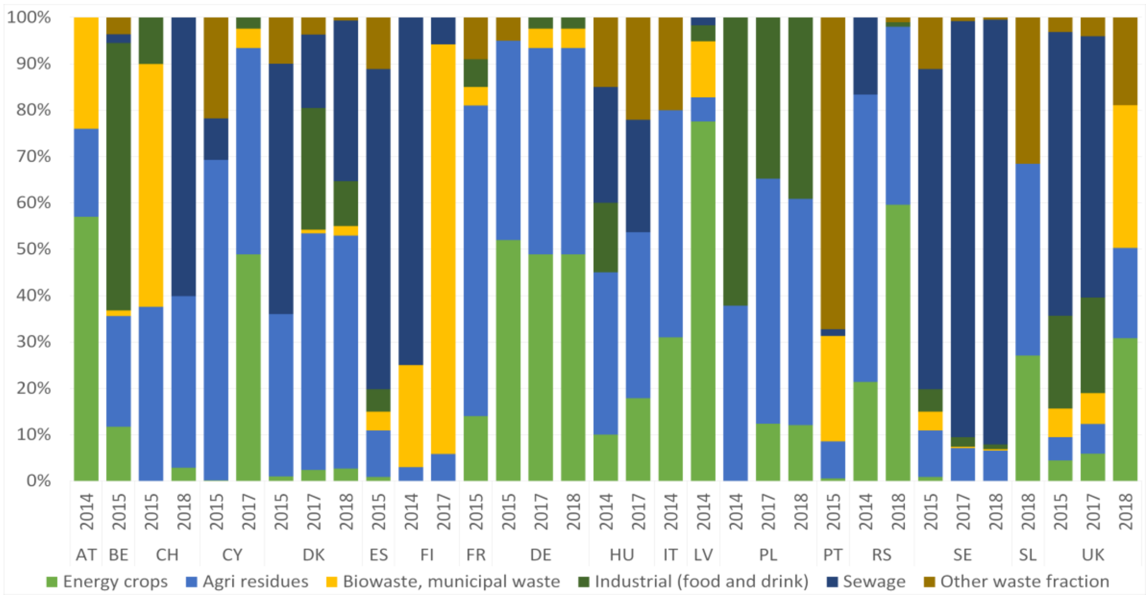

Figure 0.5 Feedstock use (excluding landfill) for biogas production in 18 European countries, expressed as a mass percentage (EBA, 2020)

In sheer number of biogas plants, the European top 5 in 2018 was held by Germany (11,084 plants), Italy (1,655 plants), France (837 plants), the United Kingdom (715 plants) and Switzerland2 (634 plants) (EBA, 2020). As depicted in Figure 0.5, roughly half of Germany's digested feedstock comprises of energy crops, whereas the other half consists mainly of agricultural substrates (which includes

[2] Tailed by the Czech Republic with 574 plants.

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manure). In the case of the United Kingdom, agricultural substrates - excluding energy crops - contribute to a small part of the total feedstock profile (about 20%). In Italy, Poland and Denmark, about 50% of the processed feedstock is from agricultural origin (excluding energy crops), whereas in Switzerland agricultural residues amount to about 40% of the total processed feedstock.

Cow manure is widely available resources and is the most commonly used type of manure in AD. The main drawbacks of all types of manure are the low energy density and lignocellulosic nature, which result in relatively low biomethane yields (Table 0.1). That is why co-digestion of manure with feedstock of higher cellulosic content is usually preferred in order to enhance biogas production (Ma *et al.,* 2017). Another problem encountered with manure is the low C/N ratio which can lead to microbial inhibition and process failure, when used as a single feedstock. This is especially the case with chicken manure - which has the highest N content of all livestock manure (Hassan *et al.,* 2016) - but also for pig manure (Lymperatou *et al.,* 2017).

Table 0.1 Total solids (TS), volatile solids (VS), total carbon (TC), total nitrogen (TN), C/N ratio and methane yield of different types of manure (Akhiar, 2017).

Manure type	TS (%)	VS (%)	TC (% of TS)	TN (% of TS)	C/N	Methane yield (L/kg VS)
Cow dung	9-29	7-20	26-42	1.2-5.1	6-24	136-302
Cow manure (mixed with straw)	31	20	14.6	0.38	39	84
Liquid fraction of cow manure	5.8	4.2	ND	6.2	ND	206-223
Pig manure	48	36	39	3.9	10	356-410
Horse manure	20-37	17-31	-	-	22-42	-
Rabbit manure	28	25	37.7	2.1	17.9	323
Sheep manure	54	49	30.3	1.4	22.5	99
Chicken manure	42-50	35-45	18-43	2.2-9.0	3.8-8.9	118-377

France is the biggest producer of manure in Europe, with an estimated yearly production of 214.3 Mt (Scarlat *et al*., 2018). About 80% of the total digested substrate in France originates from agricultural origin (70% when subtracting energy crops) as shown in Figure 0.5. This suggests an interesting alignment between the quantity of manure, as an agricultural substrate, which is being processed through AD and the considerable volumes of manure which are produced in France, although data indicating the tonnage of manure which is being currently processed anaerobically is lacking. The estimated yearly manure tonnage in other leading European countries is as follows: 175 Mt in Germany, 112 Mt in the United Kingdom, 108.3 Mt in Spain, 91.3 Mt in Poland, 89.4 Mt in Italy, 69.4 Mt in Ukraine, 62.9 Mt in the Netherlands (Scarlat *et al*., 2018).

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In total, livestock (cattle, pigs, sheep/goats) and poultry in the EU-28 produce an estimated 1,200 Mt of fresh manure per year[3] (Scarlat *et al*., 2018). When considering suitable areas for biogas production facilities - which would require high concentration of feedstock within an acceptable transport distance to the AD plants and adequate road networks - an estimated 860.7 Mt of fresh manure could be collected and processed. This quantity of collectable manure leads to a conservative biogas potential of 16 billion m^3 which translates into 11,655 to 16,595 potential new biogas installations (Scarlat *et al*., 2018). In 2011, an estimated 56 Mt of digestate (from all feedstock) was produced annually in Europe (Saveyn and Eder, 2014) suggesting that, compared with the amounts of manure currently being produced, AD still has considerable room for growth.

Conclusion

The overall effect of the AD process on CNP flows can be summarized as:

- *Effect on C*: although the removal rate depends on the composition of the substrate (i.e. the ratio between cellulose, hemicellulose and lignin), as an order of magnitude, approx. 70-80% of C can be expected to be converted into biogas under typical AD conditions. Biogas can replace the use of fossil fuels and contribute to the reduction of GHG emissions. The remaining undigested fraction is made up of recalcitrant C which ends up in the digestate. The lower C content in the digestate is compensated by the lower decomposition. No negative impact on soil organic carbon stocks is therefore expected.
- *Effect on N and P*: digested manure has higher agronomic qualities over undigested manure. The partial mineralization of both N and P via AD allows for a higher nutrient use efficiency.

In the context of CNP flows, advantages (+) and disadvantages (-) of the AD technology have been summarized as follows:

(+) AD can play a pivotal role in rationalizing high volumes of manure, especially in areas known for intensive animal husbandry (associated with high nutrient leaching) and/or Nitrate Vulnerable Zones.

(+) Nutrients of interest for the plant (e.g. N and P) that are contained in the initial feedstocks (including manure) are partly mineralized during the AD process. As a result, the digested materials present a higher NH_4^+-N/total N and $P_{inorganic}$/total P ratios compared with undigested materials.

(+) AD is a versatile technology that can fulfil several roles at once: energy production, nutrient recycling, abatement, decarbonising. The environmental benefits of AD (e.g. avoided CH_4 and CO_2 emissions, renewable energy production, waste recycling) are in perfect alignment with European environmental policies (Circular Economy, BioEconomy, Green Deal).

[3] Average values from 2009 to 2013.

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(-) AD still relies heavily on support schemes (state subsidies) for its viability. While some countries remain supportive, a general trend towards reducing incentives has been observed in Europe in recent years.

(-) Market perspectives are still uncertain regarding both biomethane and digestate products. Regarding the latter, economic viability of such products has not yet been established. The development of proper supply chains is still under construction.

1.10 Mechanical separation

Description of the technology

Mechanical separation of raw manure (or digestate) is carried out with the objective of separating manure into two flows, a solid fraction (SF) and a liquid fraction (LF). This allows up-concentration of phosphorus (P) and organic matter (OM) in the SF, and up-concentration of nitrogen (N) and potassium (K) in the LF. Mechanical separation is not only done as a pre-treatment to nutrient recovery techniques, but is also considered to be an the performance of mechanical separation by reducing the content of P in the interesting manure (or digestate) management technique as the SF (with a dry matter (DM) content of about 25-30%) is a much more concentrated than the raw manure (or digestate), and therefore the total transportations costs are lower for the SF.

Mechanical separation can be achieved by using a screw press, filter press, belt press, centrifuge, grate, drum filters, etc. Addition of chemicals like flocculants/coagulants can improve LF, reduction of water content in the SF, and by enhancing the capacity of separation equipment (Hjorth *et al.,* 2008). Previous studies have shown that mechanical separation can also help to reduce odour emission (Zhang and Westerman, 1997). SF and LF are preferably applied to arable land. Alternatively to direct application, the SF could be composted or used as a feedstock for incineration or anaerobic digestion (AD). SF is suitable for these processes as it is rich in OM and contains lower water content (Møller *et al.,* 2007 and Hjorth *et al.,* 2009). On the other hand, LF can be further treated biologically (i.e. nitrification/denitrification), evaporated, filtrated via reverse osmosis, etc.

Centrifugation is considered to be the most effective separation technique, albeit, a more expensive one. In comparison to the screw press, centrifugation was found to be five times more expensive (Møller *et al.,* 2000). Separation using a flocculation step is considered very effective, although farmers' attitude towards it is influenced by the costs involved in obtaining polymers, additional equipment, etc. (Popovic *et al*., 2017). Screen and filter belts are considered by some researchers to be the best separation techniques performed on flocculated slurry (Hjorth *et al.,* 2011).

An overview of CNP flows in the technology

When it comes to raw animal manure, mechanical separation is mostly applied on pig and cow slurries (Table 0.2).

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Table 0.2 Mean composition of different animal slurries collected from different sites with variations between them (modified from Hjorth et al., 2011).

Slurry origin	DM (g/kg)	TN (g/kg)	NH_4-N (g/kg)	P (g/kg)
Sows	23 ± 15	3.2 ± 0.9	2.0 ± 0.7	0.8 ± 0.2
Finishing pigs	67 ± 26	7.5 ± 2.5	4.5 ± 2.1	2.1 ± 0.8
Dairy cows	82 ± 24	3.7 ± 1.7	5.0 ± 9.3	1.0 ± 0.2

The microbial transformation of OM during the storage phase of the manure before separation affects the N and P distribution between the SF and LF of the slurry. Based on the separation efficiency of DM and P, mechanical separators are ranked as: centrifugation > sedimentation > non-pressurized filtration > pressurized filtration (Table 0.3). Though N and NH_4+ also follow the same pattern, the separation efficiency is lower than that of P and DM (Hjorth et al., 2011). The separation of nutrients between SF and LF by using decanting centrifuge and screw press is shown in Table 0.4 to give a clear idea of the nutrients distributed in each stream.

Table 0.3 Separation indexes (the mass of a compound in the solid fraction compared to the mass of a compound in the original raw slurry) of dry matter (DM), total nitrogen (TN), ammonium nitrogen (NH4-N) and phosphorus (P) for different types of mechanical separation (Hjorth et al., 2011)

Separation technique	Separation index (%)			
	DM	**TN**	**NH_4-N**	**P**
Sedimentation	56	33	28	52
Centrifugation	61	28	16	71
Non-pressurized filtration	44	27	23	34
Pressurized filtration	37	15	-	17

Table 0.4 Mean values of dry matter (DM), total nitrogen (TN) and total phosphorus (TP) in solid fraction (SF) and liquid fraction (LF) (in ranges) after separation using a decanting centrifuge and screw press (Modified from Møller et al., 2002)

Slurry origin	Separation equipment	Separation index (%)	DM (g/L)		TN (g/L)		TP (g/L)	
			SF	**LF**	**SF**	**LF**	**SF**	**LF**
Pig slurry	Centrifuge	4.7 - 13	178 - 279	14 - 28	9.4 - 11	2.2 - 4.9	4.2 - 8.7	0.17 - 0.43
Pig slurry	Screw press	0 - 4.2	344	21 - 43	6.6	3.7 - 5.0	2.1	0.91 - 1.2
Cattle slurry	Centrifuge	12 - 21	199 - 212	25 - 30	5.9 - 6.0	2.1 - 2.8	2.7 - 3.2	0.13 - 0.21
Cattle slurry	Screw press	2 - 5	250 - 365	40 - 46	4.4 - 6.0	2.7 - 3.8	1.6 - 2.0	0.47 - 0.63

Table 0.4 gives a clear indication on how mechanical separation by centrifuge can achieve 3.1-11 times higher concentration of DM, and 4.6-12.5 times higher concentration of P in the SF as compared to its

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values in untreated manure. In the case of screw press, the concentrations of DM and P in the SF were higher by 4.77-6.47 and 1.69-3.38 times respectively (Møller *et al.,* 2002). The concentration of P removal in this case is lower, which supports previous studies that screw press is only efficient in the removal of DM from manure (Møller *et al.,* 2000 and Pain *et al.,* 1978).

Various chemicals like $FeCl_3$, $Fe_2(SO_4)_3$, $AlCl_3$, $Al_2(SO_4)_3$ and $CaCO_3$ are added to manure to coagulate it. In a study by Hjorth *et al.* (2008), flocculation enhanced the removal of P during mechanical separation. This study concluded that at a polymer charge of 2.8 meq/kg manure corresponding to 0.6 g/kg of highly charged branched polymer or 0.85 g/kg of less-charged, linear polymer produced an optimum flocculation where 95% P was removed during separation using centrifugation, gravity drainage and pressure filtration. The study also states how the addition of 10 mmol of ferric chloride salt/kg manure could precipitate 2% more P. $FeCl_3$ salts are considered the most effective additives before mechanical separation (García *et al.,* 2011). The addition of 278 mg l^{-1} Fe from $FeCl_3$ caused a removal of 89% DM, 56% N and 88% P (Barrow *et al.,* 1997).

Geographical representation of the technology and farming systems

Countries like Denmark, the Netherlands, Spain and Belgium have shown an interest in mechanical separation, especially by screw press or centrifuge (Fangueiro *et al.,* n.d.). According to the report on livestock manure processing techniques in Europe (Foged *et al.,* 2011), 11,130 installations in the EU used separation to treat 49 million tonnes of manure in 2011. This number equals to 3.1% of total manure production in the EU. These installations collectively treated 196 Mt N and 53 Mt P. From total 11,130 installations, 10,935 are farm-sized, 120 small/medium-sized and 75 large-scale installations. Most of the farm-sized installations are based in Italy (8,800), while maximum small/medium-sized and large-scale installations are located respectively in Belgium (76) and Spain (53).

Different separation techniques are applied to different types of manure (Table 0.5). Most often mechanical separation is applied in pig and cattle farming. Separation by settling occurs under the influence of gravity. In Flanders, mechanical separation by filtration is commonly used for separation of manure. The undissolved components present in the manure are removed using a perforated plate, drum or woven cloth. The filtration in combination with pressing out of the separated parts, for example, using belt/auger press can be done (Lemmens *et al.*, 2007).

Table 0.5 Types of mechanical separation used for different types of animal manure (Lemmens et al., 2007)

Type of separation	Type of manure
Settling	liquid sow manure with < 6% dry matter, liquid fraction after mortar press
Straw filtration	pig manure
Shaking sieve	pig manure
Auger	solid pig manure, cattle manure
Sieve belt press	pig manure
Centrifugation	pig manure, cattle manure

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There have also been some recent developments in the separation of manure at source, as a measure of emission control. Vermeulen Construct (Ieper, Belgium), along with Beton Dobbelaere (Tielt, Belgium) has developed an innovative stabling system for manure separation, called the VeDoWS. The VeDoWS system ensures efficient separation of animal excreta and urine, aiming to counteract the formation of urease, which is harmful to both humans and animals due to the emission of ammonia (NH_3). By using manure and liquid manure gutter with manure scraper, the VeDoWS stabling system separates the drainage of manure and urine. Underneath the slatted floor, a shallow cellar is constructed which enables the separation of urine and solid manure. Using a scraper, the solid manure is removed from the manure gutter daily. This primary separation of manure in the cellar helps in lowering the NH_3 emissions, thus lowering the loss of N by volatilization (Vermeulen Construct). The ratio of NH_4 to TN in the separated urine is 0.85, with almost no P content in it.

Conclusion

The overall effect of the mechanical separation on CNP flows can be summarized as:

- *Effect on C*: almost entire C (c. 95%) ends up being concentrated in SF in the form of OM, depending on separation type.
- *Effect on N*: most of the mineral N will be found in the LF, with mineral N/total N ratio reaching even 80% as compare to compared to raw animal manure with ratio of c. 50 - 60%
- *Effect on P*: almost entire P (above 95%) ends up being concentrated in SF in the form of OM, depending on separation type and the use of flocculants.

In the context of CNP flows, advantages (+) and disadvantages (-) of the mechanical separation have been summarized as follows:

(+) Separation, as a pre-treatment for nutrient recovery technologies, allows further treatment of separated flows with an aim towards individual recovery of nutrients

(+) Separation into P-poor LF allows its use as a NK-fertiliser in regions with P-rich soils

(+) Reduction in water content, thus reducing cost of transportation of SF

(-) Techniques like centrifugation are expensive and may not be favoured by many farmers

(-) Use of additives for flocculation/coagulation can increase the overall expense of the separation technique

1.11 Membrane filtration

Description of the technology

For a better separation of the manure, especially for the liquid fraction, other techniques than mechanical separation are required. Manure processing plants with membrane filtration are able to separate the liquid fraction of pig or cattle slurry into mineral concentrate, a solid fraction and water.

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Membrane filtration is an additional treatment step to increase the final level of purification (Świątczak et al., 2019). There are four main categories of membrane filtration: reverse osmosis, nanofiltration, ultrafiltration and microfiltration. Microfiltration and ultrafiltration membranes can isolate nutrients associated with particles such as P. Nanofiltration or reverse osmosis is required for the separation of ammonia and potassium (Masse et al., 2007). Reverse osmosis membranes can purify water to such extent that it can be re-used. Membrane filtration is needed because most of the organic matter in the liquid phase of digestate is recalcitrant and present in the form of suspended solids and colloids (Świątczak et al., 2019). Figure 0.6 illustrates the step-wise approach of the membrane plant. Solid-liquid separation takes place in the first step using the screw press. Centrifugation separates solid and nutrients. In the third step a membrane is used to separate mineral concentrate and water. Reverse osmosis (step 4) and zeolites refining (step 5) are the final steps to purify the water. This water is now clean enough to re-enter the water streams. Ammonia stripping is a simple desorption process used to lower the ammonia content of the wastewater stream (Step 6).

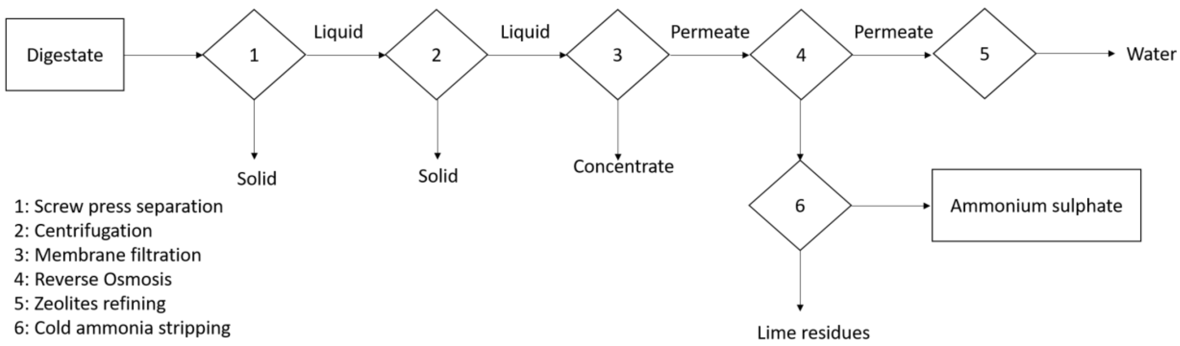

Figure 0.6 Six-step approach of the membrane plant (after Fangueiro et al., 2017)

Reverse osmosis membranes perform best by removing 95 to 99% of the salts and organics (Masse et al., 2007). The membranes have a pore size larger than 0.1µm and the liquid fraction is pressed through the membrane using 0.1-3 bar. Membranes can be organo-polymeric or ceramic. Organo-polymeric membranes are cheaper but they are difficult to clean and they cannot stand high pressures. Deposition and accumulation of materials can cause membrane fouling. It is characterised by a decline in the flux through the membrane surface or within the pore structure (Masse et al., 2007). Thermo-chemical cleaning is essential to recover the flux.

The costs of membrane filtration technology are between 4 and 12 euro/m^3. In digestion plants the technology showed good performances (Ledda et al., 2013), but at smaller scale the technique has suffered some problems (Vaneeckhaute et al., 2016). The removal efficiency of membrane filtration are very high. In a study of Świątczak et al. (2019) the removal efficiency was 98% for chemical oxygen demand, 96-99% for total nitrogen and 95% for total phosphorus (Świątczak et al., 2019). The technique can also be combined with stripping (Tampio et al., 2016; Menkveld and Broeders, 2017).

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Within the EU, the number of digestion plants is increasing (Vaneeckhaute et al., 2017), especially in the countries with manure surplus (e.g. the Netherlands, Belgium and Germany).

An overview of CNP flows in the technology

The mineral concentrates that result from membrane filtration are an interesting nutrient source, which can replace mineral fertilisers. The technology will dominantly influence the N and P cycle, because the fraction of organic carbon and phosphorus that is left at the stage where membrane filtration takes place is limited. Organic matter has dominantly been separated in earlier stages of the separation process (screw press and centrifugation). The composition of the digestate strongly influences the permeate quality, ammonia volatilisation and flux. Therefore, the composition of mineral concentrates also differs between producers. Hoeksma and Buisonjé (2012) took an average of four digestion plants, which resulted in a composition of 0.16g/kg P, 8.15 g/kg N_{tot}, 7.51 g/kgNH_4-N and 14.0 g/kg organic matter.

Experimental tests on the replacement value of mineral concentrate and mineral fertiliser resulted in a nitrogen fertiliser replacement value ranging between 72 and 84% for arable land. For grassland the nitrogen fertiliser replacement value ranged between 54 and 81% for calcium ammonium nitrate and between 79 and 102% for liquid ammonium nitrate. Potassium is equally effective as mineral potassium fertilisers (Systemic, n/a). When this technology will be applied on the large scale it will replace mineral fertilisers, because it can become cheaper compared to mineral fertilisers (Bergsadvies, 2019) and the performances of mineral concentrates are only slightly lower than calcium ammonium nitrate and similar to liquid ammonium nitrate. There is also no evidence that mineral concentrates lead to a higher risk of accumulation of nitrate in soil or groundwater. Volatilization of ammonia and N_2O emissions are possible when using mineral concentrates. Ammonia volatilisation can be limited by incorporating the mineral concentrate into the soil. N_2O emissions caused by mineral concentrates are higher compared to calcium ammonium nitrate but lower when compared to urea (Systemic, n/a).

Conclusion

The overall effect of membrane filtration technology on CNP flows can be summarized as:

- *Effect on C*: The membrane plant will result in solid carbon rich products, which can be applied as fertiliser. However, membrane filtration separates mineral concentrate and water.
- *Effect on N*: The mineral concentrate resulting from membrane filtration results in a product that is almost equally effective as N mineral fertilisers. Therefore, it can significantly influence the N cycle by replacing mineral fertilisers.
- *Effect on P*: The mineral concentrate resulting from membrane filtration results in a product even as effective as P mineral fertilisers.

In the context of CNP flows, advantages (+) and disadvantages (-) of the membrane filtration technology have been summarized as follows:

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(+)	Efficiency of mineral concentrate resulting from this technology is almost comparable to mineral fertiliser.

(+)	The risk of nitrate accumulation in soil- or groundwater is not higher compared to mineral fertiliser.

(+)	Membrane filtration can be used in combination with stripping.

(+)	Membrane filtration will not have any waste streams.

(-)	The technique is expensive and most likely be used by large full scale operating digestion plants.

(-)	The higher the separation performance, the higher the energy consumption (Fangueiro et al., n/a)

(-)	The composition of the digestate has major impact on the permeate quality, ammonia volatilisation and flux.

(-)	Volatilisation of ammonia or N_2O emissions are possible during the application of mineral concentrate.

1.12 Composting

Description of the technology

Composting, is considered to be the oldest method for managing biodegradable materials and recovering valuable nutrients such as carbon (C), nitrogen (N), and phosphorus (P). It is used for processing biodegradable waste from agriculture, forestry, food production and the organic fraction of solid municipal waste or sewage sludge. Composting is a complex process of decomposition of organic matter (OM) in the presence of oxygen and under the activity of specific microorganisms (Haug, 1993). During composting, processes such as ammonification, nitrification, denitrification, humification, etc. occur (Caceres *et al.,* 2018). Composting consists of four phases: (1) mesophilic phase, (2) thermophilic phase, (3) cooling phase, and (4) curing phase (Haug, 1993). During these phases, OM is decomposed through complex processes into a material that is rich in C, N and P, stable, free from pathogens, weeds, and odour. As a product, compost can be safely applied to soil if it fulfils the requirements for fertilisers and soil improvers. The temperature during composting can reach up to 70°C, which allows product sanitation (Haug, 1993). There is a number of composting technologies but mainly the process can be performed in two types of systems: in-vessel composting and windrow composting (Epstein, 2011).

Composting is a complex process, and thus there is a number of requirements that need to be followed to assure efficiency and quality of composts. At the initial stage of composting, i.e. selection and preparation of the composting mixture, the most critical parameters are moisture, OM content, C/N ratio, pH, and air-filled porosity. In general, the most crucial parameters for achieving and maintaining proper temperatures are (Table 0.6): assuring adequate oxygen concentration (e.g. through forced aeration or windrow turning) and maintaining proper moisture content (Haug, 1993).

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Table 0.6 Overview of essential parameters to control composting efficiency (Rynk, 1992).

Parameters	Typical	Optimal
Moisture content, %	40-65	45-60
C/N	20-40	25-35
Oxygen concentration, %	>5	>10
pH	5.5-9.0	6.5-8.0
Temperature, °C	43-66	54-60

Manure composting is one of the methods to manage poultry, pig or cattle manure. In order to compost animal manure, manure needs to be mixed with a proper bulking agent, e.g. straw, woodchips or sawdust to achieve the required moisture content, C/N ratio and air-filled porosity. During the composting the temperature reaches 50-60°C, allowing sanitation of the composting mixtures and the volume and mass reduction by 40-50%. This is the main reason why manure is being compost in countries with a manure surplus, as the excess manure has to be exported, for which sanitation is required. Depending on the selection of technology, the time of composting could vary from 8 to 16 weeks.

Proper composting allows the production of compost that complies with the specific requirements for physical and physicochemical properties, sanitary and maturity. For example, compost applied to soil as an organic fertiliser or soil improver should comply with the legal requirements on the content of OM (at least 30% on dry basis), the concentration of N, P, K (i.e. N>0.3%, P as P_2O_5 >0.2%, K as K_2O> 0.2%), and also the concentration of heavy metals (i.e. this should not exceed: Cr – 100 mg, Cd – 5 mg, Ni – 60 mg, Pb – 140 mg, Hg – 2 mg) (Polish Fertilisers and Fertilizing Act, 2007).

An overview of CNP flows in the technology

The flow of C, N and P during composting of different types of organic waste has been investigated by several researchers (Hao and Benke, 2008; Wei *et al.,* 2016; Czekała *et al.,* 2016; Janczak *et al.,* 2017; Neugebauer and Sołowiej, 2017) (Figure 0.7). During the composting process, N losses can occur in the form of NH_3 ranging from 13-70% of the initial concentration of N depending on the substrate used. C reduction, in the form of CO_2 and CH_4, can range 42-62%. The higher value of C losses occur when composting in a heap (windrow composting). In a composting reactor, this value ranges from 30-54%. P losses, in the form of HPO_4^{2-} and H_2PO_4, can range 14-50%, the higher values occur in case of wet conditions when leaching will occur. In professional indoor composting installations the P losses will be very low. Compost, as a final product, contains 1-3% N, 0.02-2.2% P and 2-40% total C (Hao and Benke, 2008; Harrison, 2018; Tiquia *et al.,* 2002).

The ranges of CNP losses from manure composting as shown above are large as the losses depend very much on the composting conditions and input material. The losses depend on:

- the type of substrates used, which vary in N, C, P ratios (e.g. pig, cow, poultry manure, vegetable waste, process waste, sewage sludge, etc.);

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- the proportion of the substrates used;
- volatilization of nitrogen, mainly ammonia, into the atmosphere from the windrow, whereas in a composter the emissions can be more effectively controlled by collecting the released gases in appropriate tanks as condensate or use filters to limit the release of gases;
- the type and composition of the feed, which determines the composition of the manure;
- the amounts of pharmacological substances used in animal production systems;
- the type of composting in the reactor/windrow, and the influence of weather conditions. Leaching nutrients from windrow during heavy rainfall;
- the influence of temperature on the decomposition of organic matter in the composter/windrow. The longer process with high temperature will contribute to the decomposition of nutrients.
- the turning over / mixing the compost during the process, affects the uniform composting, without the formation of anaerobic zones (adversely affecting the decomposition of nutrients). But this process can result in a faster breakdown of nutrients compared to unmixed compost.

One of the most pressing issues in composting of organic materials with high N content, such as poultry manure (about 4% on dry basis), is N loss through ammonia (NH_3) volatilization and leaching (Czekała *et al.,* 2016; Janczak *et al.,* 2017). For example, the addition of amendments such as biochar to the composting mixture of poultry manure and wheat straw has been reported to reduce the emission of NH_3 but not to affect the loss of N in leachates. During composting of poultry manure mixed with straw and amended with 5% and 10% of biochar, a reduction of gaseous emissions was achieved by 30% and 44%, allowing a reduction of total N loss by 14% and 21%, respectively (Janczak et al., 2017).

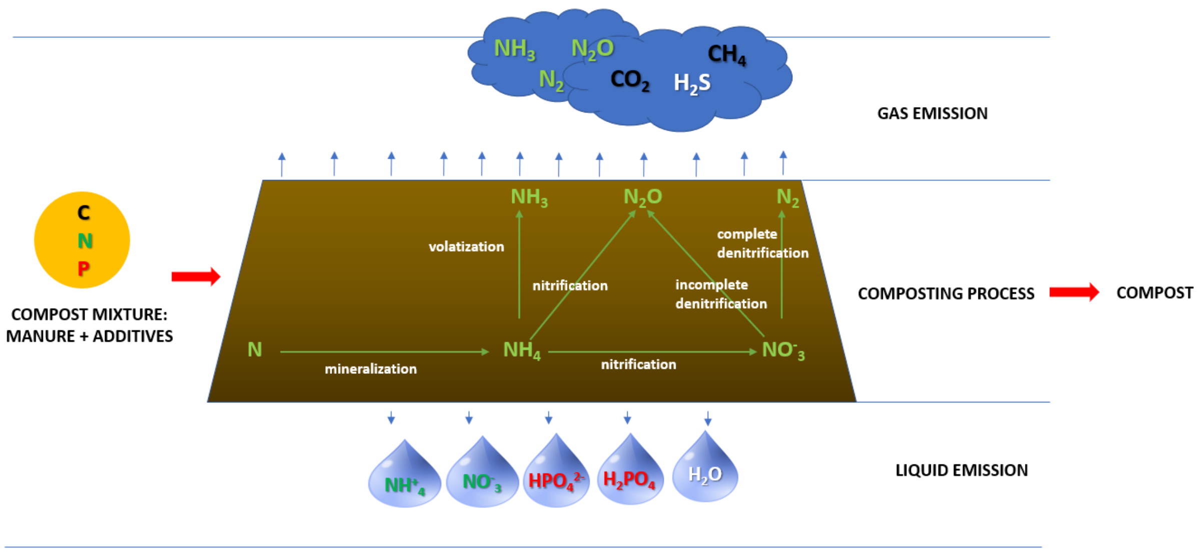

Figure 0.7 The flow of C, N, P during composting.

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Although composting has been extensively studied, there are still difficulties with managing the process on a technological level. The most common problems in composting, in particular for materials with high N content such as poultry, pig or cattle manure, are:

- Odour and gaseous emissions – not only CO_2 and water vapour are formed during composting but also other gases such as NH_3, CH_4, N_2O, H_2S, NO_x, and also volatile organic compounds. These compounds can have a significant impact on the quality of air (e.g. NH_3 and H_2S, and also volatile organic compounds are behind the formation of odour).
- Formation of bioaerosols is possible during transportation and reloading of organic waste, the mixing of the composting substrates, the aeration of windrows or the sieving of composts. The bioaerosols could pose a risk of respiratory system diseases among workers and people living in the vicinity of a composting facility (Wei *et al.,* 2017).
- Formation of leachates when composting is not managed correctly. Leachates usually contain significant concentrations of organic substances, and thus cannot be stored at composting facilities. The composition of leachates depends on the quantity and type of waste in a composting mixture and temperature of the process.
- Production of composts for soil application that do not comply with the quality requirements for micro and macronutrients (mostly C, N, P).

Geographical representation of the technology and farming systems

Composting can be done on-site, at farms or at individual composting facilities. According to Foged *et al.* (2011), in 2011 there were 1,288 composting installations in Europe that produced over 3.4 million tonnes of compost annually, resulting in 44 Mt N and 10 Mt P. Out of total 1,288 composting installations, 1,180 were small-scale, 101 medium-scale and 7 industrial-scale compost installations. Spain has been reported to have the largest number of installations amounting to 107 composting installations that in 2011 produced 257 Mt compost per year, containing 5 Mt N and 1 Mt P. In Belgium, it is estimated that 250 Mt manure per year are composted in composting facilities, whereas in Germany this is about 2,000 and in Sweden about 12,000 (Hogg et al., 2009). To our knowledge, detailed information on animal manure composting on-site or in centralized composting facilities in each EU country is not available**.**

Conclusion

The overall effect of the composting on CNP flows can be summarized as:

- Effect on C: C content may decrease by almost half due to mineralization with CO_2 formation. Finally, however, C in compost will be more stable.
- Effect on N: depending on the used substrate, 13-70% of the initial N concentration can be lost via NH_3 volatilization, some of the ammonia can be recovered by air scrubbers in indoor installations. The remaining N will be mostly in the form of organic N and in plant available form as NO_3

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- *Effect on P*: P losses might occur in the form of HPO_4^{2-} and H_2PO_4, and can range 14-50% of the initial P concentration.

In the context of CNP flows, advantages (+) and disadvantages (-) of the composting have been summarized as follows:

(+) Social acceptance as a biological method that is environmentally friendly as opposed to e.g. landfilling,

(+) Compliance with the circular economy if manure would otherwise be incinerated or exported,

(+) Converting biodegradable waste into a stable, sanitary safe, free from odour and pathogenic microorganisms product,

(+) Application as an organic fertiliser or soil improver to improve soil properties,

(+) Low investment costs for composting technologies,

(-) Properties of biodegradable waste and suitability for composting (e.g. high moisture content, low C/N or low air-filled porosity are considered to be limiting factors),

(-) Necessity to prepare a suitable composting mixture that fulfils the requirements for moisture content, C/N and air-filled porosity,

(-) Relatively long time of the process and the necessity for continuous monitoring.

1.13 Incineration

Description of the technology

Waste incineration/combustion is the thermo-chemical conversion of (preferably) organic matter (OM) at oxygen-rich conditions (oxygen-to-fuel stoichiometric ratio >1) to reduce the mass and volume of the waste and/or extract energy from the waste. Considering the complete burn out of the OM, the main products of the process are CO_2 and H_2O as part of the flue gas, ash, and heat. Nevertheless, the wastes, including manures, contain a certain amount of impurities causing air pollution. In case of incineration, we may consider nitrogen (N), sulphur (S), chlorine, fluor (F), and volatile metals (e.g. mercury (Hg)) as the main impurities resulting in the air pollution after their volatilization and oxidation. In addition, the flue gas released to the atmosphere may be polluted by dust particles as the result of abrasion and cracking of the solid fuel particles. Therefore, regarding the air quality control and management, the flue gases from waste incineration must comply with emission limits given in part 3 of Annex VI of Directive 2010/75/EU of the European Parliament and of the Council (European Parliament, 2010) and Commission implementing decision 2019/2010 (European Commission, 2019). Additionally, the waste incineration in terms of the Directive (European Parliament, 2010) must be operated in such a way that the gas resulting from the incineration of waste is raised, after the last injection of combustion air, in a controlled and homogeneous fashion and even under the most unfavourable conditions, to a temperature of at least 850 °C for at least two seconds. Further comprehensive description on incineration technology regarding the manure treatment can

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be found e.g. in the report on the Best Available Techniques (BAT) for manure processing (Lemmens *et al.*, 2007).

An overview of CNP flows in the technology

Simplified fate (flow) of C, N, and phosphorus (P) during manure incineration is displayed in Figure 0.8. Suggesting the process temperature > 850 °C, the N species of the manure are volatilized and oxidized. As multiple possible reaction mechanisms in homogeneous and heterogeneous phase occur (Svoboda *et al.*, 2000), the main N gaseous species present in the flue gas are N_2, N_2O, and NO_X (sum of NO and NO_2). To meet emission limits, further flue gas cleaning is required to reduce N oxides to molecular N_2. Similarly, C contained in the manure is volatilized and oxidized to CO and CO_2. CO is the result of incomplete combustion; however, with efficient (complete) burn out, the C is primarily lost as CO_2. As the result, the ash (potential fertiliser) contains null to very low amounts of N and C (Foged *et al.*, 2011; Christel *et al.*, 2014; Hou *et al.*, 2017).

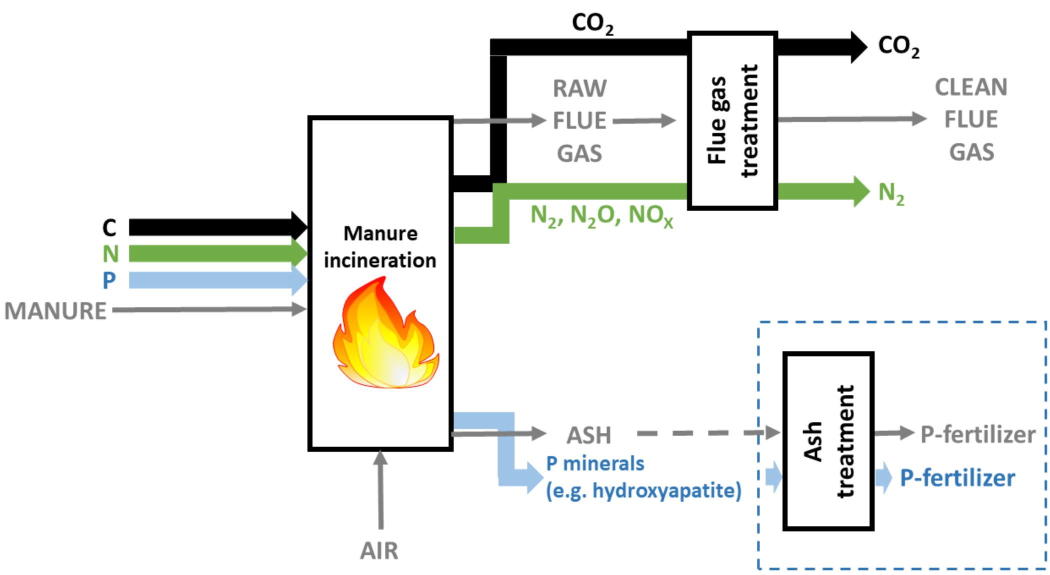

Figure 0.8 Simple schematic mass and elemental flow during manure incineration.

Unlike N and C, virtually all P in the manure is retained in the ash from incineration (Hou *et al.*, 2017). However, further attention should be given to P plant availability (solubility) from the ash as it has been reported by a number of studies to be lower than P plant availability from the manure (Thygesen *et al.*, 2011; Hou *et al.*, 2017; Leng *et al.*, 2019); especially when speaking of immediate availability. That may be due to transformation of readily available P species contained in the manure into low soluble crystalline species during the incineration. P, preferably present as phosphate, has tendency to bound to divalent and trivalent ions. Since there is a significant amount of Ca in the manure and the ash respectively, species like hydroxyapatite ($Ca_5(PO_4)_3(OH)$) and $KNaCa_2(PO_4)_2$ were observed as the most abundant P species in the manure ash (Kaikake *et al.*, 2009; Leng *et al.*, 2019), which are practically insoluble in the water. Regarding the low P availability, applying the manure ash on soil as soil fertiliser/improver/conditioner would prevent loss of P, and it could rather be considered as slow

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release long-term fertiliser. On the other hand, the manure ash may be considered as P-source material (P_2O_5 content c. 8–15 wt. %) and might be further treated, for example by acid dissolution, to obtain specific P products.

Geographical representation of the technology and farming systems

Manure incineration does not belong to typical manure practices and, to our knowledge, only four industrial scaled manure incineration plants have been reported in Europe, three located in the United Kingdom and one in the Netherlands, processing poultry manure/litter in either grate boilers or fluidized bed furnaces (Florin *et al.*, 2009; Foged *et al.*, 2011; Williams *et al.*, 2016). Those plants process approximately 33% of the poultry manure/litter in the mentioned countries. Several other plants have been proposed, mentioned, or investigated in Denmark, Sweden, Ireland, Belgium, France, Germany, Italy, Portugal, and Spain (Florin *et al.*, 2009; Quiroga *et al.*, 2010; Foged *et al.*, 2011; Williams *et al.*, 2016; Hou *et al.*, 2017; Santonja *et al.*, 2017), however, their contribution to manure incineration treatment is negligible, if any at all.

One of the problematic issues of manure incineration is the high water content (i.e. moisture content (MC)) of the manure which hinders proper auto-thermal combustion. This is the case specifically for pig and cattle manures, which would require pre-treatment prior to incineration. The MC of poultry litter is lower than other manures, and its dry matter (DM) content (50–60 wt. %) makes it energetically more interesting feedstock for incineration than the other types of manure (Lemmens *et al.*, 2007; Billen *et al.*, 2015; Santonja *et al.*, 2017). This is one of the reasons why manure incineration is primarily applied on poultry manure. Other practical disadvantage of manure incineration may be the irreversible loss of N and carbon (C) to the flue gas.

Conclusion

The overall effect of the incineration on CNP flows can be summarized as:

- *Effect on C*: practically all C is volatilized and oxidized to CO_2 which is released as part of the flue gas.
- *Effect on N*: practically all N is volatilized and oxidized/reduced and is released ideally as N_2 together with the flue gas.
- *Effect on P*: practically all P is incorporated in mineral phase of the incineration ash.

In the context of CNP flows, advantages (+) and disadvantages (-) of the incineration have been summarized as follows:

(+) Significant reduction of the mass and the volume of the waste,

(+) C neutral energy production, saving fossil fuels,

(+) Lower ammonia and greenhouse gasses release (CH_4, N_20),,

(+) Destruction of organic pollutants,

(+) The ash as a potential component material for EU fertilising products,

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(+)	Use of the ash to meet specific crop nutrient demands.
(-)	Additional technologies needed for manure pre-treatment and flue gas treatment,
(-)	High initial and operating costs,
(-)	Centralized large scale installation is preferred,
(-)	Relying on sufficient manure source,
(-)	Low P plant availability from the ash,
(-)	N and OM loss,
(-)	Public awareness.

1.14 Nitrification – denitrification

Description of the technology

In regions with surplus manure production, biological nitrogen (N) removal is generally used to manage liquid fraction (LF) of pig and cattle manure or digestate (VCM, n.d.). This is achieved through an activated sludge process (ASP), where bacteria oxidize the organic matter (OM) in manure and transform the N. A commonly known ASP is nitrification-denitrification (NDN), which is a two-step process (Metcalf and Eddy, 2003). During nitrification, ammoniacal N (NH_3-N) in liquid manure is oxidized into nitrate (NO_3^-) by autotrophic, nitrifying bacteria which requires inorganic carbon (C) for its growth. This process occurs under aerobic conditions, through the presence of free oxygen and agitation. In the denitrification step, nitrate is reduced by facultative, heterotrophic, bacteria to produce inert N gas (N_2). This process, in contrast to nitrification, occurs under anoxic conditions and requires an organic C source.

As explained in Section 3.2.2, raw manure is firstly pre-treated through a solid-liquid separation before further processing (Figure 0.9). The liquid fraction is then pumped to the NDN system for N removal, which is carried out in two separate tanks. Nitrification occurs in the aerobic tank, which is the second stage of the system. After nitrification, the NO_3^- rich flow is recirculated to the anoxic tank, which is also connected to the inflow of an organic C source (raw LF of manure) and a chemical C source (methanol, acetic acid). The chemical C source has to be added in order to obtain a nearly complete denitrification. After NDN, the treated effluent is separated from the active sludge in a clarifier and a part of the sludge is usually returned to maintain bacterial activity. The remaining sludge can be used as a soil conditioner whereas the treated effluent, which is poor in N and P, can be used as a potassium (K) fertiliser (VCM, n.d.).

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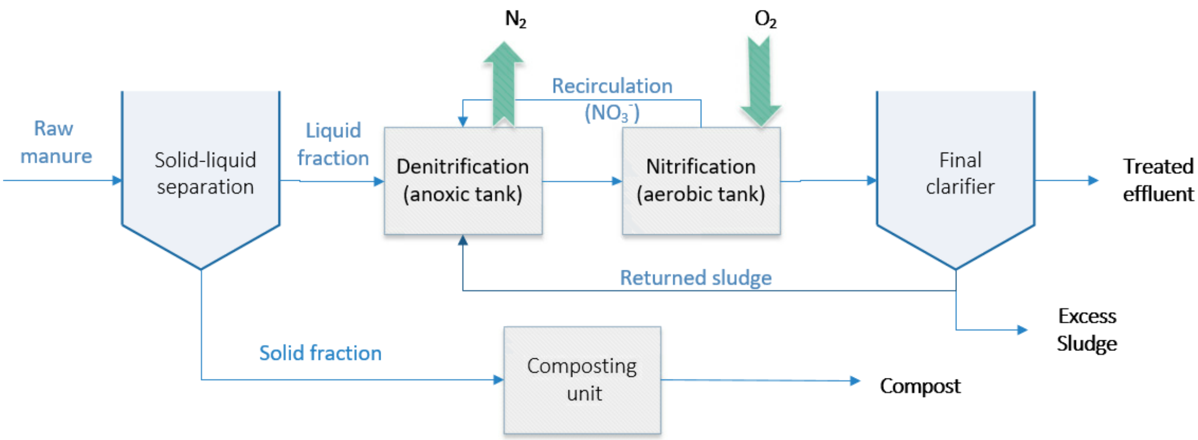

Figure 0.9 Process flow of a Nitrification-Denitrification system for N removal

An overview of CNP flows in the technology

Appropriate pre-treatment using solid-liquid separation is crucial for the success of an NDN system, since it makes the treatment of LF more economical and feasible (Martinez-Almela and Barrera, 2005). The separation is done usually by using a centrifuge or a screw press and this also helps in concentrating the P to the solid phase (Beline *et al.,* 2008). The separation efficiency of P to the solid fraction (SF) is higher for a centrifuge (70-80%) when compared to a screw press (20-50%) (Beline *et al.,* 2008; Smet, 2003).

The overall removal efficiencies in the NDN system for N ranges from 70 to 97% (Beline et al., 2008; Riaño and García-González, 2015; Santonja *et al.,* 2017) and the total COD removal is approximately 97% (Beline *et al.,* 2008; Santonja *et al.,* 2017). According to Foged *et al.* (2011a), the performance of the NDN system can be influenced by factors like manure composition, efficiency of oxygen transfer from the aeration equipment, and reactor temperature.

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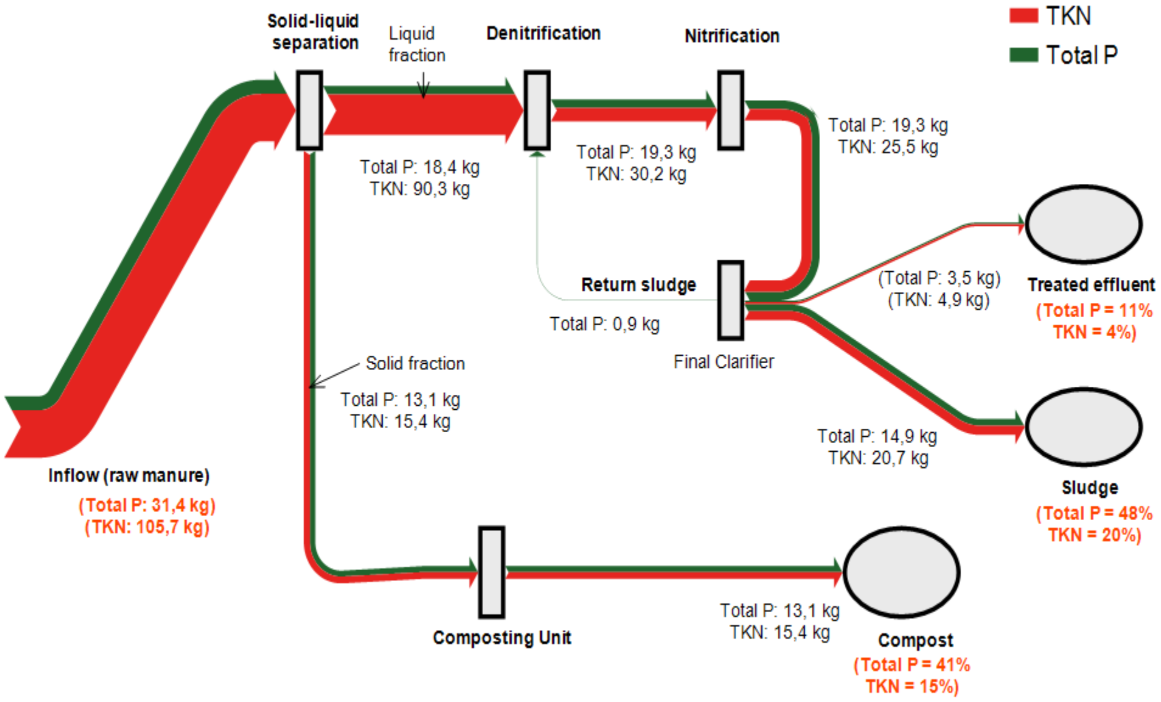

Figure 0.10 Illustration of TKN and P flows (in kg.day) from an NDN plant in Caldetenes, Spain (adapted from Foged et al., 2011a).

Figure 0.10 presents an illustration of Total Kjeldahl Nitrogen (TKN) and P flows from an NDN plant in Caldetenes, Spain. The overall TKN removal at the facility was approximately 61% and the P was mostly concentrated in the sludge (48%) and compost (41%) (Foged *et al.,* 2011a).

According to Lemmens *et al.* (2007), it is difficult to establish an emission factor for N_2O and NH_3 since their formation in the NDN system is not well known. However, based on a measurement campaign at an installation in Langemark-Poelkapelle in West Flanders, a N loss of around 0.8% (via NH_3 and N_2O) over the NDN basin is considered to be acceptable. In a recent study, Hou et al. (2017) explained the break-up of N emissions (NH_3, N_2O), CH_4 emissions during the NDN process and sludge storage using the MITERRA-EUROPE model (Table 0.7).

Table 0.7 Emissions from a NDN facility (adapted from Hou et al., 2017)

Emission factor (EF)		Values used in MITERRA-EUROPE	Range	Source
During NDN process	EF N_2O	9%	1-20%	(Willers *et al.*, 1996; Béline and Martinez, 2002; Melse and Verdoes, 2005; Loyon *et al.*, 2007)
	EF NH_3	0.5%	0.1-0.8%	(Melse, 2005; Willers *et al.*, 1996)
	EF TN	70%	52-80%	(Beline *et al.*, 2008; Beline and Martinez, 2002; Riaño and García-González, 2015)
	EF CO_2	15%	52-80%	(Loyon *et al.*, 2007)

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	EF CH_4	0.25%	0.04-0.34%	(Loyon, 2007; Melse, 2005)
During sludge storage	EF N_2O sludge	0.1%	-	Assumption
	EF NH_3 sludge	1.5%	-	(Loyon *et al.*, 2007)
	EF CH_4 sludge	0.25%	-	(Loyon, 2007)

Geographical representation of the technology and farming systems

Based on a 2011 survey, around 229 farm scale, 76 medium scale and 23 industrial scale installations across the European Union (EU) were equipped with the NDN technology to process the LF of manure (Foged *et al.,* 2011b). From Figure 0.11, it can be seen that these facilities are mostly concentrated in regions with a manure surplus, i.e. the Netherlands, Belgium and France.

Biological N removal using NDN is still widely applied in Flanders (Belgium) with 81 out of 118 manure treatment installations equipped with these systems (Snauwaert & Vannecke, 2017). Since NDN systems operate on liquid streams, mostly LF of pig or cattle manure will be subjected to NDN.

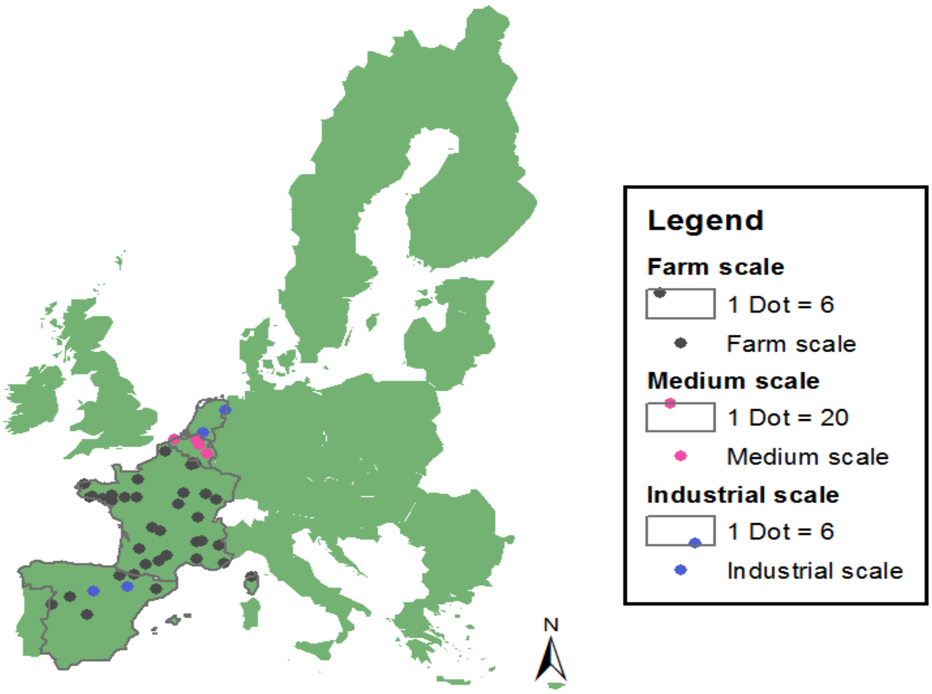

Figure 0.11 Distribution of NDN facilities across the European Union (adapted from Foged et al., 2011b).

Conclusion

The overall effect of the nitrification/denitrification technology on CNP flows can be summarized as:

- *Effect on C*: to our knowledge, effect of C flow has not been reported in literature

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- *Effect on N*: the NDN system converts up to 70% of N from the influent raw slurry to N_2, with losses ranging from 0.1-0.8% in the form of NH_3 and around 9% in the form of N_2O
- *Effect on P*: around 70-80% of influent P can be concentrated to the solid fraction of manure if a centrifuge is used.

In the context of CNP flows, advantages (+) and disadvantages (-) of the nitrification/denitrification technology have been summarized as follows:

(+) Helps in NH_3-N removal from manure, especially in regions with a manure surplus.

(+) The NDN system reduces odours as well as the Chemical Oxygen Demand (COD) as a result of aeration.

(-) Fertiliser value of manure diminishes since NH_3-N is removed.

(-) The aeration system must be well managed to avoid partial nitrification (Hou et al., 2017; Santonja et al., 2017). If not, there is a potential risk of NH_3 or N_2O emissions, which has a global warming potential (GWP) of 298 (over a time horizon of 100 years).

(-) The NDN system is energy intensive, thereby increasing operational costs as well as indirect carbon dioxide emissions.

(-) The NDN generates a higher quantity of sludge when compared to anaerobic treatment systems.

1.15 Stripping/scrubbing

Description of the technology

Ammonia (NH_3) stripping/scrubbing is a physico-chemical process used to recover volatile NH_3 from different waste sources, including dewatered sewage sludge (Janus and van der Roest, 1997), landfill leachate (Ferraz *et al.*, 2013; Raboni *et al.*, 2013), urea fertiliser plant wastes (Minocha and Rao, 1988), condensates from sugar beet factory (Benito and Cubero, 1996), cellulose-acetate fibres wastewater (Saracco and Genon, 1994), anaerobic digestate and animal manure (Sigurnjak *et al.*, 2019).

NH_3 stripping/scrubbing consists of two phases. During the stripping phase NH_3 is transferred from the liquid waste to the gas phase, usually by air, and it is subsequently recovered in the scrubbing phase, usually by means of acidic solution to form the so-called air scrubber water (ASW) (Figure 0.12). The stripping step typically takes place in vertical columns, filled with packing material to increase the liquid/gas contact where the wastewater is injected from the top and the stripping gas enter from the bottom in counter-current. To enhance the conversion of ammonium ions (NH_4^+) to free NH_3, pH and/or temperature can be increased. Sodium hydroxide (NaOH), potassium hydroxide (KOH) and calcium oxides (CaO and $Ca(OH)_2$) are the most common reagents used to enhance the pH increment. Notwithstanding, the equilibrium between NH_4^+ and volatile aqueous NH_3 is influenced as well by air to liquid ratio, air supply rate and hydraulic loading rate. When combining anaerobic digestion (AD)

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with N-stripping process, either biogas or Combined Heat and Power (CHP) flue gas can be used as suitable strip gases, as alternatives to air or steam (Serna-Maza *et al.*, 2014; Bousek *et al.*, 2016). Moreover, the heat necessary to increase the solution pH can be provided by the CHP engine associated with the biogas installation.

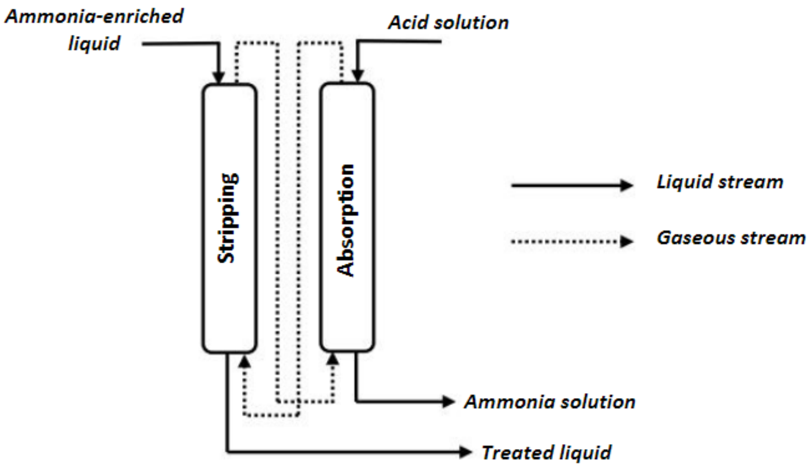

Figure 0.12 Schematic overview of the N-stripping process (Bernal et al., 2015).

Regarding the scrubbing step, if NH_3 is absorbed onto sulphuric acid solution (H_2SO_4) ammonium sulphate ($(NH_4)_2SO_4$) will be formed, whereas the use of nitric acid (HNO_3) as a scrubbing agent would result in ammonium nitrate (NH_4NO_3) solution. Alternatively, the use of gypsum ($CaSO_4$) results in the production of a mixture of ammonium sulphate and calcium carbonate ($CaCO_3$), whereas the application of citric acid would result in the formation of ammonium citrate (Starmans, 2011; Vaneeckhaute *et al.*, 2017). The generated ASWs contain nitrogen (N) entirely in mineral form, and as such represent an interesting alternative for the substitution of synthetic mineral N fertilisers.

Several attempts to recover NH_3 in the form of ammonium sulphate from animal manure have been reported in the literature. According to Zhang and Jahng (2010), NaOH or KOH were preferred over $Ca(OH)_2$ to adjust pH more effectively. In their study, the stripped manure was subsequently used as feedstock for AD (Zhang and Jahng, 2010). At pH 9.5, Laureni *et al.* (2013) recorded NH_3 recovery above 90% from swine wastewater with low COD content (< 10 g l^{-1}). The recovered ammonium sulphate (6% N and low carbon contamination) was assessed as a good marketable fertiliser product (Laureni *et al.*, 2013). Finally, in a study by La *et al.* (2014) almost 83% of the initial NH_3 contained in raw slurry was recovered in the form of ammonium sulphate. This was achieved by using microwave radiation in alternative to air stripping on pig slurry (pH 11, 5 minutes, 700 W) (La *et al.*, 2014).

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An overview of CNP flows in the technology

Since the aim of N-stripping/scrubbing is N recovery, carbon (C) and phosphorus (P) flows are not affected by this technology (Figure 0.13). Part of the NH_3 is segregated from manure (or digestate) to ASW and the amount transferred is strictly dependent on the process operational parameters. A minor transfer of C in the form of VOC may occur during the stripping phase, however, this is negligible for the overall C distribution (Bernal *et al.*, 2015). Finally, P is entirely retained in the stripped effluent.

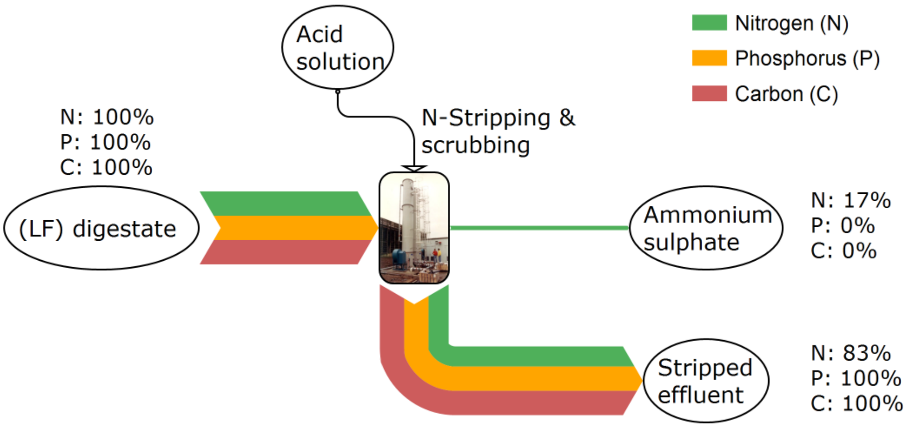

Figure 0.13 N, P and C fate during digestate processing by means of N-stripping, where 17% of total N is recuperated as ammonium sulphate solution. Adapted from Bolzonella et al. (2018).

Geographical representation of the technology and farming systems

Although several scientific studies have been performed on a laboratory scale, there is no mention of N-stripping/scrubbing systems on raw animal manure in the *Inventory of manure processing activities in Europe* (Foged *et al.*, 2012). In the mentioned report, only 1 case of N-stripping/scrubbing from digested manure was reported in the whole EU, more precisely in Italy. However, in more recent years few studies have identified several full-scale cases of N-stripping/scrubbing systems from manure and/or digestate in the literature: 2 in Italy (Ledda *et al.*, 2013; Bolzonella *et al.*, 2018), 1 in Germany and 1 in Belgium (Sigurnjak *et al.*, 2019).

Since ammonia toxicity can occur during AD process of N rich feedstock (such as poultry manure), N-stripping/scrubbing can be coupled to AD systems with the aim to reduce toxic NH_3 levels. Moreover, application of AD prior N-stripping/scrubbing will reduce the amount of volatile organic solids (VOC) transferred to the ASW, as volatile organic matter is turned into biogas (Bonmatı and Flotats, 2003). Coupling N-stripping/scrubbing technology after AD, in general, means to remove N from produced digestate and perform re-circulation of the N-poor effluent from N-stripping column back to the AD for further biogas production. A similar concept is installed at a full scale AD plant in Germany, and it allows 31% of N recovery from the digestate (generated from chicken manure and silage maize

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digestion) in the form of ammonium sulphate (Sigurnjak *et al.,* 2019). Alternatively, N-stripping can be placed after the AD step and applied on the liquid fraction (LF) of digestate, in a configuration known as end-of-pipe N-stripping. The N-Free® process described by Ledda *et al.* (2013) was implemented in Italy as post-treatment to digested cow and swine manure. It included a cascade separation (mechanical separation and membrane filtration) prior to the N-stripping unit where the processing of the concentrate after reverse osmosis resulted in 22-31% AS solution. 17% and 33% of N was recovered from respectively digested cow manure and digested swine manure (Ledda *et al.*, 2013). A recent study by Bolzonella *et al.* (2018) reported the implementation of a N-stripping system at an Italian farm AD installation fed on cow manure, pig effluents and energy crops. The treatment of the LF digestate allowed to recover 17% of N contained in the digestate (Bolzonella *et al.*, 2018). The last example of N-stripping on the LF of manure or digestate is located at a pig farm in Belgium, where horse manure, pig manure and food waste are processed via anaerobic treatment. The produced digestate is mechanically separated and the LF of digestate (or alternatively the LF of pig manure) is processed in a N-stripping unit which employs DETRICON technology. Around 87.5% of the NH_3 fed to the system is recovered in the form of 48% ammonium nitrate (Sigurnjak *et al.*, 2019).

A modification of NH_3 stripping / scrubbing units are air scrubbers, which are used to process exhaust gases rich in NH_3 and mitigate therefore N emissions to the atmosphere, see also Section 3.1.2. Air scrubbers are implemented as well at composting installations or coupled with drying units for the dewatering of solid substrates (solid fraction of manure/digestate) (Brienza *et al.*, forthcoming 2020). In conclusion, similarly to NH_3 stripping/scrubbing installations, air scrubbers have a direct effect on N removal from air (up to 100%). No effects are reported on C and P flows.

Conclusion

The overall effect of the stripping/scrubbing technology on CNP flows can be summarized as:

- *Effect on C*: a minor transfer of C in the form of VOC may occur during the stripping phase, however, this is negligible for the overall C distribution (Bernal *et al.*, 2015).
- *Effect on N*: to our knowledge, N-stripping/scrubbing allows for the recovery of 10%-31% of the total-N contained in the processed digestate. Recovery efficiencies are strictly dependent on process configurations and composition of the treated effluent.
- *Effect on P*: P is entirely retained in the stripped effluent.

In the context of CNP flows, advantages (+) and disadvantages (-) of the stripping/scrubbing technology have been summarized as follows:

(+) Compared to N removal technologies, N-stripping/scrubbing allows for the recovery of N in the form of NH_3 salts, suitable as fertilising products (Mehta *et al.*, 2015)

(+) When coupled with AD of N-rich feedstock, N-stripping/scrubbing reduces the risk that NH_3 concentration reaches toxic levels for microorganisms (Pedizzi *et al.*, 2017)

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(+) Compared to biological activated sludge, N-stripping/scrubbing has lower capital costs, higher process robustness, higher capability to treat N-rich effluents, lower surface requirements, immediate start-up, ease of automation (Vaneeckhaute *et al.*, 2017)

(-) High N removal via N-stripping/scrubbing are generally achieved at high temperature and pH conditions, which may require additional heat consumption and chemicals addition, with higher operational costs (Vaneeckhaute *et al.*, 2017)

(-) Risk of scaling and fouling of packing material (Vaneeckhaute *et al.*, 2017)

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Precision fertilisation

1.16 Introduction

Definition

Technological innovations can stimulate the efficiency and productivity of agricultural systems. These innovations make it possible to reduce greenhouse gas (GHG) emissions while increasing agricultural productivity (Balafoutis et al., 2017). A farm management strategy that makes optimal use of these technological innovations is precision agriculture. The precision agriculture management strategy relevant to the Nutri2Cycle project is precision fertilisation. The strategy adapts the fertiliser use based on the crop nutrient requirements. It combines GPS, proximal or remote sensors, and computers on agricultural machinery and tractors in order to observe, measure and respond to spatial and temporal variation in crop nutrient requirements (Zarco-Tejada et al., 2014). As a result, crop growth becomes more stable within a field and between years, and losses of nutrients to ground -or surface waters or the atmosphere will be reduced. Precision fertilisation can be applied to a wide variety of crops and it can fit in various farming strategies. The win-win strategy of precision fertilisation makes it a promising strategy in the transition towards circular agriculture.

Precision fertilisation follows the 4R Nutrient Stewardship: applying the right fertiliser, in the right rate, at the right time, and at the right place. The implementation of best management practices can result in increased production, increased farmer profitability, enhanced environmental protection and improved sustainability is expected (Johnston and Bruulsema, 2014). Precision agriculture is also a climate-smart agricultural practice. These practices aim to increase agricultural productivity and income, adapt and build resilience to climate change and reduce and/or remove GHG emissions.

Figure 0.1 The 4R Nutrient Stewardship identifies the steps precision fertilisation involves.

Environmental benefits

Conventional fertilisation techniques aim to distribute the fertiliser equally over the land at fixed moments during the growing season. This technique results in areas and time periods with excessive or limited amounts of nutrients, because there is spatial and temporal variation in soil nutrient

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availability and crop nutrient requirements. Precision fertilisation is able to apply a variable amount of fertiliser to the soil. Making sure that the soil nutrient availability equals the nutrient requirements, will reduce the risk of N and P leaching to ground -and surface water or N emission (e.g., N_2O, NO_x, CH_4 and NH_3) to the atmosphere. Precision fertilisation can also be applied for soil carbon sequestration. Identifying the spatial variation in C sink capacity can help C sequestration. Different tools that are used for precision agriculture can reduce gaps and overlaps in fieldwork and the compaction caused by heavy machinery (Van der Wal, 2014). From an environmental perspective, precision fertilisation can stimulate C sequestration, optimize crop growth, and improve or restore soil life and soil structure. Indirectly, it can improve ecology, biodiversity and human health by reducing environmental losses.

Adoption of precision agriculture

Reducing the costs farmers spend on fertilisers (Lencses et al., 2014) while increasing agricultural productivity (Robertson et al., 2007; Robertson et al., 2009) makes precision agriculture an attractive adoption strategy. The adoption of precision fertilisation is increasing throughout Europe. According to CEMA (2016), about 70 to 80% of new farm equipment sold has a precision farming component. In most cases this will refer to GPS devices on tractors, for specific equipment related to precision fertilization, e.g. for variable rate technology, the adoption will be much lower. The main benefits of precision agriculture mentioned by Dutch farmers were: (i) the reduced gaps and overlaps in fieldwork, (ii) the possibility to work more accurate, and (iii) the techniques are time savers and make farmers less tired (Van der Wal, 2014). Another benefit for farmers mentioned by Silva et al. (2011) is the managerial improvements, which leads to informed decision making.

Farm size, the willingness of farmers to adopt and country-specific agricultural systems are important drivers in the adoption of precision fertilisation (Blackmore et al, 2006). Dutch farmers that did not adopt to precision agriculture mentioned the small size of their arable fields, the expected lack in financial benefit and awaiting for further developments as major reasons (UNIFARM, 2015). The adoption of precision fertilisation can be stimulated by reducing the investment cost (Fountas et al., 2005), organising trainings and providing technical support (Robertson et al., 2007), easing the use of data, and providing user friendly software (Fountas et al., 2005). Improved collaborations between developers and users of precision fertiliser tools, and between research institutes working on accelerated adoption of technologies and solutions for climate change mitigation would boost the adoption of precision fertilisation (Beck et al., 2014).

1.17 Fertiliser spreading technologies

Variable rate fertiliser technologies exist for inorganic fertilisers (e.g., N and P), organic fertilisers (i.e., carbon-rich digestate) and lime application. Which technology to use depends on the type of fertiliser. Inorganic fertiliser can be spread as liquid (e.g., aqueous solutions of ammonium nitrate or urea) or solid granules (e.g., mixtures of nitrogen, phosphate and potassium). Organic manure can be spread as slurry (e.g., pig faeces) or solid manure (e.g., chicken faeces). Liquid inorganic fertilisers can be spread using the variable rate pesticide sprayer technology. The spinner spreader and pneumatic spreader are most common granular fertiliser spreaders. A spinner spreader drops fertiliser granules

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on one or more spinning disks, throwing the particles into the field. The variable rate spreading of granules depends on the machine settings and the fertiliser's physical properties (Behiç Tekin and Okyay Sindir, 2013; Hijazi et al., 2014). A pneumatic spreader uses airflow to convey fertiliser particles from the metering units to the distributors (Beck et al., 2016). The granules are divided over a piped spreading boom. Fertiliser drills (i.e., machinery that places the fertiliser into the soil) can be used to increase the placement accuracy (Maleki et al., 2008), because this machinery does not throw the granules into the air. The mass flow rate can be variable by changing the size of the orifice at the bottom of the hopper, by changing the speed of the conveyor belt or the metering rollers that deliver fertiliser to the delivery system (Beck et al., 2016), or by using load cells (i.e., transducers that create an electrical signal) to measure the dynamic weight of the spreader with fertiliser.

Slurry applicators spread organic manure by pressuring the slurry tank or pumping the slurry from the tank (Funk and Robert, 2003). The slurry flow rate can be set by a controller or by a real-time soil sensor. This sensor measures the nitrogen content of the slurry, the ground speed of the vehicle and the working width (Brambilla et al., 2015). The nitrogen content of the slurry was measured because of the inconsistent nutrient composition of slurry. This makes the nutrient application more accurate. Solid manure spreaders use an apron that pushes the manure towards a dispensing system. The impact of this spreader on crop nutrient responses and soil nutrient loading was small according to Agriview (2013) and Moshiaa et al. (2015).

1.18 Precision agriculture technologies

Many different tools and techniques exists for precision agriculture. Tools can vary from a parallel tracking systems on tractors with Differential Global Position System (i.e., a GPS system which is supplemented with a series of ground-based stations) to full mapping capabilities of the fields, variable rate applications and automated guidance systems.

The tools and techniques for precision agriculture developed rapidly over recent decade. For example, the Real Time Kinematic-GPS became in 10 years' time more popular in auto-steering systems than ever expected. Tools and techniques that are being used for precision agriculture can be divided in different categories. However, researchers came up with different categories. McBratney et al. (2005) divided the tools into: (i) hardware and sensors, (ii) data analysis and decision support systems, and (iii) commodity and whole-farm focus. The JRC Report on Precision Agriculture and the New CAP (Zarco-Tejada et al., 2014) categorized the tools and techniques into: (i) remote sensing, (ii) guidance systems and (iii) variable rate applications. Most comprehensively are the categories defined by the FP7 project Future Farm (Schwarz et al. 2011): (i) guidance systems, (ii) recording technologies and (iii) reacting technologies. All three technologies need to be combined to make precision fertilisation succeed.

The first category, guidance systems, includes all tools based on automatic steering/guidance for tractors and self-propelled agricultural machinery. The techniques helps farmers measuring, mapping, responding and using the spatial aspects of the fields. The tools make use of Global Navigation Satellite Systems (GNSS) systems. Most common GNSS systems are: GPS-NAVSTAR, GLONASS, BeiDOU and

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Galileo. The Real Time Kinematics is another GNSS technique. The technique provides high performance positioning in the vicinity of a base station (ESA, 2015). Another GNSS system is the Precise Point Positioning that combines precise satellite positions and clocks with a dual-frequency GNSS receiver. The accuracy of GNSS systems ranges between 1cm and 10m. There is a trade-off between the accuracy of the system and the costs.

Machine guidance can be subdivided into driver assistance and machine auto-guidance. Driver assistance is not integrated in the tractor's system, while machine auto-guidance is integrated. Driver assistance helps reducing fuel costs, input costs, time, labour, soil compaction and increases the overall field efficiency. Examples of commercially available driver assistance systems are the Trimble EZ-Steer and the Raven RGL Lightbar System. Tractor manufacturers implement standard machine guidance with GNSS nowadays. Guidance systems can make CNP flows more efficient by allocating the areas that require nutrients accurately. Guidance systems can operate manually or automatically. Nearly all studies on the difference between both showed that a higher accuracy could be reached using automatic guidance (Baio and Moratelli, 2011; Shinners et al., 2012). Shockley et al. (2011) concluded that machine guidance during fertiliser application led to cost savings of 2.2%. For Denmark, Jensen et al. (2012) reported a reduction in fertiliser use of 3-5% for the crops wheat, rape seed, maize and sugar beets. Controlled Traffic Farming confines machinery loads to the least possible area of permanent traffic lanes. The technique has significant effect on CNP flows as it reduces compaction by approximately 60% (Gasso et al., 2013). Therefore, fertiliser uptake increases by approximately 15%, which reduces the leaching of N and P to ground -or surface water. The soil can also retain more organic matter and soil living organisms when compaction is limited. This decreases the oxidation of organic carbon into CO_2. Gaseous exchange will also be stimulated because soil structure will not be destroyed.

The second category, recording technologies, is used to monitor and store data on pedoclimatic parameters and crop factors during the growing season. Many different tools are available to collect data on the spatial variation of chemical and physical soil properties and crop growth. The data help farmers to make informed decisions on the required type and quantity of fertiliser. Soil data can be obtained by: (i) a GNSS receiver that can provide elevation maps, (ii) soil sampling and laboratory analyses, (iii) on-the-go soil sensors (e.g., electrical and electromagnetic, optical and radiometric, mechanical, acoustic and pneumatic, and electrochemical sensors), (iv) distant electro-magnetic instruments, like the Geonics EM28DD or the DUALEM-21, that collect data on the soil electrical conductivity, (v) pH sensors that measure the soil pH, (vi) soil γ-ray sensors that measure multiple soil properties, and (vii) volumetric or tensiometric soil moisture sensors (Beck et al., 2016). Data on crop growth can be obtained by: (i) grain flow sensors that provide data on the harvested grain volume, (ii) grain moisture sensors that provide data on the grain moisture variability, (iii) clean grain elevator speed sensors that can improve the accuracy of grain flow measurement, (iv) a yield monitor display and header position sensors that determines the location of the measurement, and (v) travel speed sensors that determines the distance a harvester travels during a certain time interval (Beck et al., 2016). Most important commercial tools to monitor crop growth are: RDS Technology Ltd, Greenstar, Case IH, Deutz-Fahr Teris System, GRAIN-TRAK, and Fieldstar.

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Near sensing and remote sensing are used in recording technology. Near sensing uses spectroscopy and is able to measure the quality (e.g., greenness) of a crop. Remote sensing technologies make use of radar to provide precise, geocoded information on the spatial variation of a soil or crop. Light Detection and Ranging (LiDAR) remote sensing can measure the distance from the sensor to the feature by illuminating the feature with light. This technology is mainly used for monitoring crop growth. Last but not least, there are Unmanned Aerial Vehicles (UAVs) (e.g., drones) used as recording technology. UAVs are aircrafts that are controlled autonomously or by a pilot on the ground. There are fixed wing or multi-rotor UAVs. For variable fertiliser application the on-the-go treatment sensors can be used. Examples of these sensors are AgLeader, Topcon, Yara, Fritzmeier, Rometron.

The third category, reacting technologies, implements the data. Real-time sensor-based variable rate pesticide and liquid fertiliser application is an example of a reacting technology. The technology avoids application to undesired areas of the field or plant canopies (Karkee et al., 2013) and it can reduce spray overlap (Batte and Ehsani, 2006). The main types of pesticide application technologies are: (i) flow-based control that keeps the application rate constant by varying the nozzle flow rate, (ii) direct chemical injection that utilizes a controller and a chemical pump to manage the rate of injection into a stream of the water carrier, (iii) chemical injection with carrier control that utilizes a control system that changes both, the chemical injection rate and the water carrier rate to respond to ground speed or application rate changes, and (iv) spraying nozzle control system that uses conventional sprayer nozzle assemblies that work in conjunction with direct-acting, in-line solenoid valves to rapidly open and close the outlet of a nozzle (Beck et al., 2016).

1.19 Effect of precision fertilisation on CNP flows

Variable rate fertiliser application technologies is able to equalize the soil nutrient availability and the crop nutrient requirement. Raun et al. (2001) estimated a nitrogen use efficiency increase of 15% for winter wheat due to precision fertilisation. A literature review on the keywords “Precision ferti*” and “Europe” resulted in the selection of 161 manuscript. Only half of these selected manuscripts (83) did analyses on C, N or P, of which 77% focus on N, 18% focus on P and 5% focus on C. It is expected that CNP losses will reduce in the near future because of the increased use and availability of technologies for precision agriculture (Bai, 2018).

Precision fertilisation on reducing N and P losses

Most studies on precision fertilisation focus on the effect of variable rate fertiliser application on yields. The yields of crops that strongly depend on the N and P availability during the growing period increased after the introduction of variable rate application (Kharim et al., 2019). The N and P application differs per field and per year, because the N and P requirements are crop, soil and climate dependent. Therefore, applying N and P using variable rate technologies resulted in some studies to a decrease in N and P use (Kharim et al., 2019), whereas in other studies the N and P use increased (Chen et al., 2015). There is consistency among authors about the increased N and P use efficiency (in some studies over 15%) and reduced losses to the environment due to variable rate application

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(Baeckström et al., 2006; Lu et al., 2019; Obreza and Sartain, 2010). The Future Farm Project used between 2 and 20 kg N/ha less N fertiliser due to the application of precision fertilisation technologies. Other studies showed decreases between 5 and 30% and 8 and 40% (Barnes et al., 2017). Emission reductions, analysed by the Greenhouse gas - Air pollution Interactions and Synergies (GAINS) model, are assumed to range between 6 and 18%. Studies on N and P variable rate application focus on the reduction in mineral fertilisers, while the transition towards circular agriculture aims for fertiliser free agriculture using recycled N and P products.

Precision fertilisation on reducing C losses

Limited research has been carried out on the effect of variable rate application of C-rich products (e.g., solid manure, compost, carbon-rich digestate) on C sequestration and soil C stock. Farmers can reduce the CO_2 emissions from agricultural soils by reducing or stop their tillage practices. Limiting the driving of heavy machinery on land can also reduce CO_2 emissions. Tools and techniques that are used for precision agriculture can be used for assessing the C sink capacity (Jarecki and Lal, 2003). Based on this capacity, C can be applied to the soil using variable rate application. This actively restores/increases the soil organic carbon content. Carbon costs and carbon leakage are expected to decrease using precision fertilisation (Liu et al., 2016). A modelling study for the EU27 on the effect of GHG emission using Machine Guidance and Variable Rate Nitrogen Application technology resulted in a reduction of 0.13-4.4 Mt CO_2-eq/year and 2.1-6.5 Mt CO_2-eq/year respectively (Barnes et al., 2017).

Conclusion

The overall effect of precision fertilisation on CNP flows can be summarized as:

- *Effect on C*: precision fertilisation has so far been mainly been used in combination with mineral fertilizers, therefore the effect on C is very limited.
- *Effect on N*: precision fertilization can better match the N application with the crop demand and reduce therefore the N emissions to water and air. Emission reduction is rather context specific but on average a reduction of about 10% is possible.
- *Effect on P*: although most precision fertilization is aimed on N, also P can be applied with precision fertilization, which will reduce potential losses

In the context of CNP flows, advantages (+) and disadvantages (-) of precision fertilisation have been summarized as follows:

(+) Fuel use and related GHG emissions are reduced
(+) Cost for fertilizer purchase can be reduced
(+) Most new tractors are now equipped with detailed GPS systems
(+) Crop yields can increase if crop demand is better match with nutrient supply
(-) Investment cost can limit the uptake of precision fertilisation
(-) Precision fertilization with organic fertilizers is possible, but so far only limited applied as appropriate machinery is hardly available

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Mixed farming systems

1.20 Definition of mixed farming

The EIP-AGRI Focus Group on mixed farming systems (2017) used the following working definition for mixed farming systems: 'Systems including at least one type of cash crop and one type of livestock production, considered both at farm and at regional level, as a combination of specialized farms exchanging resources between them' (EIP-AGRI, 2017).

Various definitions for mixed farming systems exist in scientific literature. Whereas some authors refer to mixed farming systems, others use the terms 'integrated crop-livestock systems' or 'mixed crop-livestock systems'. European studies using any of these terms are considered in this literature review, as long as they comply with the working definition of the EIP-AGRI Focus Group.

The integration (or mixing) of crops and livestock could occur within a farm or amongst farms on a regional level (Lemaire et al., 2014; Moraine et al., 2014; Schut et al., 2021). At field- or farm level this would include grazing livestock on crops, crop residues or forage crops; crop-grassland rotations and understory grazing in vineyards or orchards. At regional level integration includes cooperative arrangement between farms; regional planning to match supply and demand for livestock feed and trading animal manure, crop residues or land between farms (Martin et al., 2016).

Eurostat uses a definition for mixed farming systems that only considers mixing on farm level: 'an agricultural farm where neither livestock nor crop production is the dominant activity; an activity is called dominant if it provides at least two-thirds of the production or the business size of an agricultural holding'. With this definition, from the total number of EU farms 52.5% are defined as crop specialist, 25.1% as livestock specialist and 21.1% as mixed farming (Figure 0.1).

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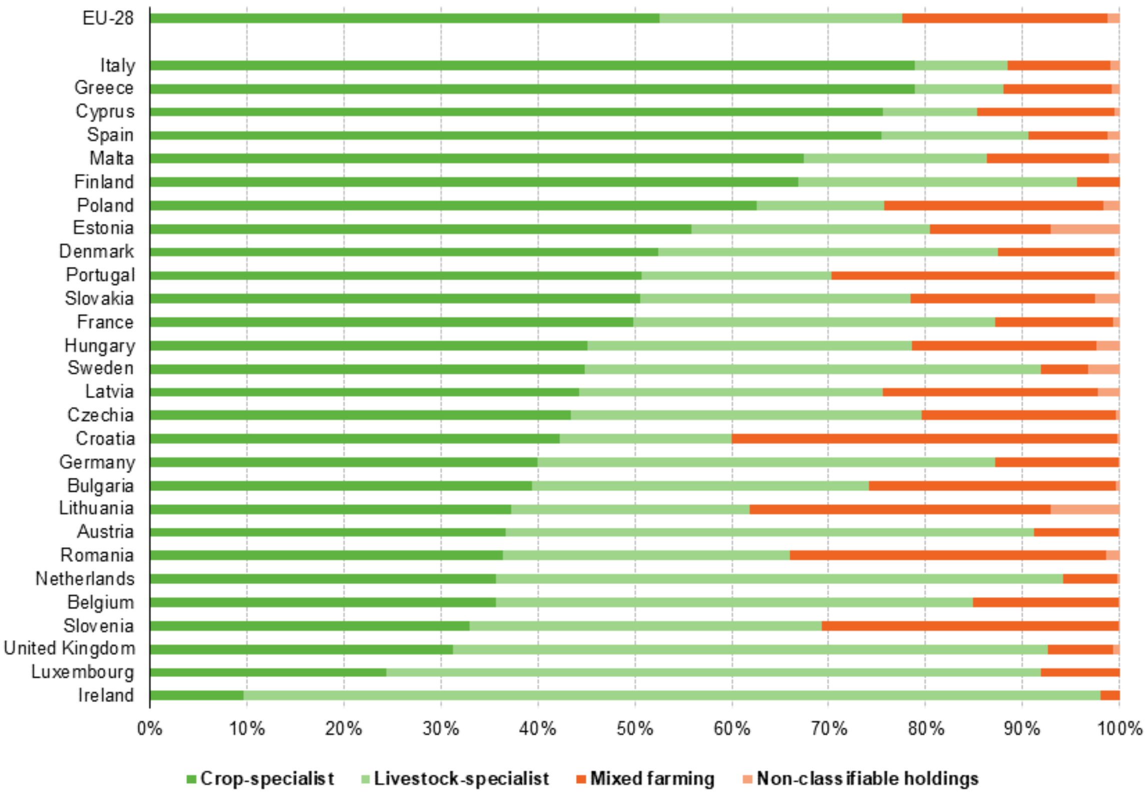

Figure 0.1 The EU farming specialisation and mixed farming (% of total holdings, Source: Eurostat)

1.21 The potential benefits of mixed farming systems

Mixed farming systems as compared to specialized farming systems are often postulated to have several environmental benefits, both by policy makers and in scientific literature. Mixed farming systems are considered to reduce dependency from external inputs and use available resources more efficiently, through favourable exchanges between agricultural partners, sectors, or products. It has therefore been suggested as an effective approach for closing N and P cycles in agriculture. Mixed farming could therefore contribute to ecological intensification, which is needed for achieving future food security and environmental sustainability (Lemaire et al., 2014). The EIP-AGRI Focus Group sees opportunities for environmental sustainability in the sense that mixed farming can 'increase self-sufficiency in animal feeding through multiple use of local resources and efficient use of nutrients; recouple nitrogen and carbon cycles through legumes/grasslands in arable rotations; improve soil quality through organic manure and crop diversification' (EIP-AGRI, 2017).

Mixed farming is often proposed as an alternative to highly specialized farming (on both farm and regional level), thereby reducing the negative environmental effects of these type of farming systems. As discussed by the EIP-AGRI focus group, specialized crop farms have problems maintaining soil organic matter content and soil fertility all over Europe. Straw has continued to be transported from arable areas to intensive livestock production systems, but manure has not been returned due to

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issues such as transport costs. The use of inputs, such as mineral fertilisers and pesticides, has helped to overcome the need for rotations to build soil fertility and control weeds, pests and diseases, but is now facing serious economic and environmental limits. At the same time, high livestock density regions are facing water- and air pollution due to an excess of manure. Moreover, they highly rely on external inputs, particularly on protein for feed. According to Schut et al. (2021), larger-scale specialized farms tend to concentrate problems in comparison to mixed farms. With more animals per production unit, impacts on the local environment are greater. High concentrations of specialized farms in one region often exacerbate environmental issues associated with agriculture such as N deposition in nearby natural areas, on top of other problems related to human health.

Although mixed farming systems are thought to have several environmental benefits compared to highly specialized systems, these statements are rarely supported by quantitative evidence. This literature review aims to evaluate European studies on mixed farming regarding C- N and P cycling. More specifically, in this chapter we aim to provide supportive evidence for the evaluation of four main indicators related to CNP cycling namely reduce primary resource P; reduce fossil energy; reduce emissions to the environment; increase soil organic matter.

1.22 Studies on mixed farming in Europe

A literature search on studies that quantified the effect of mixed farming in terms of CNP cycling showed that only a limited number of studies are available for European countries. In this section the most relevant case studies which compare mixed and specialized farms are discussed one by one. These studies cover a wide range of mixed farming systems, reference systems and scales (farm or regional). Moreover, these studies use a variety of different indicators for environmental sustainability, such as nutrient surpluses, nutrient use efficiencies, mineral fertilizer requirements, GHG emissions and non-renewable energy use. The results of the literature review are summarized in Table 5.8.

1.22.1 Case studies on farm level: mixed farming within the farm system

A study by Ryschawy et al. (2012) compared the environmental performance of individual mixed crop-livestock farms vs. specialized farms from a set of 48 farms within the same region in France. They used the farmgate N surplus (kg N/ha/yr) as an indicator, where a higher N surplus can lead to higher emissions to the environment. Mixed farming systems had a higher farmgate N surplus (24 kg N/ha/yr) compared to specialized crop farms (-12 kg N/ha/yr), but lower than specialized beef farms (38 kg N/ha/yr) and specialized dairy farms (60 N/ha/yr). The nitrogen farm gate balance calculation indicate that mixed crop-livestock farms had intermediate nitrogen inputs and outputs, the crop farms had high nitrogen inputs and outputs and beef farms had the lowest nitrogen inputs and outputs. The total amount of N in purchased inputs was lower in mixed farms than in specialized crop and dairy farms, but higher than in beef farms. Dairy farms had the highest nitrogen inputs - mainly due to the large quantities of purchased concentrates and fertilisers- and intermediate nitrogen outputs. The results within this region were compared to Farm Accountancy Data Network (FADN) data at regional, national and European scales, and the authors report that this data confirmed the results from this study regarding the N surpluses of different systems. All in all, the mixed farms never turned out the

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most favourable system, but neither the least favourable system regarding environmental indicators (N in inputs and N surplus). Regarding the N surplus per kg N in the outputs the mixed farm performed better (0.43 kg N surplus per kg N in outputs) than the dairy (0.81) and the beef farm (2.2), but worse than the specialized crop farm, which did not have a nitrogen surplus. Although this study makes clear that there are differences between mixed and specialized farms, it does not necessarily provide evidence that mixed farming systems has a lower N surplus than separate arable and dairy/beef systems with the same total N outputs in crops and milk or meat.

Bos & van de Ven (1999) took a different approach and quantified the effects of mixing a specialized farming system by making a farmgate N and P balance of both systems. The mixed farming system was hereby a hypothetical variant on both separate systems, and the nutrient balance of the mixed system was compared to the total nutrient balance of both specialized systems. No other changes in the farm plan were made, in order to merely quantify the effects of mixing, whereby mixing is defined as intensively co-operating, exchanging land, labour and machinery. Differences between the combined nutrient balance of both specialized farms and that of the mixed farming system were small, and neither the N use efficiency nor the N surplus were improved. It was however concluded that in a mixed farming system it is possible to realize a higher income without increasing environmental pollution, since the N surplus per kg N in the outputs were slightly lower in the mixed system (1.37 kg N surplus per kg N in outputs) compared to the total of both specialized systems (1.45 kg N surplus per kg N in outputs).

A case-study by Bonaudo et al. (2014) compared two types of mixed crop-livestock farms. A ‘conventional’ mixed farm was compared to a ‘sustainable’ mixed farm which aims to improve the resilience, self-sufficiency, productivity and efficiency of mixing crop-livestock by applying several agroecological principles. The sustainable mixed farm prioritizes self-sufficiency and minimizing external input of feed and fertilizers. The comparison of both systems shows that the sustainable mixed farm spends less on feed imports ($376 vs $660 per ha), has a 33% lower N load (121 vs 161 kg N per ha), and a 33% lower energy consumption per litre milk (43 vs 65 Eqf[4] per 1000 l milk). Although this case-study does not compare a mixed system to a non-mixed system, it illustrates very clearly that the type of management in mixed farming can have serious consequences for its performance on environmental sustainability.

Veysset et al. (2014) compared three groups of farms on their individual environmental performance, namely specialized beef farms with 100% grassland, specialized beef farms with both grassland and feed crops, and mixed beef farms with grassland, feed crops and arable crops. Regarding their environmental performance, these groups of farms were evaluated for their N surplus (kg N/ha), GHG emissions and non-renewable energy consumption. Averaged over the group of farms, the specialized beef farms had a lower N surplus (kg N/ha), slightly lower GHG emissions (kg CO_2-eq per kg liveweight or per ha), and a lower non-renewable energy consumption (MJ per kg liveweight or per ha). This study does however not account for external environmental impacts avoided by the arable crops produced within the mixed farming system. Therefore, it cannot be deducted from this study if mixed

[4] Equivalent litre fuel

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farming in comparison to specialization changes the overall environmental impact of the food produced.

Marton et al. (2016) performed a lifecycle assessment to compare the environmental impact of specialized or mixed dairy production system at farm output level (milk, meat, and crops). The mixed system had a lower non-renewable energy use, a lower P use, and a higher K use. GHG emissions and N eutrophication were not significantly different. The contradictory results between P and K use might have been a result of the way crop production was modelled. Based on the modelled results of the life cycle assessment, the authors argue that mixed farming has the potential to reduce environmental impacts, but that this should be tested with real farm data. This study is therefore not conclusive, and the question remains whether the theoretical benefits of mixed farming can be translated into a real advantage over specialized farming.

Specifically on grassland-cropping rotations, Lemaire et al. (2015) reported that rotations including grassland can temporally and spatially capture the benefits of leys for minimizing environmental impacts, while still maintaining periods and areas of intensive cropping. Long-term experimental results illustrate the potential of such systems to sequester C in soil and to reduce and control N emissions to the atmosphere and hydrosphere. Overall, average nitrate concentration below grassland–crop rotations decrease exponentially as the proportion of grassland phase within the rotation increased. In mixed farming systems, the arable crop rotation is likely to be widened with grassland, which creates the opportunity of C sequestration and reduced N emissions.

1.22.2 Case studies on a regional level

A study by Garnier et al. (2016) analyses a scenario where livestock is reintroduced in a specialized cropping area, thereby reconnecting organic cropping- and animal production systems at regional scale. This scenario assumes that 20% of the agricultural area in the region is converted to permanent grassland, and that alfalfa is introduced in the crop rotation (2/8). Compared to the specialized organic crop rotation (on 100% of the agricultural area) the N surplus of the mixed system is higher (31 vs. 15 kg N/ha/yr), and the higher N surplus of the mixed system mainly results from the livestock area. Regarding the N surplus per kg N in the outputs (crops, meat and milk) the mixed cropping system also appears less efficient (0.52 vs. 0.11 kg N surplus per kg N in the outputs). However, this study does not consider the potentially avoided N pollution outside the region by the reintroduction of livestock in this specific region. Furthermore, the comparison between mixed and specialized farming systems would be fairer if the specialized farming system consisted of a separate crop- and livestock system instead of merely a specialized cropping system. This emphasizes the difficulties with quantitatively analysing different systems, the importance of good reference systems and the issues with accounting for external effects.

A Swedish study by Sasu-Boakye et al. (2014) showed that enhancing local protein feed production can lead to significant reductions in GHG emissions per kg meat or energy corrected dairy milk. They used a life cycle assessment to compare a scenario with an alternative feeding system that uses protein feedstuff grown in Sweden to a scenario where protein feed is imported from Brazil, both for a pig and a dairy cow production system. Emissions from feed production, manure management and enteric fermentation (determined by feed composition) were considered in the LCA. GHG emissions

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were reduced by 4.5% in the pig production system, and by 12% in the dairy cow system. Local feed production came at the cost of additional land occupation in Sweden, by 11 and 25% for pigs and dairy cows respectively. Local pig feed production improved the diversity of cereal-based crop rotations, leading to decreased use of mineral fertilizer and fossil fuels and higher grain yields. For local dairy cow feed production, the mineral fertilizer use was reduced by the use of legumes, and the digestibility of animal feed increased which in turn led to lower emissions from enteric fermentation. Mixed farming systems at regional level create an opportunity for more local protein feed production, and based on the results of this study it can be argued that this can lead to lower GHG emissions.

Regan et al. (2017) studied cooperating farm groups in different European countries, and compared them to non-cooperating farm groups, using indicators such as input autonomy, nutrient cycling and nutrient use efficiency. Cooperation between specialized farms were compared to non-cooperating baseline farms (specialized and mixed) in each case study area. In Spain, cooperation was built on the strategy of local exchange of straw and manure, it was shown that mixed dairy farms had a higher N use efficiency and a lower N surplus than non-cooperating and cooperating dairy farms. Cooperating arable farms had a higher N use efficiency than non-cooperating arable farms and mixed dairy farms, and a lower N surplus than mixed dairy farms. In the Netherlands, cooperation was built on the strategy of land renting between dairy and arable farms. Here it was shown that mixed dairy farms had a higher N use efficiency and lower N surplus than the non-cooperating dairy baseline and cooperating dairy farms. Cooperating arable farms had a higher N use efficiency and lower N surplus than non-cooperating arable, or mixed dairy farms. Farmers usually opted to use the local resources, made available via cooperation, to intensify and specialize as opposed to diversifying their operations. Therefore, some of the expected benefits of recoupling crop and livestock production via farm cooperation were not realized, such as lower external input use and improved N fertilizer autonomy. This study therefore shows that recoupling crop and livestock production via cooperation among specialized farms does not lead to many environmental benefits but instead helps specialized dairy and arable farmers to further intensify and specialize their farming systems through more intensive use of otherwise inaccessible or underutilized local resources. This type of intensification -based on optimized use of local resources such as feed, land and labour- can be considered more sustainable than intensification based on increased external inputs.

In a regional analysis of a French district, Nesme et al. (2015) estimated the effect of crop and livestock segregation on phosphorous resource use. This analysis shows that total P fertilizer use increased with the spatial segregation of crops and livestock, due to over-fertilization and highly positive soil nutrient budgets in areas with excess manure. The authors furthermore show that segregation acts as a driver of mineral fertilizer use, and that spatial segregation hampers the exchange of feed and manure amongst specialized farms. This leads to strong imbalances in nutrient management, i.e. both increased mineral fertilizer use in arable areas and local excess of manure supply to soils in livestock areas. This study provides the quantitative evidence that regional segregation of crop and livestock can be detrimental to nutrient cycling. The study makes a strong plea for mixing farming systems at an intermediate spatial scale (103-104 km^2), which could help to better close the local P cycle and to save mineral P resources. Central to this study is the scale of segregation, as the authors argue that

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segregation at a local scale (10-100 km^2) remains compatible with material exchanges and recycling of nutrients amongst neighbouring specialized farms.

Table 5.8 Overview of the consulted literature, their approach, scale, used indicators for environmental performance, and their main conclusions

Author	Approach, reference systems	Scale	Indicator	Conclusion
Ryschawy et al. (2012)	Comparison of the environmental performance of individual mixed crop-livestock farms vs. specialized farms from a set of 48 farms within the same region in France	Farm	N surplus; N in purchased inputs	N surplus in mixed farms was lower than in specialized dairy or beef farms, but higher than in specialized crop farms. The N in purchased inputs in the mixed farms were higher than in beef farms, but lower than in specialized crop and dairy farms.
Bos & van de Ven (1999)	Farm gate nutrient balance of mixing a specialized arable and dairy farm	Farm	N surplus; N Use Efficiency	No decrease in N surplus or increase in N Use Efficiency by mixing both specialized systems, although the N surplus per kg N in the outputs was slightly lower.
Bonaudo et al. (2014)	Comparison of two types of mixed crop-livestock farms. A 'conventional' mixed farm is compared to a 'sustainable' mixed farm where agroecological principles are applied	Farm	N load; Energy use per l milk; Feed import costs	The sustainable mixed farm (with applied agroecological principles) had a lower N load, a lower energy use per l milk and lower feed import costs compared to the conventional mixed farm.
Veysset et al. (2014)	Comparison of three groups of farms on their individual environmental performance: specialized beef farms with 100% grassland; specialized beef farms with both grassland and feed crops; and mixed beef farms with grassland, feed crops and arable crops	Farm	N surplus; GHG emissions per kg product or per ha; Non-renewable energy use	Mixed beef farms did not perform better on these indicators than specialized beef farms.
Marton et al. (2016)	A lifecycle assessment comparing the environmental impact of specialized or mixed dairy production system	Farm	Non-renewable energy use; GHG emissions; P and K use; N eutrophication	Lower energy use, lower P use, higher K use in mixed system, similar GHG emissions and N eutrophication.
Lemaire et al. (2015)	A literature review on grassland-cropping rotations	Farm/ Field	C sequestration; N leaching	Compared to only arable cropping, grassland-cropping rotations can increase C sequestration and reduce N leaching when managed properly.
Garnier et al. (2016)	Scenario analysis where livestock is reintroduced in a specialized cropping area	Regional	N surplus	The mixed system had a higher total N surplus, and a higher N surplus per kg N in the outputs then the specialized cropping system.
Sasu-Boakye et al. (2014)	Life cycle assessment to comparing scenarios with protein feedstuff grown in Sweden to a scenario where protein feed is imported	Regional	GHG emissions per kg meat or milk; Mineral fertilizer use	Reduced GHG emissions per kg meat or milk; reduced mineral fertilizer use in crop rotations.

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Author	Approach, reference systems	Scale	Indicator	Conclusion
Regan et al. (2017)	Case studies in different countries, comparing cooperating specialized farms with non-cooperating mixed and specialized farms	Regional	N Use Efficiency; Mineral fertilizer use; N surplus	Cooperation leads to intensification; mixed and cooperating farms do not necessarily score better on all indicators compared to non-cooperating specialized farms.
Nesme et al. (2015)	Assessment of the effect of regional segregation of crop- and livestock segregation on mineral P fertilizer use and P excretion in France	Regional	Mineral P use Total P application to soils	Segregation on an intermediate scale led to P overapplication in livestock regions, and increased mineral P fertilizer use in arable regions.

1.23 Discussion

The reviewed literature did overall not provide strong evidence that mixed systems on farm level provide strong benefits regarding environmental performance. The studies found on mixed farming on farm-scale do either find no improvement on the environmental indicators compared to specialized crop- or dairy farms, or do not have a suitable reference system for comparing mixed to non-mixed farming. Comparing mixed farming systems with specialized crop or dairy farms does not provide evidence that mixed farming systems intrinsically provides environmental benefits. Only if mixed farms would be compared to a similar system (area, animal numbers etc.) without any coupling of the crop- and livestock components it could be argued that mixed farms perform better than non-mixed farms. Many studies provide indicators on a hectare basis rather than on a product basis. Whereas this is useful for the evaluation of local environmental impacts of farming systems, it does not account for the externalized environmental impacts of food production outside the system. Based on the results of this literature review it can therefore not be concluded that mixed farms compared to specialized farms provide benefits for the use of primary resource P or fossil energy. Judging from the N surplus, in many cases the local environmental impact of mixed farms was not improved compared to specialized farms. Higher N surpluses on farm level usually originate from the livestock component in either specialized or mixed livestock systems. It will depend on the spatial allocation of the manure application whether there is a benefit in terms of water quality. Soil organic matter might be improved for specialized arable farms when grassland is included in the rotation. Vice versa, when arable crops are included in sod-based rotations the soil organic matter content will likely decrease.

Although it is difficult to provide fair quantitative evidence on farm-level, this does not directly imply that there can be no environmental benefits to mixed farming systems. On a regional level, segregation of arable and livestock farms can lead to inefficient use of nutrients such as P (Nesme et al., 2015). Having both arable and livestock farms within a region enables the exchange of nutrients in the form of feed or manure. In turn this could lead to more efficient nutrient use, and increased circularity on a regional level. Local protein feed production can furthermore result in significantly reduced overall GHG emissions, and a lower dependency on mineral fertilizers in the arable crop rotation (Sasu-Boakye et al., 2014). The integration of grassland in the crop rotation (which can be stimulated by mixed farming) can furthermore reduce N leaching and increase C sequestration

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compared to solely arable cropping rotations (Lemaire et al., 2015). Mixing on farm- or regional scale can lead to intensification without increasing external inputs, by using the available local resources more efficiently (Bos & Van De Ven, 1999; Regan et al., 2017). Bonaudo et al., (2014) furthermore illustrate that the type of management in mixed farming can have serious consequences for its performance on environmental sustainability. The authors showed that the application of certain agroecological principles can strongly reduce its dependency on external inputs, lower the N load and reduce overall energy consumption.

In a literature review, Garrett et al. (2017) analysed the current knowledge and remaining uncertainty of mixed crop livestock systems, regarding both social and environmental aspects. Based on the consulted literature, the authors conclude that mixed crop-livestock systems can reduce N and P loss in soils, and often increase yields per unit of N or P input. However, nutrient and crop performance outcomes are greatly dependent on co-management factors and the specific context. As to GHG emissions, mixed systems often have lower GHG emissions per unit of land compared to continuous cropping systems and lower GHG emissions per unit of food in comparison to continuous grazing or animal confinement systems. A lack of knowledge on the net GHG and nutrient emissions per unit of food produced is identified as a major knowledge gap in current literature. Although there is potential for GHG reductions by mixed crop-livestock systems, few life cycle data are available to evaluate this potential systematically across production systems. Other knowledge gaps are the potential of mixed crop-livestock systems to reduce nutrient leaching and emissions to the air compared to very high intensity livestock systems.

Looking at the results of the reviewed literature in Section 0, it appears that a main knowledge gap is indeed lack of quantitative evidence on the net GHG and nutrient emissions per unit of food produced. Many studies comparing mixed and specialized systems do so based on emissions, fertilizer- or energy use per ha, rather than per kg (N or P) in the outputs. We furthermore identify a lack of clear reference systems in the current scientific literature, which would allow for a fair comparison between mixed and specialized farms. Due to incomparable system boundaries, it can often not be concluded if differences in environmental indicators are the result of mixing itself, or to other differences in farm-management or land use.

1.24 Conclusions

It becomes clear from the reviewed literature that the environmental benefits on farm-level might be limited, but that mixing and cooperation at a regional scale can improve the efficient and circular use of resources. Coming back to the aim of this review, namely 'to provide evidence for the evaluation of four main indicators namely reduce primary resource P; reduce fossil energy; reduce emissions to air and water; reduce GHG emissions; increase soil organic matter', we conclude the following:

- Mixing of crop- and livestock farms on a regional level can favour the efficient use of manure and decrease the use of primary resource P. Segregation of arable and dairy farming does increase the use of primary resource P, since manure is often over-applied in regions with high

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livestock density, and not transported to arable regions. This leads to higher primary resource P in regions with a high degree of arable farms.

- Fossil energy use can be reduced if more feed is produced locally.
- No quantitative evidence was found that (nitrogen) emissions to the environment were reduced by mixed farming on farm- or regional level. Nitrogen emissions seem to be rather dependent on specific farm management and efficient use of resources on both farm- and regional level.
- The impact of mixed farming on GHG emissions was often not included in the studies. A specific impact on methane emissions is not expected, and based on the effect on the evidence for N emissions we do not expect an effect on N_2O emissions neither.
- No quantitative evidence was found that mixed farming on a farm- or regional level would overall increase soil organic matter, and this will likely depend strongly on farm management or the type of cooperation. In arable systems, soil organic matter would likely increase when grassland or other feed crops are included in a (widened) crop rotation. Vice versa, in grassland areas soil organic might decrease when grassland is rotated with arable crops.

All in all, some environmental benefits for mixed farming systems can be identified, especially on a regional level. Mixed farming is no silver bullet to solving environmental issues, but exchange of feed, straw and manure between highly specialized farms or regions may enhance nutrient use efficiencies and reduce losses. However, it is difficult to quantify these benefits and they often depend on specific farm management and the nature of cooperation within a region.

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Conclusions

This literature review provides a description on current techniques and systems that are being used to improve cycling of CNP flows within Europe and their effects on CNP flows. This review comprises both practices that are already widely applied, but also techniques that are only used at larger scale in a few countries, e.g. most of the manure processing techniques are mainly used in countries/regions with manure surpluses. Also techniques to reduce emission are mostly applied in countries with strict environmental legislations. In this section we provide a summary overview of the effects of these practices and techniques on CNP flows.

In Nutri2Cycle Deliverable 1.1 a list of indicators is proposed, that can be used for comparison and benchmarking the solutions and practices in the project. These indicators are grouped into four main dimensions; i) use of primary resources, ii) emissions to environment, iii) resilience to climate change and iv) productivity. As in this Deliverable 1.4 the main focus has been on the effect of the practices on CNP flows, we have made a selection of the main indicators relevant for recycling of nutrients and carbon. These i) to reduce the use of primary resources, i.e. rock phosphate and fossil energy (related to energy use and production of mineral N fertilizers), ii) reduce emissions to the environment, which refers mainly to nitrogen emissions to air and water, and iii) reduce GHG emissions and increase soil organic matter, which contributes to climate change mitigation and improves soil quality. Based on the literature review each of the current practices and techniques has been assessed in terms of positive effect (+), negative effect (-) or no effect (0), see Table 0.1.

The table shows that there is no practice/technique that scores positive on all five indicators. To reach optimal circularity of CNP a combination of practices and techniques will be required, which address the different components of the manure management chain (Hou et al., 2015), i.e. animal feeding, animal housing, manure storage and manure and fertilizer application. The table shows that most current practices/techniques have no or only limited effects on the reduction of the primary resource of rock phosphate. The main way to increase circularity of P is by returning lost P at the consumer part of the food chain, i.e. P in organic waste and sludge, back to agriculture as new fertilizer products. Within agriculture the main option to improve circularity is to match P supply with P crop demand. Here manure processing options such as mechanical separation and membrane filtration can help to produce manure products that better match the crop demand.

Manure processing is relevant for areas with manure surpluses, where processing can lead to increased nutrient use efficiency, where N and C can be used locally and P can be exported to regions that are low in P supply. However, not all of the manure processing techniques contribute to circularity, as nitrogen (and carbon) can be lost, such as incineration and nitrification-denitrification and other techniques might have higher emissions or high energy demand (Hou et al., 2017).

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Table 0.1. Summary table of effect of practices/techniques to improve CNP cycling on five main indicators

Practice/technique	Reduce primary resource P	Reduce fossil energy	Reduce N emissions to air and water	Reduce GHG emissions	Increase soil organic matter
Emission reduction in animal production					
Low N and P feeding strategies	0/+	0/+	+	0/+	0
Stable adaptations	0	0/+	+	0	0
Manure acidification	0	+	+	+	0
Manure application techniques	0	0/+	+	-	0
Manure processing					
Anaerobic digestion	0	+	+/-	+	0
Mechanical separation	0/+	0	0	0	0/+
Membrane filtration	0/+	-/+	0	0	0/+
Composting	-/0	-/0	-/0	0	+
Incineration	0	-/+	0/+	0	-
Nitrification – denitrification	0	-	-/+	0	0
Stripping/scrubbing	0	-/+	+	0	0
Precision fertilisation	0/+	+	+	+	0
Mixed farming	+	0	0/+	0	-/+

Most of the practices and techniques contribute to the reduction of emissions to the environment. Most techniques are aimed at reducing NH_3 emissions, but in some cases there are trade-offs to other emissions, e.g. N_2O emissions increase for manure injection and manure processing through nitrification-denitrification. Only few of the practices in the table contribute to increasing soil organic matter, however there are other practices that have not been discussed in the literature review that do contribute. The build-up of soil organic matter is mainly determined by the crop and land use choices, where grassland has the highest, cereals intermediate and root crops the lowest contribution to soil organic matter. But also management practices around cover crops, crop residue management and tillage practices affect the soil organic matter content. Not all these practices are addressed in Nutri2Cycle, but solutions should at least not have a negative effect on the input of organic matter to the soil.

Overall, we can conclude that already a wide range of techniques and practices to improve nutrient cycling are available and to different extent used in European farming. In regions with high livestock densities and manure surpluses the use of manure separation, where possible in combination with anaerobic digestion, can be useful to provide a better balance between demand and supply of nutrients, and reduce the volume of exported manure. Incineration and nitrification-denitrification of

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manure cannot be considered as techniques that fit in circular agriculture. Other regions that are more relying on inputs from mineral fertilizers, should try to increase the input of organic matter to the soils and make use of precision fertilization, which currently is mainly used for mineral fertilizer application. The environmental benefits of mixed farming systems are limited at farm level, but on regional level the cooperation between livestock and arable farmers can be a good alternative towards improved nutrient cycling, with a more local exchange of feed and manure. The solutions developed in Nutri2Cycle should enhance such a collaboration.

The survey on current practices showed that several practices are already common in most of the member states, but the survey also shows that other practices are hardly being applied. Although this was only a limited survey, it showed that there is potential in promoting the uptake of current practices. Increased uptake of these practices can contribute to improved CNP cycling and probably at lower cost compared to the new solutions that are currently being investigated in the Nutri2Cycle project. Two aspects that were not included in the literature review and survey on current practices are fertiliser management plans and soil analysis. These are not practices that directly affect CNP flows, but indirectly can be very important, as they provide insight in the current status of the soil quality and nutrient demand for the specific crops. Performing regular soil analyses and making specific fertilizer plans can therefore increase the nutrient use efficiency and prevent nutrient losses.

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Annex 1. Overview of current practices per main farming system

A.1 Introduction

The Nutri2Cycle project focuses on a selection of (integrated) technical and management solutions for farming systems aimed at closing nutrient loops. These solutions have been collected using a bottom-up approach, where Innovative solutions were provided by the Nutri2Cycle partners and stakeholders via Operational Groups and pioneering farmers & agri-businesses. For the potential application of these solutions it is relevant to know which practices and techniques are already implemented and how they could be combined with the current farm management practices.

Data on the application of agricultural management practices are not widely available, as these are not systematically collected in surveys such as the Farm System Survey of Eurostat or in international databases such as FAOSTAT. Some relevant information can be found in the one off Survey on Agricultural Production Methods (SAPM), which was part of the 2010 Farm System Survey. Information was collected on soil management, manure storage systems and manure application techniques. However, the usefulness of this data set is limited due to lack of good definitions and some flaws and inconsistences found in the database, which hamper its proper use (Hou, 2016).

The objective of this Annex is to provide an overview of the current application of management practices that improve CNP cycling in the main farming systems in the EU. Ideally a full farmers survey should be set-up in the EU member states, but such a survey is beyond the scope and possibilities of the Nutri2Cycle project. Instead a questionnaire was sent out to the Nutri2Cycle partners to obtain an expert opinion on the use of the agricultural management practices in each N2C country. The results of this survey can therefore only be used in a qualitatively manner and should not be used for any statistical analysis. The results provide an overview to what extent management practices are used in the main farming systems in Europe.

A.2 Approach questionnaire

Partners in the 12 countries of the Nutri2Cycle project were asked to fill in a questionnaire for the main farming systems in their countries, which were selected based on the information as shown in the maps presented above. The objective of these questionnaires is to establish a baseline of current practices that are commonly employed to reduce nutrient losses and close the agricultural C, N, and P cycles. The partners were asked to summarize the main farming systems relevant for their country and specify which nutrient and agronomic management practices are currently in use. Therefore, different questionnaires were sent out for arable, beef/dairy, pig, poultry, permanent cropping, and mixed farming systems.

The different questionnaires for the various farming systems are included in Annex 2. In short, the recipients were first asked to describe the farming systems briefly, in terms of size, surface area, animal numbers, production, and common crops. Secondly, there were several specified questions to describe regular farming practices. These related to management decision tools, availability of independent farm advisors, feed sources (for animal farming systems), nitrogen (N) and phosphorus

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(P) application and excretion rates, fertilisation timing, etc. The latter part of the questionnaire consisted of a table that featured several management practices to improve nutrient cycling. These practices were divided into three categories: field-related, animal-related, and manure-related measures. Recipients were asked to indicate whether each of the practices were used 'commonly', 'uncommonly', or 'not at all'. Additionally, there was an opportunity to add practices that were not listed. Finally, the experts were asked whether any of the previous practices were often used jointly and what specific practices they expected to be up-and-coming for the different farming systems.

Table A.1 Overview of the returned questionnaires per country/project partner per farming system. For the column Region: NW = northwest Europe, S = south/Mediterranean Europe, C = central Europe.

			Farming system					
Country	**Region**	**Partner**	**Arable**	**Beef/dairy**	**Mixed**	**Permanent**	**Pig**	**Poultry**
Belgium	NW	Inagro	X	X			X	
Denmark	NW	UCPH	X	X			X	
Germany	NW	Thünen	X	X			X	X
Ireland	NW	Teagasc		X				
Netherlands	NW	ZLTO	X	X			X	X
France	NW/S	CA						
Italy	S	UMIL	X			X	X	
Portugal	S	ISA		X			X	
Spain	S	IRTA	X			X	X	X
Croatia	C	IPS	X		X	X		
Hungary	C	Soltub	X		X			
Poland	C	PCz	X		X		X	X

Most experts responded timely and provided an overview of the farming systems. This led to a total of 33 completed questionnaires, divided over the six farming systems. Table A.1 gives an overview of the different partners that responded and which questionnaires they sent back.

To ease the interpretation of the questionnaire results, the countries were separated into three different regions: Northwest Europe (Belgium, Denmark, Germany, Ireland, and the Netherlands), South/Mediterranean Europe (Italy, Portugal, and Spain), and Central Europe (Croatia, Hungary, and Poland). This was done because it can be expected that farming practices of the same farming type (e.g., beef/dairy) differ substantially across Europe.

A.3 Results questionnaire

A.3.1 Description of the typical farming systems

Arable farms

General characteristics of arable farms differed substantially per country. According to the questionnaire respondents, the typical size of European arable farms differed from less than 10 ha, to

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hundreds of hectares (Table A.2). These numbers should be seen as an indication of an example farm, as naturally there can be a wide variety of farm sizes within one country. For example, in Germany, the average farm size is larger in the East, than in the West. Moreover, particularly in Hungary, a large number of farms exists with but a few hectares of land, but most of the arable surface area is owned or rented by large farming companies. Cereals and maize are the arable crops that were mentioned most often and are grown throughout the entire continent. There are several other crops that seem more country- or region-specific. In countries in Northwest Europe, potatoes are commonly used as well, as is sugar beet. In Denmark, a significant part of the agricultural land is used for seed production, whereas in Italy, arable farms are used to grow silage maize and rice as well.

In all countries that responded, some sort of advisory service is available to arable farmers. This varies from large scale government-regulated advice to farm management, soil testing, or fertiliser companies. There is often a choice between independent advice (from governmental sources, universities, or institutes) and industry sources (from software, commercial houses, or fertiliser companies). Farms in most countries use soil testing (and associated fertilisation plans, which may be mandatory by law) to help with making on-farm management decisions. In some countries, such as Denmark, Spain, and Hungary, computerized field-planning tools are used to predict the crop nutrient needs or digital soil mapping tools can be applied for precision fertilisation purposes. Sometimes tools like these, due to the costs, can only be utilized by the larger farms, and at other places (Croatia) they are still being established.

Table A.2 Questionnaire responses on typical or average arable farm size, commonly used crops, and an example crop rotation per country.

Country	Region	Typical or average farm size	Commonly used crops	Example crop rotation
Belgium	NW	14 ha	potato; cereals; maize; pasture; sugar beet	1. potato 2. wheat 3. green cover 4. maize/sugar beet
Denmark	NW	72 ha	cereals; seed crops; potato; sugar beet	1. spring barley 2. winter rapeseed 3. winter wheat + cover crop 4. spring barley 5. winter rye
Germany	NW	100 ha (West); 350 ha (East)	rapeseed; cereals; sugar beet	1. rapeseed 2. winter wheat 3. winter wheat/winter barley
Netherlands	NW	60-100 ha	potato; cereals; sugar beet; onion	
Italy	S		cereals; maize (silage); rice; soybean; sunflower	maize (silage) and grass

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Country	Region	Typical or average farm size	Commonly used crops	Example crop rotation
Spain	S	24 ha	cereals	1. fallow 2. wheat/barley 3. pea/vetch/sunflower
Croatia	C	6 ha	maize; cereals; oil seed crops; forage crops; potato; tobacco; vegetables	1. wheat 2. sugar beet 3. maize 4. soybean
Hungary	C	800-1200 ha	maize; cereals; rapeseed	1. wheat 2. autumn barley 3. corn 4. rapeseed/sunflower
Poland	C	10 ha	cereals; maize; rapeseed; lupine; sunflower	1. winter rapeseed 2. wheat/barley/maize 3. wheat/barley/maize 4. wheat/barley/maize

Nutrient application often occurs as a combination of manure/slurry (or other organic products) and mineral fertiliser. The share of manure/organic fertiliser depends on the proximity of animal farms as potential organic fertiliser sources. Several respondents (e.g. the Netherlands and Spain) indicated that arable farms in areas with high livestock densities use a significant amount of manure. Due to the EU nitrate directive, no more than 170 kg N/ha is applied as manure annually in nitrate vulnerable zones, which cover a large part of the countries in this project. The total rates at which N and P are applied often depend on wat is legally allowed, and they commonly vary per crop and soil type. For N, typical application rates vary between 100 and 200 kg N/ha/y, although the Italian partner indicated that for silage maize application rates of 300-350 kg N/ha are not uncommon either. In Spain, there is a division between humid and arid areas, where arid areas receive considerably less. For P, annual application rates vary between 15 and 50-60 kg P/ha. Countries with high livestock density and many P-rich soils, such as the Netherlands and Belgium, often apply all P in the form of organic fertilisers. Fertilisation occurs mostly during the growing season. Application bans in winter are common, although the exact duration of the period in which spreading is allowed varies per country. There are also occasions were P fertilisers and N fertilisers are applied at different times of the year (Hungary).

Beef/dairy farms

Most responses to the beef/dairy questionnaire came from partner countries in Northwest Europe and practices on dairy farms in these countries were largely comparable. Additionally, there was a response from Portugal, describing a type of dairy farm with a slightly lower efficiency and output. Overall, typical dairy farm sizes varied from around 50 to 80 ha, with exceptionally large farming systems in East Germany (Table A.3). For beef operations, the common size was a bit smaller than for

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dairies. In terms of animals, sizes also vary between and within countries, but typical animal numbers from 40 to close to 200 mature cows were provided by the respondents.

In most countries, grassland (sometimes with legumes such as clover included) is a major part of the land use on beef and dairy farms. In some cases, grassland can amount up to 75% (Netherlands) or even 90% (Ireland) of the cropping areas. This can either be pasture used for grazing, or (non-)permanent production grassland for forage production. In Denmark, pastures are usually located on marginal lands. Next to grassland, the most common crop grown is silage maize, but cereals such as wheat and barley can occur as well. Other crops include sugar beet and potato (for which farm fields are rented to arable farmers). The grass and silage maize grown on farm is used as feed for the cows and often accounts for most of the forage in the diet of the animals. In many cases, farmers can grow all the forage they need on-farm, and they will import the grains, concentrates, and minerals to supplement the diet. Farms with a high livestock density, however, may have to import part of the forage (such as silage maize) as well. There are some ration differences between countries, but generally speaking about 70% of the diet consists of forage and the remaining 30% is grain, concentrates, and minerals. In Denmark, there is an overall slightly higher share of grain (60% forage, 40% grain and concentrates), whereas in Ireland cows are mostly grass fed (at least 80% forage). Next to grass and maize, other examples of feed products are beet press pulp, brewer's grain, soybean, rapeseed, or oilseed cake. Diets on organic farms in Denmark generally have more grass, less maize and more grains instead of concentrates than their conventional counterparts. Grazing is very common in Ireland and the Azores, to a lesser extent in the Netherlands, but less common on conventional farms in Denmark, Germany, and the mainland of Portugal. The grazing period mainly covers the growing season. Food companies, such as dairy companies and supermarkets may stimulate grazing by paying more for milk from grazing cows.

Table A.3 Questionnaire responses on typical or average size and animal numbers of beef/dairy farms and the typical N and P excretion per (mature) animal.

Country	Region	Typical/average farm size		Typical/average excretion	
		Area	Animals	N	P
Belgium	NW	49 ha (dairy); 35 ha (beef)	130 cows/farm	81-131 kg/cow	11-19 kg/cow
Denmark	NW	72 ha	172 cows/farm	159 kg/cow	23 kg/cow
Germany	NW	80 ha (West); up to 1000 ha (East)	50 cows/farm (west); 194 cows/farm (east)	115 kg/cow	12 kg/cow
Ireland	NW	60 ha (dairy); 27 ha (beef)	80 cows/farm (dairy); < 20 cows/farm (beef)	85 kg/cow (dairy); 65 kg/cow (beef)	13 kg/cow (dairy); 10 kg/cow (beef)
Netherlands	NW	50 ha	100 cows/farm	130 kg/cow	18 kg/cow
Portugal	S	?	40 cows/farm	82 kg/cow	15 kg/cow

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As in arable farming systems, beef and dairy farms commonly use soil testing to determine the nutrient status of their soil, as well as corresponding fertilisation rates. In most countries, additional tools are available (and sometimes even mandatory) to monitor and finetune nutrient cycling on the farm. In Belgium and the Netherlands, nutrient imports and exports (nutrient balances) are required to be recorded. Denmark has a mandatory programme for fertilisation planning and a software tool that determines the crop's nutrient requirement, as well as the optimum timing, distribution, and method of fertilisation. The questionnaire response from Portugal indicated that these nutrient management tools are relatively uncommon. In addition to soil testing and nutrient balance tools, farmers have regular feed analyses to test for nutritional value and digestibility. These data are sometimes used to identify soil nutritional problems as well. Advisory services to help with nutrient/feed/fertiliser planning are often available to farmers. Like for arable farms these services can independent from industry, but many feed and fertiliser companies also offer advices. The latter is more common in countries like the Netherlands and Portugal, whereas farmers in Denmark, Germany, and Ireland make more use of independent consults through research institutes, agricultural associations, or governmental organizations.

The excretion N and P per cow depends strongly on productivity (milk production, for dairy farms) and diet. Table 3 shows a range of N and P excretion rates for the different respondents. Typical or average numbers for N excretion ranged from 80 to 160 kg N/cow/y and for P this was 11-23 kg P/cow/y. Beef cows in Ireland generally have a lower excretion than dairy cows. The manure produced is often stored as liquid manure on farm, in most cases in a manure pit that is connected to the housing area by a slatted floor. Farms with pack- or farmyard manure systems are still in use (especially on the Azores, Portugal), but in Denmark this number is decreasing as the increase of herd sizes make it more difficult to maintain this system.

The liquid manure is often applied in spring and manure/fertiliser applications are mostly prohibited during the winter months. On grasslands, applications continue throughout the growing season. Rates usually depend on the national guidelines for crops and soil types. The EU Nitrates Directive caps the amount of N applied as manure at 170 kg/ha. Many of the countries have derogation however, which increases the allowed application rate. Common rates vary from 80-100 kg N/ha for grass on the Azores, to 230-250 kg/ha for farms with derogation in the Netherlands, Belgium or Denmark. In Ireland, manure application rates on beef farms are often lower than on dairies. In general, manure N applications can be supplemented with N from mineral fertiliser to further increase yields. For P, this is generally not done or even allowed, as the P in manure is sufficient for crop needs, and many of the areas with high livestock densities suffer from a manure (and phosphorus) surplus. If a farm produces more manure than it can allocate on its land-base, farmers may opt to treat or export manure. This can become very costly, however, if there are no nearby farms willing and able to accept the manure.

Pig farms

The eight completed questionnaires on pig farming revealed a large variation of pig farm characteristics and systems throughout Europe, and often within countries as well. The Belgian

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respondent indicated that it was difficult to describe a 'typical' pig farm, as the operations had various management systems that differed in the frequency of its operations. In Spain, many pig farmers do not own the animals themselves, but get paid to house and feed them for larger companies that supply the pigs, along with feed and medical care. In Portugal, there is a clear distinction between intensive pig farms around Lisbon, which have no land to grow crops, and more extensive farms in the south of the country, where pig farming is combined with growing oak trees for cork production.

Animal numbers varied from an average of 47 animals per farm in Portugal to large intensive operations in Northwest Europe that house thousands of animals simultaneously. Not all of these farms have cropping fields, but in the Netherlands and Belgium a 15-20 ha land base is common for pig farms. In Denmark, a land base is even required for all pig operations, so that a part of the animal's diet might be grown on-farm. The share of homegrown feed ranges from zero or hardly any in Mediterranean countries like Spain and Portugal to over 70% in Denmark. Maize and cereals are often grown as pig feed, and this is supplemented with imported feed, like concentrates or sometimes waste products of the food industry. Alternatively to growing crops to feed the pigs, farms (for instance in Belgium and Denmark) may sell the grown crops to a feed company and buy back a prepared feed mix against a discount. Management tools are more common in Northwest Europe, than in Mediterranean countries, where they are mostly used by the intensive/modern farms. Advisory services for feed rations are generally available everywhere, but may not always be independent.

In intensive systems, pigs are often kept indoors and (liquid) manure is stored in a pit under a slatted floor. In some countries, like Poland or Spain, manure is sometimes stored outside, on fields or in lagoons, but only for a limited amount of time. In areas with intensive pig farming, manure may (have to) be exported to other farmers, or to manure processing plants. This is particularly common in the Netherlands, Denmark, and Belgium. For manure spreading, if applicable, the same patterns are apparent for pig farms as for dairy farms. Nutrients are supplied with manure as much as possible and up to the legal application limits. Mineral fertiliser is then added to supplement this, mostly for N. Manure is applied in spring or throughout the growing season, depending on the crop. Solid farmyard manure may be applied slightly closer to winter.

Poultry farms

For poultry farming, four partners returned a questionnaire. A distinction between laying hens and broiler farms can be made, where the animal density in broiler farms is usually higher. Several of the respondents indicated that the number of poultry farms has declined over the year and that the existing farms have become a lot larger. Typical animal numbers for farms in the Netherlands and Germany are around 40,000-70,000 chickens per farm, with a lower number on free-range farms. In Germany, farms in the East are usually larger than those in the West. In Spain, the poultry industry is set up similar to the pig farms, where farmers host and feed the chickens without owning them. Around 80% of the Spanish poultry industry is owned by the 10 largest companies. Most poultry farms have no or a very small land base, which means that they do not grow their own feed crops. Instead, the entire ration is bought from factories. Smaller farms with a land base are able to grow their own

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crops and include them in the diet. In Poland, some extensive farms grow 80% of the feed themselves and import the other 20% from factories. Consultation services focus mostly on feed management, but sometimes advice on biosecurity is also provided.

Typical excretion rates for chickens are around 0.03 kg N/kg and 0.01 kg P/kg. The poultry manure (often solid) is usually collected from the stable after the chickens have left the farm (in the case of broiler chickens) or a few times per week (for laying hens) and subsequently stored in a barn, but in some cases also on land outside (in Spain and Poland). As poultry farms usually do not have arable fields, the manure has to be exported to other farms or to manure treatment plants. In Poland, an alternative use for the manure is as a substrate for mushroom farming. When poultry manure is applied to arable fields, the rates are usually well below 170 kg N/ha, and substitution with other sources is recommended to prevent large changes in soil pH.

Permanent crops farms

Permanent crops are crops that grow over multiple years, such as orchards, vineyards and tree nurseries. Spain, Italy, and Croatia submitted a questionnaire on permanent cropping systems. The most common crops were apple orchards, vineyards, and olive groves, but the type of crops varied among and within countries. In Spain, for example, citrus trees and avocados are grown mostly in the south, whereas vineyards, apple orchards, and stone fruit are more common in the north of the country. For field-based management tools, soil testing is often used, but other tools are not very common. In Spain, field mapping and leaf nutrient testing is done to support variable fertilisation and increase nutrient use efficiency. Application rates of manure and mineral fertilisers are relatively low compared to arable and beef/dairy systems, often in the range of 30-50 kg N/ha and 10-15 kg P/ha, although higher N rates for olive orchards were also suggested. The precise rates are largely dependent on crop type and region. Although the use of manure or organic fertilisers is not common everywhere, it might be used to increase the soil organic matter content in permanent cropping systems.

Mixed farms

Mixed farming systems are farms where crops and animals are grown at the same time. They are a combination of the farming types explained above. For instance, in Poland a combination of pig and arable (cereal) farming is most common, but dairy and arable farming is combined as well. Basically, all animal farms with enough land-base to grow arable crops to produce their own feed can be considered mixed farming system.

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A.3.2 Summary of current practices

The second part of each of the questionnaires contained a table with several listed measures/practices and respondents were asked to indicate whether these were applied 'commonly', 'uncommonly', or not at all. Questionnaires for all the different farming types contained field-based practices, although for farms without land base, these were usually not applicable. The results for field-based practices are summarized in Figure A.1. Taken over all farming systems, practices like incorporation of manure or fertiliser, liming, and vegetative buffer strips are used frequently. For manure incorporation (marked as 'common' in 76% of the returned questionnaires), many respondents indicated that this (or sometimes manure injection) was required by law. Manure or fertiliser injection was still relatively common (42% common; 36% uncommon), but seems not to occur as frequently as incorporation.

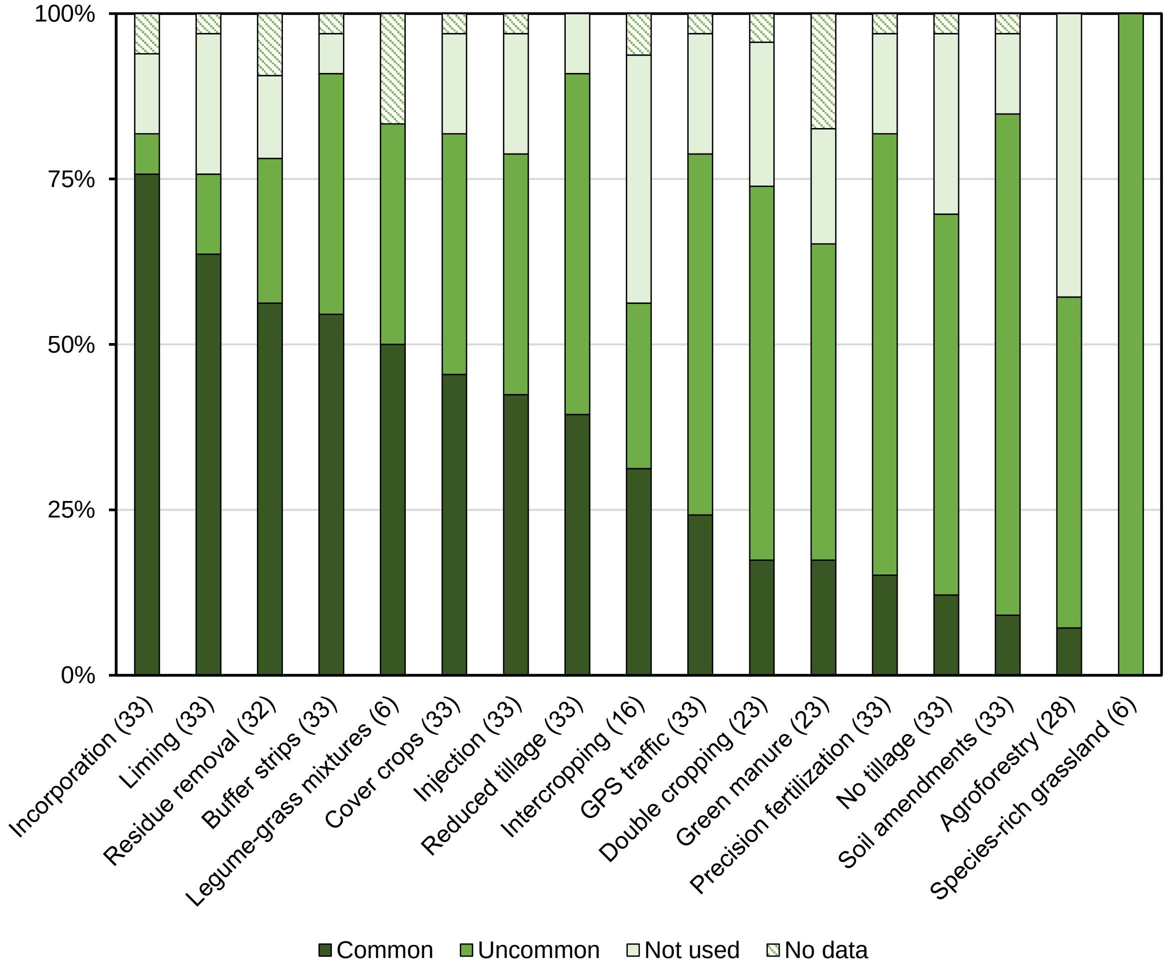

Figure A.1 Overview of field-based measures/practices used in the various farming systems and the frequency of occurrence, according to the questionnaire recipients. Numbers between brackets indicate the number of questionnaires that returned information on the measure/practice.

Liming ('common' in 64% of the cases) is a well-established practice to improve soil fertility, but the applicability strongly depends on region and corresponding soil types and agricultural practices. The

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removal of plant residues (mostly for cereals/grain crops) is often done in animal farming systems where the straw can be used as bedding for animals. Nevertheless, in some countries (Poland for example), the straw is left on the field. Vegetative buffer strips are enforced in several cases, but the details, such as the width of the buffer differ per country. Catch crops or cover crops too are mandatory in some cases (Denmark, Netherlands, Belgium) to prevent nutrients from leaving the field. In Spain, they are only used in combination with no-tillage systems.

For reduced tillage practices, controlled traffic with GPS, and precision fertilisation techniques, several respondents indicated that the practices were gaining in interest and adoption. Practices like soil amendments (other than manure applications) and agroforestry were hardly used at all, according to the questionnaires. As for double cropping, the potential for agroforestry strongly depends on the location, climate, and environmental conditions. The practice of including species-rich grasslands was only included for beef and dairy systems. Although this does occur, it is not common and mostly used in organic farming systems.

Animal- and manure-related practices were only included in the questionnaires on animal-based farming systems (so not in arable and permanent cropping systems). Overall, feed additives seemed the most common practice (Figure A.2). This was mainly true for pig and poultry systems, and less so for beef/dairy farming. However, from the questionnaire it was not always clear what kind of feed additives are used. Feed additives comprise a range of potential nutrients or medicine, including vitamins, amino acids, fatty acids, minerals, pharmaceutical, fungal products and steroidal compounds. The additives might impact feed presentation, hygiene, digestibility, or effect on intestinal health. Some respondents commented that feed additives usually comprehend amino acids and minerals, but additives to reduce greenhouse gas emissions are rarely used. Beef and dairy farming systems relied mainly on precision feeding techniques. For beef/dairy, feed additives and manure processing/digestion were labelled as 'common' by one respondent and emission-reducing housing facilities, though more common in pig and poultry farms, was uncommon or not used at all.

In addition to the pre-defined practices, respondents were given the opportunity to mention other practices that were not on the list. Slurry acidification was suggested in responses from Denmark, where it is permitted as an alternative to manure injection. Export of poultry manure, cultivation of grassland, or reduction of young animals (calves, heifers) on farm were other practices that were provided. The Polish experts provided a comprehensive list with practices, ranging from manure storage on an impermeable surface to the use of nitrification inhibitors, anti-erosion treatments, or optimizing fertilisation timings. These are all practices that can reduce N and P (and C) losses from agricultural cycles and that are probably used in other countries, regions as well. Nevertheless, as these measures were not commonly reported in the questionnaire, they were not included in the figures presented above.

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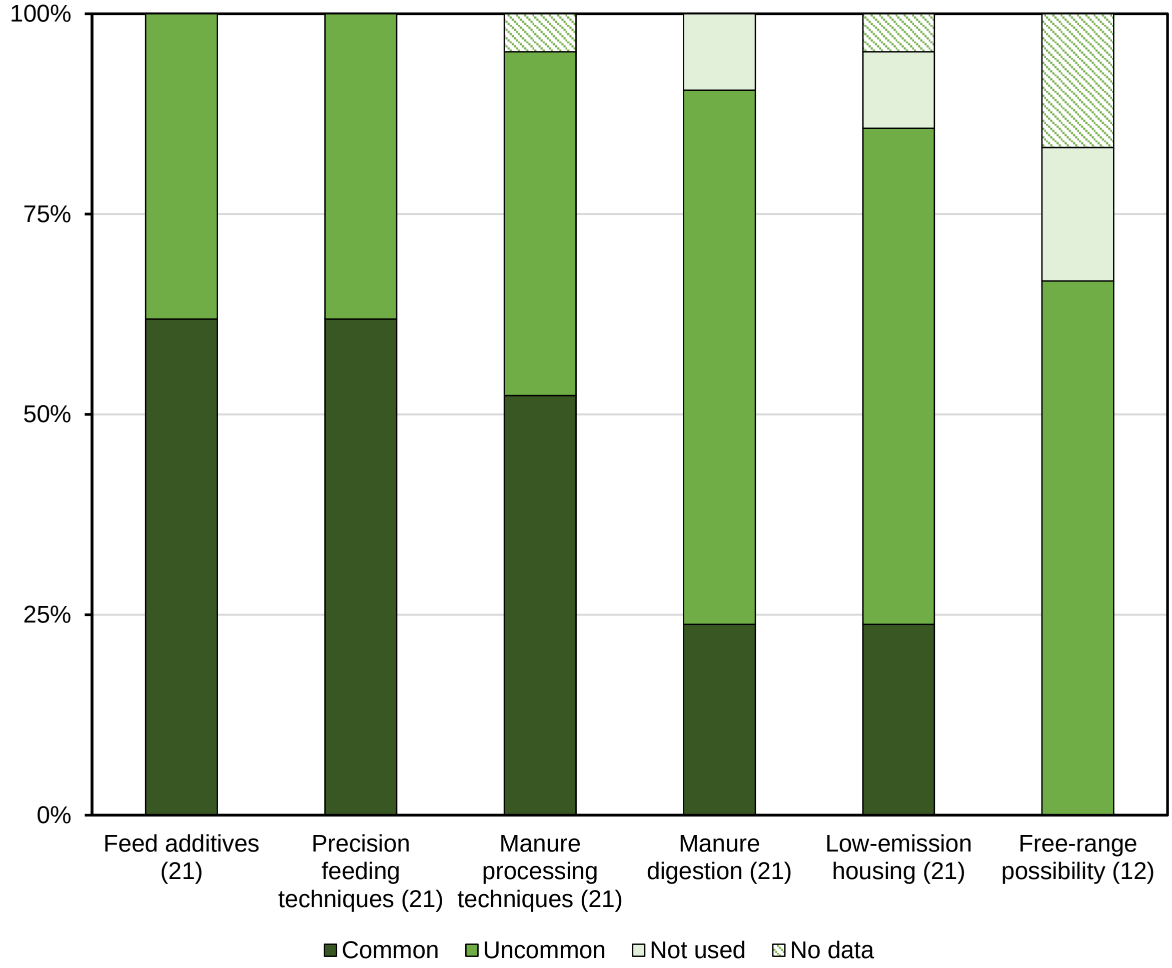

Figure A.2 Overview of animal- and manure-based measures/practices used in the various (animal) farming systems and the frequency of occurrence, according to the questionnaire recipients. Numbers between brackets indicate the number of questionnaires that returned information on the measure/practice.

When asked about nutrient management practices that are up-and coming or likely to become important in the near future, many respondents referred to further development of manure digestion or other processing techniques. Increasing the value and usability of manure will be key to closing nutrient cycles. The further implementation of good practices, such as nutrient balances, fertilisation plans, crop rotations, and soil/plant testing programmes was also a frequently mentioned issue. Additionally, measures to reduce NH_3 and N_2O losses (acidification of slurry, use of nitrification inhibitors), especially from animal farming systems and measures that increase biodiversity and long-term sustainability were mentioned by several partners.

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A.4 Concluding remarks

Through filling in and returning the questionnaires, several partners in Nutri2Cycle helped identify common and practices in several important agricultural systems in Europe, as well as differences between systems and countries. The most important conclusions are:

- Farming systems and their practices differ vastly among and within countries, and these differences depend on location, climate, soil types, historical legacy, laws and regulations, and other factors.
- Within and across the various countries and farming systems, there are many common practices or measures used to reduce N, P, and C losses and close the nutrient cycles.
- Incorporation of manure or fertiliser, soil liming, removal of plant residue, and implementation of vegetative buffers are examples of field-related practices that are currently used to reduce nutrient losses. For animal- and manure-related practices, the use of feed additives and precision feeding techniques were most common.
- Respondents indicated that practices or measures concerning good agricultural practices will be increasingly important over the next years, and that further advances on manure valorisation and processing are key to closing the nutrient cycles.

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Annex 2 – Questionnaire forms

Nutri2Cycle Questionnaire - Arable farms

This questionnaire is sent out with the purpose to identify which management practices are commonly used in Europe to improve agricultural C, N, and P cycling. With the information we can determine the baseline to which the rest of the project can be related. Please fill out the questions from the viewpoint of a the typical farming scenario in your country.

1. Please give a brief description of a typical Arable farm in your country:

2. Some specific questions:

a. *Do farms use farm- or field-based nutrient tools to make management decisions?*

b. *Do farms use management advisor(s)? (For which areas? Are advisors independent from fertiliser companies? How often are farm practices evaluated?)*

c. *What does an average crop rotation look like? How many years, which crops?*

d. *What are typical annual application rates for manure (organic fertiliser), N, and P?*

e. *How much is applied as manure (or other organic sources) and how much as mineral fertiliser?*

f. *When are nutrients (fertiliser/manure) usually applied?*

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3. Indicate (with an X) if the following techniques affecting C, N, and P cycles are used commonly, uncommonly, or not at all on Arable farms in your area. Please add any techniques / management that are in use, but not mentioned below.

	Use frequency			
Management technique	**Common**	**Uncommon**	**Not used**	**Comments?**
FIELD RELATED				
Catch / cover crops				
Green manure				
Double cropping				
Intercropping				
Removal of plant residue after harvest				
Vegetative buffer strips or no-application zones (near water bodies or field edges)				
Manure/fertiliser incorporation				
Manure/fertiliser injection				
Precision fertilisation				
Soil amendments (compost, biochar, etc.)				
Controlled traffic (GPS)				
Reduced tillage				
No tillage				
Liming				
Agroforestry				
OTHER				

4. Are any of the techniques / management practices mentioned above used in combination?

5. What important measures to improve C, N, and P cycling are up-and-coming for Arable farms in your area?

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Nutri2Cycle Questionnaire - Dairy/Beef farms

This questionnaire is sent out with the purpose to identify which management practices are commonly used in Europe to improve agricultural C, N, and P cycling. With the information we can determine the baseline to which the rest of the project can be related. Please fill out the questions from the viewpoint of a the typical farming scenario in your country.

1. Please give a brief description of a typical Dairy/Beef farm in your country:

2. Some specific questions:

a. *Do farms use farm- or field-based nutrient tools to make management decisions?*

b. *Do farms use management advisor(s)? (For which areas? Are advisors independent from feed and fertiliser companies? How often are farm practices evaluated?)*

c. *What is a typical ratio between forage and grain in animal feed?*

d. *What is a typical ratio between imported and home-grown feed?*

e. *What type manure of manure (solid/liquid) and manure storage systems is used?*

f. *What is the average excretion rate of N and P per animal?*

g. *Are other crops produced besides grass? What does an average crop rotation look like? How many years, which crops?*

h. *What are typical annual application rates for manure (organic fertiliser), N, and P?*

i. *How much is applied as manure (or other organic sources) and how much as mineral fertiliser?*

j. *When are nutrients (fertiliser/manure) usually applied?*

k. *Is there intensive/extensive grazing on the farm? How long is the grazing period?*

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3. Indicate (with an X) if the following techniques affecting C, N, and P cycles are used commonly, uncommonly, or not at all on Dairy/Beef farms in your area. Please add any techniques / management practices that are in use, but not mentioned below.

	Use frequency			
Management technique	**Common**	**Uncommon**	**Not used**	**Comments?**
FIELD RELATED				
Catch / cover crops				
Removal of plant residues after harvest				
Vegetative buffer strips or no-application zones (near water bodies or field edges)				
Species-rich grassland				
Legume-grass mixtures				
Manure/fertiliser incorporation				
Manure injection				
Precision fertilisation				
Soil amendments (compost, biochar, etc.)				
Controlled traffic (GPS)				
Reduced tillage				
No tillage				
Liming				
Agroforestry				
ANIMAL RELATED				
Feed additives/amendments				
Precision feeding techniques				
MANURE RELATED				
Manure digestion				
Other manure processing techniques				
Emission-reducing housing facilities				
OTHER				

4. Are any of the techniques / management practices mentioned above used in combination?

5. What important measures to improve C, N, and P cycling are up-and-coming for Dairy/Beef farms in your area?

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Nutri2Cycle Questionnaire - Mixed farming systems

This questionnaire is sent out with the purpose to identify which management practices are commonly used in Europe to improve agricultural C, N, and P cycling. With the information we can determine a base-line scenario to which the rest of the project can be related. Please fill out the questions from the viewpoint of a the typical farming scenario in your country.

1. Please give a brief description of typical Mixed farms in your country (What are the typical combinations of animals and crops?):

2. Some specific questions (please answer if applicable):

a. *Do farms use farm- or field-based nutrient tools to make management decisions?*

b. *Do farms use management advisor(s)? (For which areas? Are advisors independent from fertiliser companies? How often are farm practices evaluated?)*

c. *What is a typical ratio between forage and grain in animal feed?*

d. *What type manure of manure (solid/liquid) and manure storage systems is used?*

e. *What is the average excretion rate of N and P per animal?*

f. *What is a typical ratio between imported and home-grown feed?*

g. *What does an average crop rotation look like? How many years, which crops?*

h. *What are typical annual application rates for manure (organic fertiliser), N, and P?*

i. *How much is applied as manure (or other organic sources) and how much as mineral fertiliser?*

j. *When are nutrients (fertiliser/manure) usually applied?*

k. *Is there intensive/extensive grazing on the farm? How much control is there over the diet?*

3. Indicate (with an X) if the following techniques affecting C, N, and P cycles are used commonly, uncommonly, or not at all on Mixed farms in your area. Please add any techniques / management that are in use, but not mentioned below.

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	Use frequency			
Management technique	**Common**	**Uncommon**	**Not used**	**Comments?**
FIELD RELATED (if applicable)				
Cover crops				
Green manure				
Double cropping				
Intercropping				
Removal of plant residue after harvest				
Vegetative buffer strips or no-application zones (near water bodies or field edges)				
Manure/fertiliser incorporation				
Manure injection				
Precision fertilisation				
Soil amendments (compost, biochar, etc.)				
Controlled traffic (GPS)				
Reduced tillage				
No tillage				
Liming				
Agroforestry				
ANIMAL RELATED				
Feed additives/amendments				
Precision feeding techniques				
MANURE RELATED				
Manure digestion				
Other manure processing techniques				
Emission-reducing housing facilities				
OTHER				

4. Are any of the techniques / management practices mentioned above used in combination?

5. What important measures to improve C, N, and P cycling are up-and-coming for Mixed farms in your area?

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Nutri2Cycle Questionnaire - Permanent crop farms

This questionnaire is sent out with the purpose to identify which management practices are commonly used in Europe to improve agricultural C, N, and P cycling. With the information we can determine a base-line scenario to which the rest of the project can be related. Please fill out the questions from the viewpoint of a the typical farming scenario in your country.

1. Please give a brief description of a typical Permanent crop farm in your country:

2. Some specific questions:

a. *Do farms use farm- or field-based nutrient tools to make management decisions?*

b. *Do farms use management advisor(s)? (For which areas? Are advisors independent from fertiliser companies? How often are farm practices evaluated?)*

c. *What are typical annual application rates for manure (organic fertiliser), N, and P?*

d. *How much is applied as manure (or other organic sources) and how much as mineral fertiliser?*

e. *When are nutrients (fertiliser/manure) usually applied?*

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3. Indicate (with an X) if the following techniques affecting C, N, and P cycles are used commonly, uncommonly, or not at all on Permanent crop farms in your area. Please add any techniques / management that are in use, but not mentioned below.

	Use frequency			
Management technique	**Common**	**Uncommon**	**Not used**	**Comments?**
FIELD RELATED				
Cover crops				
Intercropping				
Removal of plant residue				
Vegetative buffer strips or no-application zones (near water bodies or field edges)				
Manure/fertiliser incorporation				
Manure injection				
Precision fertilisation				
Soil amendments (compost, biochar, etc.)				
Controlled traffic (GPS)				
Reduced tillage				
No tillage				
Liming				
OTHER				

4. Are any of the techniques / management practices mentioned above used in combination?

5. What important measures to improve C, N, and P cycling are up-and-coming for Permanent crop farms in your area?

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Nutri2Cycle Questionnaire - Pig farms

This questionnaire is sent out with the purpose to identify which management practices are commonly used in Europe to improve agricultural C, N, and P cycling. With the information we can determine the baseline to which the rest of the project can be related. Please fill out the questions from the viewpoint of a the typical farming scenario in your country.

1. Please give a brief description of a typical Pig farm in your country:

2. Some specific questions:

a. *Do farms use nutrient tools to make management decisions?*

b. *Do farms use management advisor(s)? (For which areas? Are advisors independent from feed and fertiliser companies? How often are farm practices evaluated?)*

c. *What type manure of manure (solid/liquid) and manure storage systems is used?*

d. *What is the average excretion rate of N and P per animal?*

Does the typical Pig farm have a land-base? If so, please address the following questions:

e. *What is a typical ratio between purchased and home-grown feed?*

f. *What does an average crop rotation look like? How many years, which crops?*

g. *What are typical annual application rates for manure (organic fertiliser), N, and P?*

h. *How much is applied as manure (or other organic sources) and how much as mineral fertiliser?*

i. *When are nutrients (fertiliser/manure) usually applied?*

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3. Indicate (with an X) if the following techniques affecting C, N, and P cycles are used commonly, uncommonly, or not at all on Pig farms in your area. Please add any techniques / management that are in use, but not mentioned below.

	Use frequency			
Management technique	**Common**	**Uncommon**	**Not used**	**Comments?**
FIELD RELATED (if applicable)				
Catch / Cover crops				
Green manure				
Double cropping				
Removal of plant residue after harvest				
Vegetative buffer strips or no-application zones (near water bodies or field edges)				
Manure/fertiliser incorporation				
Manure injection				
Precision fertilisation				
Soil amendments (compost, biochar, etc.)				
Controlled traffic (GPS)				
Reduced tillage				
No tillage				
Liming				
Agroforestry				
ANIMAL RELATED				
Feed additives/amendments				
Precision feeding techniques				
Free range possibility				
MANURE RELATED				
Manure digestion				
Other manure processing techniques				
Emission-reducing housing facilities				
OTHER				

4. Are any of the techniques / management practices mentioned above used in combination?

5. What important measures to improve C, N, and P cycling are up-and-coming for Pig farms in your area?

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Nutri2Cycle Questionnaire - Poultry farms

This questionnaire is sent out with the purpose to identify which management practices are commonly used in Europe to improve agricultural C, N, and P cycling. With the information we can determine the baseline to which the rest of the project can be related. Please fill out the questions from the viewpoint of a the typical farming scenario in your country.

1. Please give a brief description of a typical Poultry farm in your country:

2. Some specific questions:

a. *Do farms use nutrient tools to make management decisions?*

b. *Do farms use management advisor(s)? (For which areas? Are advisors independent from feed and fertiliser companies? How often are farm practices evaluated?)*

c. *What type manure of manure (solid/liquid) and manure storage systems is used?*

d. *What is the average excretion rate of N and P per animal?*

Does the typical Poultry farm have a land-base? If so, please address the following questions:

e. *What is a typical ratio between imported and home-grown feed?*

f. *What does an average crop rotation look like? How many years, which crops?*

g. *What are typical annual application rates for manure (organic fertiliser), N, and P?*

h. *How much is applied as manure (or other organic sources) and how much as mineral fertiliser?*

i. *When are nutrients (fertiliser/manure) usually applied?*

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3. Indicate (with an X) if the following techniques affecting C, N, and P cycles are used commonly, uncommonly, or not at all on Poultry farms in your area. Please add any techniques / management that are in use, but not mentioned below.

	Use frequency			
Management technique	**Common**	**Uncommon**	**Not used**	**Comments?**
FIELD RELATED (if applicable)				
Catch / cover crops				
Green manure				
Double cropping				
Removal of plant residue after harvest				
Vegetative buffer strips or no-application zones (near water bodies or field edges)				
Manure/fertiliser incorporation				
Manure/fertiliser injection				
Precision fertilisation				
Soil amendments (compost, biochar, etc.)				
Controlled traffic (GPS)				
Reduced tillage				
No tillage				
Liming				
Agroforestry				
ANIMAL RELATED				
Feed additives/amendments				
Precision feeding techniques				
Free-range possibility				
MANURE RELATED				
Manure digestion				
Other manure processing techniques				
Emission-reducing housing facilities				
OTHER				

4. Are any of the techniques / management practices mentioned above used in combination?

5. What important measures to improve C, N, and P cycling are up-and-coming for Poultry farms in your area?

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