EIP-AGRI Focus Group - Nutrient recycling

Mini-paper - *Towards increasing the mineral fertiliser replacement value of bio-based fertilisers*

Authors

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Introduction

Bio-based fertilisers have potential to fulfill crop nutrition requirements including nitrogen, phosphorus, potassium and sulphur in addition other elements. Some of the nutrients contained in bio-based fertilisers organic or organo-mineral materials may need to go through a mineralization step before becoming plant available. There is a critical need to increase the efficiency of nutrient use from bio-based sources to offset energy intensive and imported mineral fertilisers in Europe. Levelling of the playing field between bio-based fertilisers and mineral fertilisers presents challenges. These challenges include:

- Generally lower nutrient concentration of bio-based fertilisers compared with mineral fertilisers and resultant transport and application costs
- Difficulties in competing directly with mineral fertilisers on total costs per unit of nutrients
- Handling (bulkiness and for some high water content) and spreading characteristics
- Consistency and uncertainties of nutrient values and limitations of measurement by on-farm tools
- Biosecurity – potential animal and human health risks
- Odour and other nuisances for neighbours
- Mismatches in the ratio of nutrients contained in bio-based fertilisers and those required by target crops
- Uncertainties in the nutrient release characteristics of bio-based fertilisers
- The efficiency of nutrient recovery by crops from bio-based fertilisers

This paper will focus on:

A. Briefly on typical nutrient contents of common bio-based fertilisers
B. Modifying nutrient availability and the ratio of nutrients in bio-based fertilisers which are delivered to plants
    - Technologies for increasing the availability of organically bound nutrients and or changing the ratio of nutrients in bio-based fertilisers
    - Technologies to reduce N loss by ammonia emission during spreading
C. Predicting the short and long-term nutrient release characteristics of bio-based fertilisers
    - Assessing the site and season specific nutrient release profile using the soil
    - Assessing the site and season specific nutrient release profile using the plant
    - Predicting nutrient release profiles in the field using modelling

D. Barriers to adoption, bottlenecks and supports for increasing nutrient use efficiency from bio-based fertilisers
E. Recommendations for actions needed – Conclusions

A. Typical nutrient contents of common bio-based fertilisers

Animal manures

Where animal production is concentrated accumulation of manure nutrients is common. This is typically exacerbated by additional inflows of nutrients through importation of feed concentrates. A portion of the nutrient content in the feed not assimilated by the animal and exported in meat or dairy products remains in these regions in manures. The nutrient contents of these manures can vary considerably. Typical properties of common animal manures are summarised by Jensen (2013) in Table 1, including their potential first year mineral fertiliser equivalent value for Nitrogen (N-MFE).

Table 1. Typical properties for a range of manure types; dry matter (DM), total P, K and N content, ammonium share of total N, C:N ratio as well as a characterisation of the biodegradability of the organic material and typical potential first year N mineral fertiliser equivalence (N MFE%).

Manure type	DM	P	K	N total	NH_4-N	C:N	Biodegr.	Pot. N MFE
	(%)		(g kg^{-1} fw)		(% of N_t)			(%)
Deep litters	25-30	1.5	10-12	7-10	10-25	20-30	medium	20-30
FYM, pigs	20-25	4-5	8-9	9	30-45	12–15	medium	20-50
FYM, cattle	18-20	1.7	3	6	20-30	15-20	low	15-30
Broiler manure	45-50	7-9	13-16	20	10-25[a]	5	high	50–65
Layer manure	50-60	7-12	9-16	20-30	5–35[a]	10	medium	40-50
Slurry (pig)	4-7	1,0	2-3	3-5	70-75	5–8	medium	40–70
Slurry (cattle)	7-10	0.9	4-6	4-5	50–60	8-10	low	35–50
Slurry (poultry)	10-15	1-2	2-3	6-10	60–70	4	medium	70–85
Biogas digestate[b]	1-5	1.0	2-3	3-10	60-85	3–5	low	60–90
Sep. slurry liquid	1-2	0.1-1	2-6	3-5	80-95	1-2	medium	80-100
Urine	2-3	0.3	2-6	3-4.5	90	1–2	high	90–100

[a]: Depends on storage time and degree of uric acid hydrolysis, [b]: Mixed animal slurry with bio-waste co-fermentation.
Source: Stoumann Jensen (2013) Animal Manure Fertiliser Value, Crop Utilisation and Soil Quality Impacts Table 15.3 pg 315 *In: Animal Manure Recycling*.

Urban organic wastes

Many sources of organic waste are available from urban areas; these bio-based materials contain significant levels of nutrients. This material can be divided into a number of categories, these categories along with typical nutrient and dry matter contents are summarised in Table 2 from Möller (2016).

Table 2. Dry matter content (DM, as fresh matter) and macronutrient concentration (% DM basis) of composts and digestates cetified by the German compost association (in parentheses: 10 and 90% percentile values)

	DM	OM	N	P	K	S	Mg	Na
Green waste compost	62.6 (52-74)	36.9 (23-51)	1.15 (0.7-1.6)	0.22 (0.14-0.32)	0.85 (0.4-1.3)		0.44 (0.19-0.79)	
Household waste compost allowed for use in Organic Farming	64.5 (52-78)	39.5 (26-54)	1.45 (0.9-2.0)	0.31 (0.18-0.44)	0.98 (0.6-1.4)		0.45 (0.22-0.72)	
Household waste compost including other feedstocks not specified in EU regulation 2)	64.0 (52-77)	39.5 (25-52)	1.53 (0.9-2.0)	0.36 (0.18-0.49)	1.1 (0.6-1.5)		0.51 (0.22-0.74)	(0.037-0.39)
Liquid household waste digestate allowed for use in Organic Farming	12.0 (5.0-20.5)	58.1 (42-78)	4.47 (2.3-6.9)	0.68 (0.36-1.23)	3.24 (1.48-6.57)		0.65 (0.42-1.06)	(0.06-0.36)
Liquid household waste digestate including other feedstocks not specified in EU regulation	5.2 (2.3-9.1)	59.5 (45-73)	12.1 (4.5-19.1)	1.17 (0.55-3.15)	4.31 (4.5-8.7)	(0.3-0.9)	0.44 (0.16-0.73)	(0.09-6.4)
Liquid digestate of catering and retailer organic wastes (no certifica¬tion for use in Organic Farming)	3.34 (1.9-7.1)	56.5 (48-80)	16.3 (4.9-26.5)	2.2 (1.03-3.14)	4.49 (2.7-8.7)	0.86 (0.4-2.74)	0.21 (0.08-1.1)	5.6
Solid household waste digestate allowed for use in organic farming	45.8 (25-69)	61 (44-87)	1.84 (1.1-2.6)	0.6 (0.24-1.1)	1.2 (0.5-2.0)		0.51 (0.35-0.75)	

Source: Möller (2016). Assessment of alternative phosphorus fertilizers for organic farming: Compost and digestates from urban organic wastes. Available online: **http://www.coreorganic2.org/upload/coreorganic2/document/moeller2016-Factsheet_compost_and_digestates.pdf**

B. Modifying nutrient availability and the ratio of nutrients in bio-based fertilisers

Plant recovery of nutrients from bio-based fertilisers is influenced by several factors. The characteristics of the bio-based fertiliser are a key factor. If a portion of the nutrients contained in bio-based fertilisers are bound in organic forms these may not become plant available in the season of application or at a time conducive to high recovery efficiency by crops. As a result the bio-based fertiliser may not have the same level of availability as a mineral fertiliser and thus a lower mineral fertiliser replacement value. Technologies to increase the plant availability of bio-based fertilisers can help to level the playing field with mineral fertilisers.

Technologies

Anaerobic digestion

Anaerobic digestion (AD), thanks to biological and chemical processes, may be considered a bioprocess able to increase availability of nutrients contained in biomasses so that the resulting digestate can be used as a "bio-based mineral fertilizer" in partial or total substitution to non-renewable ones (Riva et al., 2016).

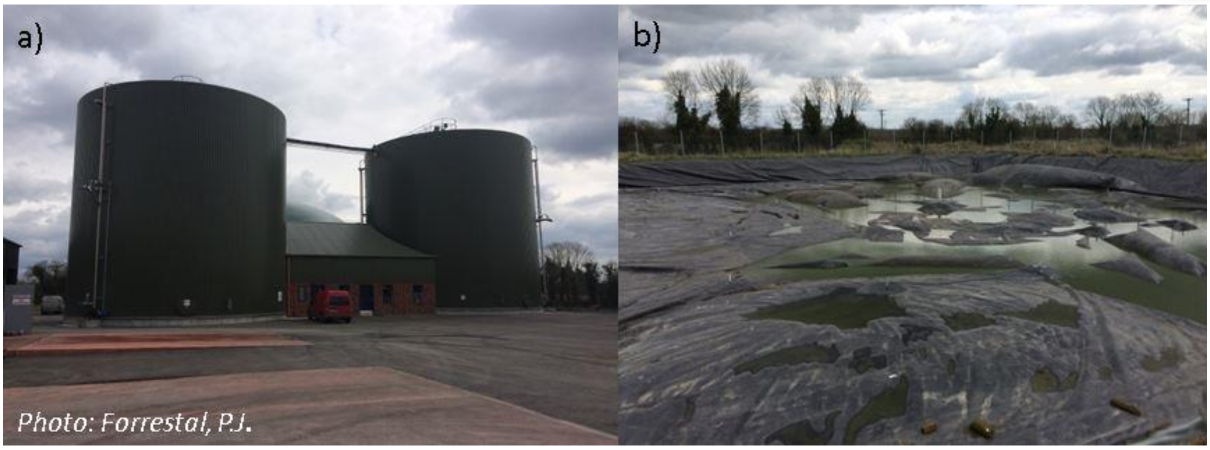


Figure 1. a) Anaerobic digestion plant and
b) Digestate storage lagoon with cover, Ireland. Photo: Patrick Forrestal.

Organic-N and organic-P are mineralized during anerobic digestion producing N-NH_4^+ and mineral P that are readily plant available, thus the digestate has enhanced fertilizing properties compared with the undigested material entering the process (Figure 2 and Table 3).

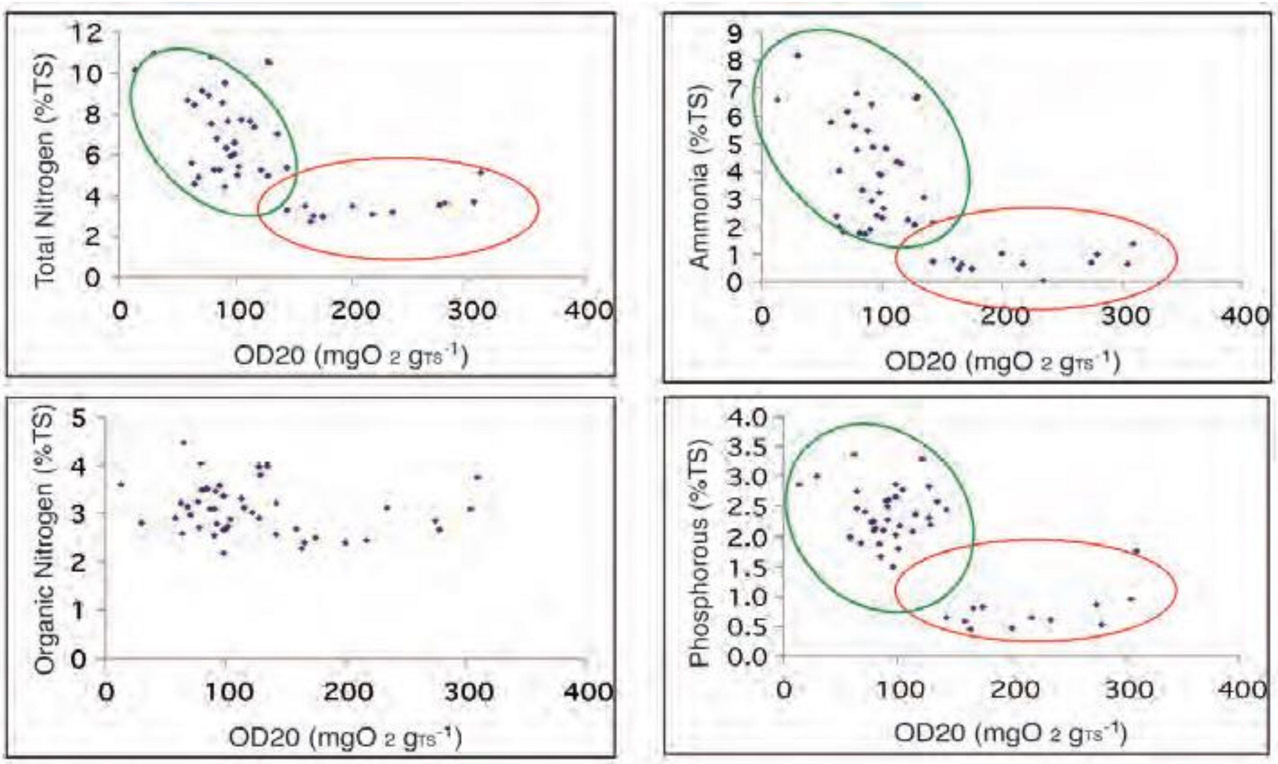


Figure 2. Changes in N and P content during anaerobic digestion vs. biological stability (OD): undigested material (red circle), digestate green circle. Source (Schievano et al., 2009).

In this way, anaerobic digestion is a bioprocess able to increase availability of nutrients contained in biomasses, so that digestate can be used as a more efficient substitute of mineral fertilizers (Riva et al., 2016). Moreover, the biological process at least partially deodorizes the final product (Orzi et al., 2010), making it more attractive for the end-users, as odour nuisance has been identified as one of the major barriers for farmers to use organic fertilisers (Case *et al.*, 2016). After anaerobic digestion about 60-75 % of N is present in ammoniacal forms depending on organic matrices used and digester retention time.

Table 3. Chemical characteristics of digestate and derived liquid and solid fraction of agricultural AD plants (Tambone et al., 2015).

Samples	Dry matter (DM) (%)	TKN ($g\ kg^{-1}$ DM)	N-NH_4 ($g\ kg^{-1}$ DM)	N-NH_4/TKN (%)	P_2O_5 tot ($g\ kg^{-1}$ DM)
D average (n = 15)	6.02±1.18 a	47.50±24.52 b	79.76±17.99 b	55.50±7.77 b	36.19±10.39 a
LF average (n = 15)	4.23±1.09 a	62.87±20.53 b	101.98±21.60 b	60.20±9.15 b	37.35±11.93 a
SF average (n = 15	21.04±3.16 b	10.06±3.25 a	29.39±5.84 a	34.41±8.65 a	31.27±10.42 a

D: Digestate; LF: Liquid Fraction; SF: Solid Fraction; DM: Dry Matter; TKN: Total Kijeldhal Nitrogen;

Through anaerobic digestion the degradation of labile organic matter contained allows for the end product to have a high grade of biological stability that is in line with that of compost (Tambone *et al.*, 2010).

Liquid solid fraction separation

Using mechanical separation techniques, e.g. a screw press or decanting centrifuge, a solid and a liquid separate may be obtained, the liquid fraction being rich in soluble nutrient (ammonium-N and K) and the solid being rich in particulate organic matter and bound nutrients (organic-N and total P) (Christensen *et al.*, 2013). After simple solid/liquid separation (screw separation) of digestate material, it is possible to get a liquid fraction containing 0.3-1 % wet weight of nitrogen of which 60-70% is in ammonium form. Using digestate centrifugation a liquid fraction containing 75-85% of total nitrogen as ammonium can be achieved. The liquid fraction of digestate has been shown to be suitable for partial or total substitution of mineral fertilizers at full scale (Riva *et al.*, 2016). On the other hand, the solid fraction of digestate still contains high amount of nutrient (Table 3) so that this fraction can be employed, also, as organic-mineral fertilizers above all for fruit and horticulture.

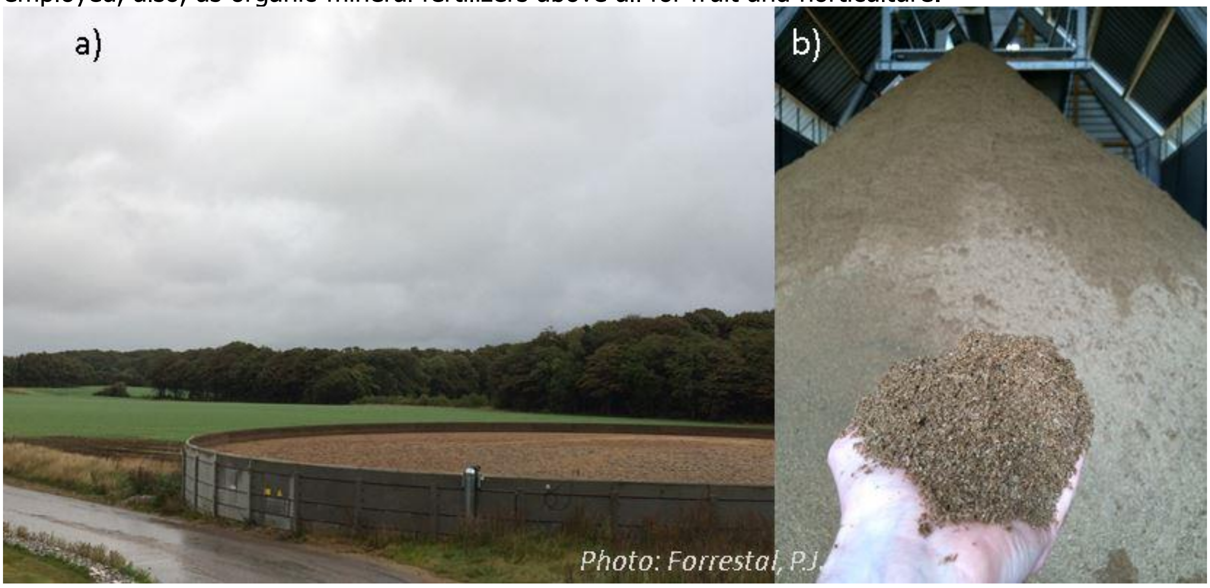


Figure 3. a) pig slurry lagoon and b) associated storage of solid faction following separation, Denmark. Photo: Patrick Forrestal.

Because the solid fraction of digestate has high organic matter content (> 80 %) it can be used as organic amendment in substitution of compost and other organic matrices In a recent study amendment properties of different organic matrices measured by using different parameters and multivariate analysis, was ranked as follows: compost = digestate (solid fraction) > digested sludge > undigested material (Tambone *et al.*, 2010). Recently it was demonstrated that digestate does not need to be composted to achieve a high degree of biological stability (Tambone et al., 2015).

Mineral concentrates

Mineral concentrates are highly nutrient-rich solutions which may be obtained via ultrafiltration, evaporation or reverse osmosis of the liquid fraction from separation of slurry or digestate, Masse *et al.* (2007). The Netherlands have the greatest experience in Europe with these technologies and with their properties and utilisation. In the Netherland a number of centralised and large-scale farm manure processing plants utilise a range of technologies in combination have been operating for a number of years (Velthof, 2011). Hoeksma et al. (2012) monitored production of mineral concentrates from pig slurry using reverse osmosis for two years at five full-scale manure processing plants in the Netherlands. The treatment process at these plants was based on chemical-mechanical separation of the raw slurry, polishing of the liquid fraction by removing the remaining solids by coagulation and flotation filtering and finally concentration of the dissolved nutrients by reverse osmosis to produce a mineral concentrate and a permeate (Figure 4, left). The mineral concentrates could be characterised as an N,K-fertiliser containing 50% of the total N (majority as ammonium) and 78% of total K in the raw slurry (Figure 4, right), and with a pH of 7.9, which implies a risk of N losses by volatilisation during and after spreading. From the raw slurry input, 95%, 45% and 19% of the P, N and K, respectively, ended up in the solid fraction (Hoeksma et al., 2012).

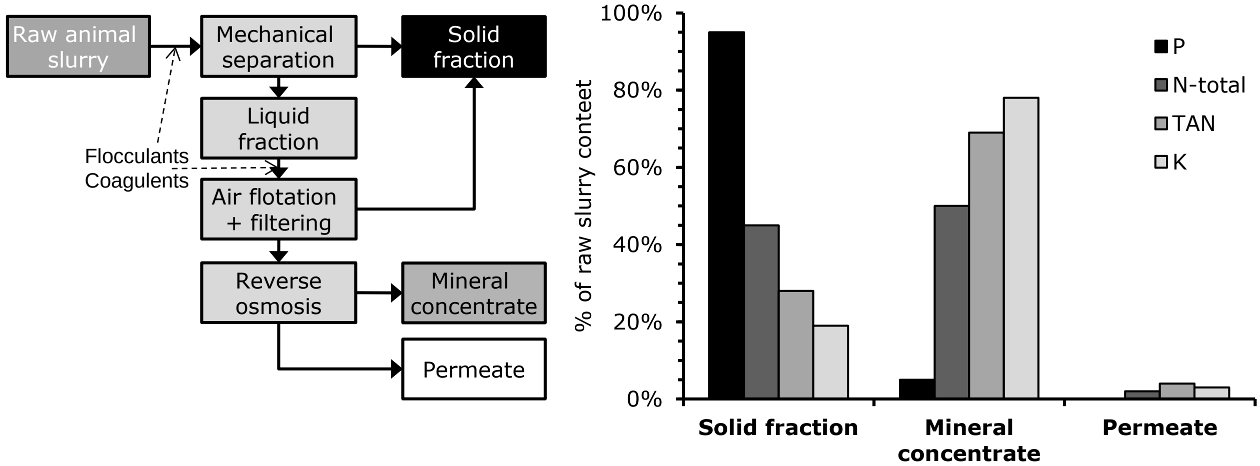


Figure 4. Production process of mineral concentrate using chemical-mechanical separation and reverse osmosis (left) and relative mass distribution of nutrients (raw slurry = 100%) after treatment of pig slurry into the solid fraction, the mineral concentrate and the permeate from reverse osmosis (right). Adapted from Hoeksma et al. (2012).

Provided that the losses can be kept to a minimum, the mineral fertiliser equivalent value of the mineral concentrates theoretically should be relatively high, as they resemble commercial liquid fertilisers, with nearly all the nutrients in a mineral, plant-available form. Injection of the concentrate into the soil to avoid gaseous losses may be needed; this can be carried out with a coulter, spoke-wheel or high-pressure injection tool,which have been shown to effectively limit potential ammonia volatilisation from mineral concentrates with a high pH (Nyord *et al.*, 2008). Table 4 summarises the Dutch results on N mineral fertiliser equivalent (MFE) value and the fate of N from mineral concentrates not taken up.

Table 4. Summary of N mineral fertiliser equivalent value and the fate of inactive N from mineral concentrates (modified from Velthof, 2011).

		Arable land	Grassland
Mineral fertiliser equivalent value (MFE)[1]	Compared to CAN[3]	84%	58%
	Effect of soil type	Yes potato sand: 92% potatoes clay: 80%	No
	Compared to liquid ammonium nitrate	117%	96%
Fate of ineffective N from mineral concentrates[2]	Non-mineralised organic N	On average 5% of applied N	
	Ammonia emission	< 10% of applied N Risk on sod injection grassland > deep inj. Risk on calcareous clay soil > sandy soil	
	Gaseous loss by nitrification and denitrification	< 10% of applied N Risk on grassland > arable land	
	Leaching	< 5% of applied N Risk on sandy soil > clay soil Risk on arable land > grassland	
	Immobilisation in soil	< 10% of applied N Risk on grassland > arable land	

[1]The MFE values in this table are based on field experiments in which mineral concentrates were tested at different nitrogen application rates. [2]The fate of the inactive nitrogen is partly based on results from the experiments and partly on estimates. [3]CAN: Calcium-ammonium-nitrate.

It was concluded that the N MFE value of mineral concentrates compared to calcium-ammonium-nitrate fertiliser was on average 80-90% on arable land (basal dressing via injection) and around 58% on grassland. The variation in MFE value was large, but the N efficiency of the mineral concentrates was similar to that of liquid ammonium-nitrate in grassland and in arable land on clay.
Mineral concentrates thus have similar N fertiliser value to liquid nitrogen fertilisers. Potassium is important for crops, however, supplying K with mineral concentrate limits the N application rate on soils where the K status is sufficient or higher (Velthof, 2011). It has been estimated that if applied to all manure in the Netherlands, the mineral concentrates and the associated solid fraction from separation could decrease the need for imported mineral N and P fertilisers by up to 15% and 82%, respectively, with little change in total NH_3 losses, N_2O emissions and N leaching, due to increased N and P use efficiency on a national scale (Oenema et al., 2012).

Microwave

Use of a microwave is an example of technology which has not been implemented at commercial scale, perhaps because of cost or technical challenges. Qureshi *et al.* (2008) reported the effect of microwave digestion of liquid dairy manure on the release of nutrients, such as orthophosphates, ammonia-nitrogen, magnesium, calcium and potassium, both with and without the aid of an oxidizing agent (hydrogen peroxide). The orthophosphate to total phosphorus ratio of the manure increased from 21% to greater than 80% with 5 minutes of microwave treatment.

Retaining nitrogen using technologies to reduce ammonia emissions during land spreading; a tool for modifying the level of N delivered to the crop

Spreading technologies

The method of spreading of liquid bio-based fertilisers has important implications for N loss through volatilization of ammonia gas. Ammonia gas loss is a critical challenge for ensuring high mineral N fertiliser replacement values from bio-based fertilisers globally. Additionally, ammonia gas causes negative environmental impacts by contributing to eutrophication and acidification of water bodies.

Ammonia also supports the formation of secondary aerosols such as NH_4NO_3 and $(NH_4)_2SO_4$ because of its alkaline nature. The transport distance of these secondary ammonium salt aerosols is considerably greater than for NH_3 gas (Warneck, 1999). Furthermore, re-deposition of volatilised NH_3 is an important source of N for the production of nitrous oxide (N_2O) via biological nitrification of ammonium (NH_4^+) (Martikainen, 1985). For reasons including those mentioned above European countries have committed to reducing national ammonia emissions. Spreading technologies are one pertinent technology to address this challenge. Addressing the ammonia challenge has potential to simultaneously help European counties meet their emission reduction commitments and to improve the mineral fertiliser N replacement value of bio-based fertilisers. Figure 5 and table 5 of illustrates different application techniques and their relative merits.

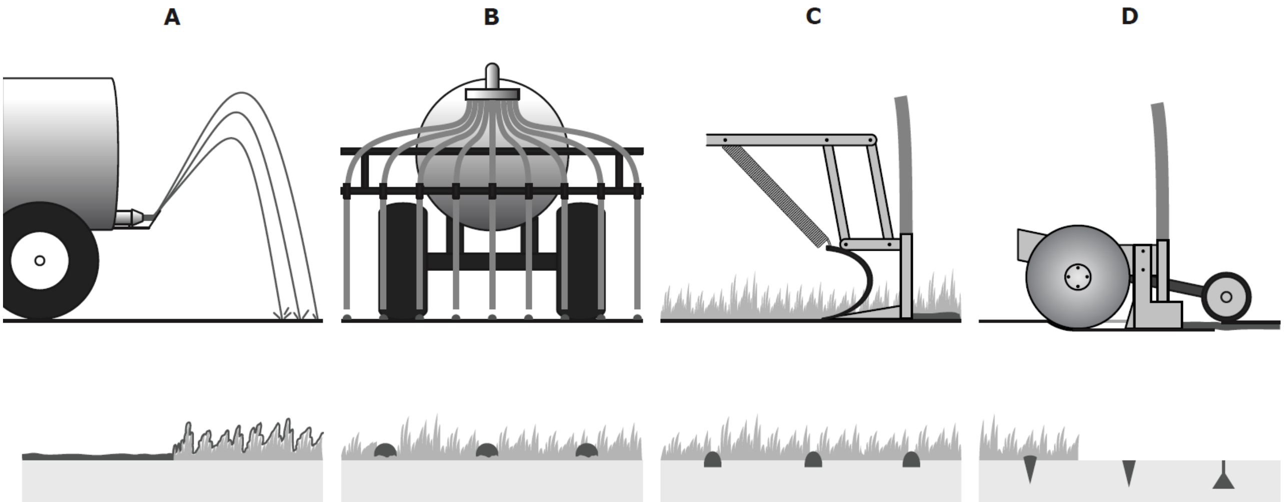


Figure 5. Illustration of principles for the four major types of slurry application methods and the associated slurry distribution within the crop-soil after application: (A) splash plate spreader, (B) band spreader, (C) trailing shoe and (D) shallow injector (© Southern Denmark University).

Table 5. Review of the characteristics of the four main slurry application methods (adapted from Birkmose, 2009), for illustration see Figure 5.

	A. Broadcast	B. Trailing hoses	C. Injection	D. Trailing shoe
Distribution of slurry	Very uneven	Even	Even	Even
Risk of ammonia volatilisation	High	Medium	Low or none	Medium
Risk of contamination of crop	High	Medium	Low	Low
Risk of wind drift	High risk	No risk	No risk	No risk
Risk of odour	High	Medium	Low or none	Medium
Spreading capacity	High	High	Low	Low
Working width	6-10 m	12-28 m	6-12 m	6-16 m
Mechanical damage of crop	None	None	High	Medium
Cost of application	Low	Medium	High	High
Amount of slurry visible	Most	Some	Little or none	Some
Especially suited for	All	Winter crops	Grass, bare soil	Grass

Acidification

Slurry acidification is an efficient technology for reducing ammonia emissions from slurries. However, it is not widely used outside of Denmark where 20-25 % (2015-2016) of all slurry is acidified prior to land application. The technology is fully implemented in the Danish environmental legislation and is also admitted as a BAT technology for reducing ammonia emissions in the final draft of the BREF for the Intensive Rearing of Poultry and Pigs. The Danish Ministry of Food and Agriculture held an international workshop on the topic in 2016 **http://www.conferencemanager.dk/acidification/the-event.html**

Figure 6. Acidification of slurry using sulphuric acid a) in house, Denmark (photo: Patrick Forrestal) and b&c) during land application, Denmark (photo: Torkild Birkmose) using the SyreN system.

C. Predicting the short and long-term nutrient release characteristics of bio-based fertilisers

The nutrient release characteristics of bio-based fertilisers are critical for crop nutrition and nutrient use efficiency, particularly in annual crops. While the nutrient release characteristics in the season of application are typically in greatest focus it is important to understand that organic manures also mineralise nutrients, particularly N over the long-term.

Prediction of organic N mineralisation in the long-term

A major fraction of the manure N not taken up by the crop remains in the soil in organic form, and this will contribute to the slow, continuous mineralisation into plant-available, but also leachable N, and the fate in subsequent years following application of the manure will depend on the synchronisation between release, crop demand and soil water percolation. Quantifying the magnitude of the residual MFE value of animal manures in subsequent years is not straightforward; Cusick et al. (2006) gives a good overview of available methods and examples of results.

Sørensen et al. (2002) and Petersen and Sørensen (2008) made an estimate using a simple model, assuming that a certain percentage of the remaining organically bound N will be mineralised each year. Based on calibration on the literature data, they estimated the yearly mineralisation rate to be around 20% in the year after application, gradually declining over the next few years to just 5% per year in all subsequent years. Mineralisation is a continuous process over the year, so crops with a longer growing period will achieve a higher MFE value. The estimated accumulated residual MFE values (Figure 7b) vary from rather moderate residual effects of only 7-8% with a short season crop even after 10 years of pig slurry application, whereas for the solid manures and a crop with a long growing season the accumulated residual MFE after 10 years can be as much as 24% (Figure 7b). However, the residual effects continue even after 10 years (Figure 7a), and for a very long time horizon, e.g. after 50 years it may amount to 17-25% for cattle slurry, 9-14% for pig slurry and 20-43% for solid manures. The estimated residual values are within the range found by Schröder (2005) and further confirmed by modelling in Schröder et al. (2007).

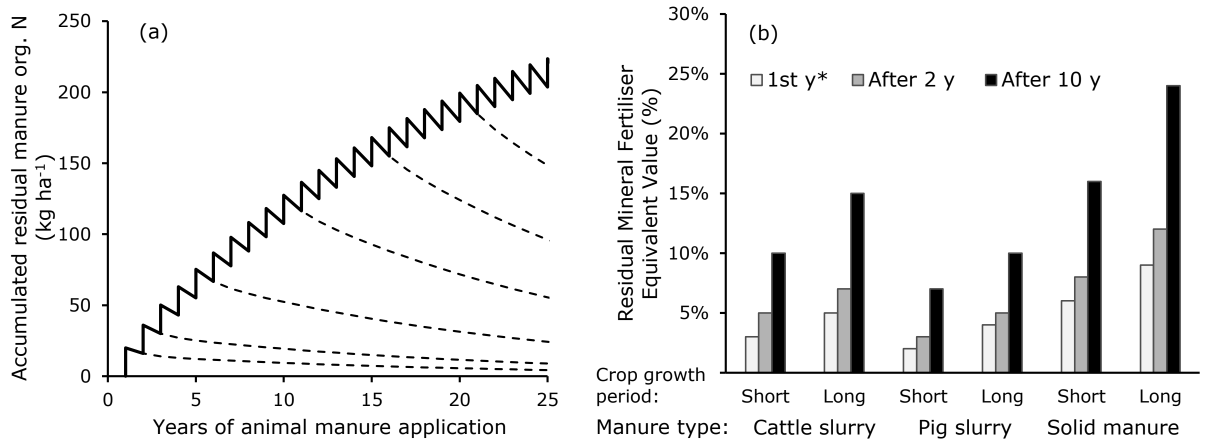


Figure 7. Modelled (a) residual manure organic N accumulated (full line) in soil over 30 years with annual application of 100 kg total N ha^{-1} in pig slurry (25% org. N, dashed line indicating decay of org. N after 1st, 2nd, 5th, 10th, 15th and 20th application) and (b) the corresponding residual MFE value of 1, 2 or 10 years of repeated applications of different types of animal manure, compared with soil only receiving mineral fertilisers. MFE given in % of annual manure total N application for crops with a short (e.g. spring cereals, 50% of mineralised N available for crop) or long growing period (e.g. maize, beet, 75% of mineralised N available for crop). Solid manure: cattle FYM and deep litter. *: effect in the year after application, the first year with residual N effect. Source: Jensen (2013).

Assessing the site and season specific nutrient release profile of bio-based fertiliser application using the soil

A common practice is to apply a set amount of bio-based fertiliser and then to top-up appropriately with mineral fertiliser for the nutrients lacking, e.g. N and K if the crop demand for P was fully supplied by the bio-based fertiliser. The approach of applying bio-based fertiliser in the seedbed gives a great deal of flexibility in a system where there are many unknowns at farm level, particularly with regard to the N availability from bio-based fertilisers.

Factors including the following are uncertain:

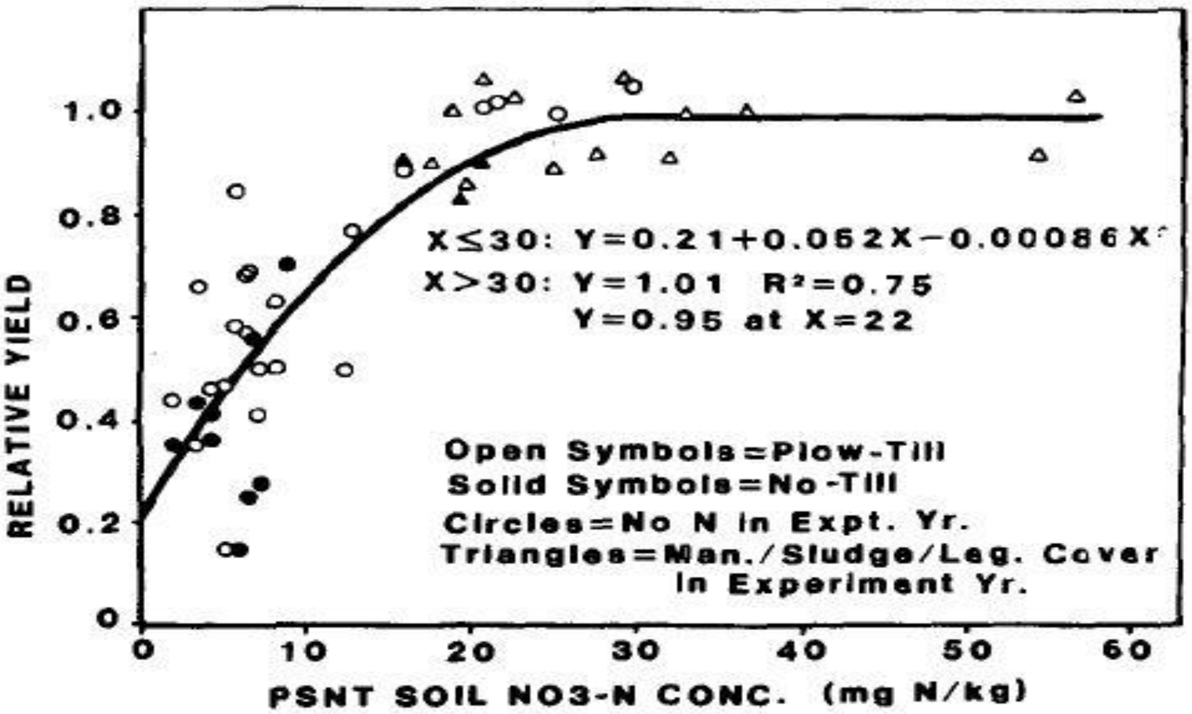
1. the actual nutrient content of the bio-based fertilisers (unless proper analyses for the specific batch is available)
2. the application rate can be difficult to set for certain materials (bulky, heterogeneous, high moisture)
3. the level of loss of ammonical N through volatilisation (depends on both application technique, soil, crop and weather variables)
4. the interaction of site and season with the plant availability of organically bound nutrients (e.g. potential leaching of soluble nutrients out of the root-zone, or denitrification of available N)

Each of the uncertainties above can and should be addressed individually. However, it may not be possible to remove all uncertainty. Some of the uncertainty generated above can be bypassed where an assessment of the nutrient release profile of the bio-based material can be made in-season based on soil or crop specific information, e.g. soil measurement of the available pool of nutrient, or measurement of crop nutrient uptake. Using this information an estimate of variations in nutrient supply requirement due to the previous uncertainties can be made. The outstanding requirement can then be met by applying mineral fertiliser accordingly. This is approach is particularly relevant to nitrogen and can overcome the issue of inter-seasonal and inter-soil variation in the nitrogen release from bio-based fertiliser. There is a great need for such site-specific decision based management tools to determine top-dress N rates.

Examples in practice:

The pre-sidedress nitrate test (PSNT) for maize/corn (*Zea mays* L.) (e.g. Meisinger et al., 1992) is used to determine the level of N sufficiency for fields fertilised with organic manures.

Figure 8. The relationship between corn relative yield and soil nitrate concentration in the surface 30 cm of soil. Source: Meisinger et al. (1992).



The PSNT test is in use across a wide maize growing section of the United States and is also widely employed in parts of mainland Europe (Olfs *et al.*, 2005).

Examples of extension factsheets on the topic:

https://extension.umd.edu/anmp/pre-sidedress-soil-nitrate-test-psnt

http://nmsp.cals.cornell.edu/publications/factsheets/factsheet3.pdf

A quicktest can be used to measure soil nitrate (Figure 9). In the future the development of smart sensors may make real time monitoring of soil nitrate levels easier and faster, improving resolution and accuracy.

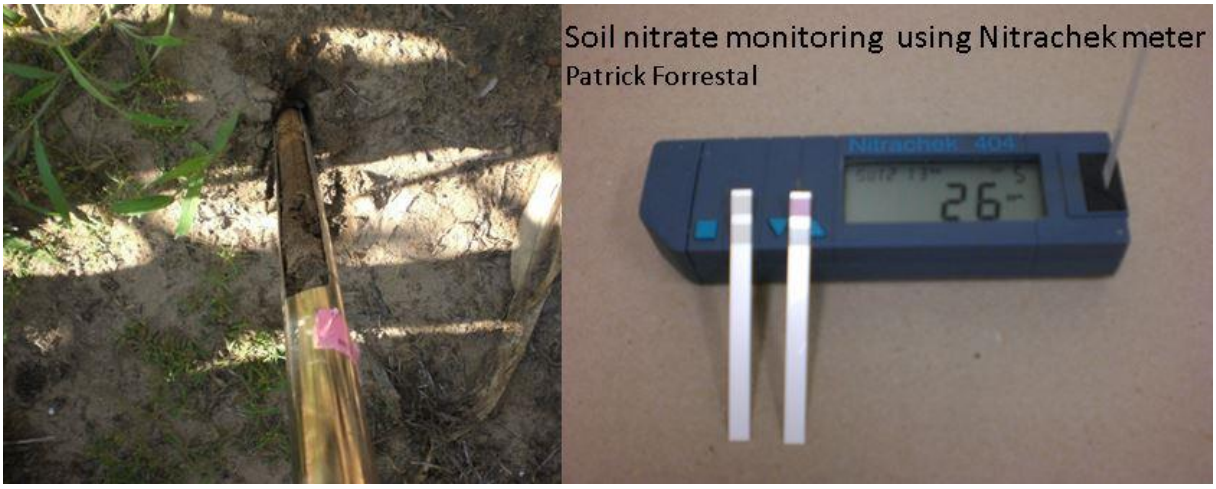
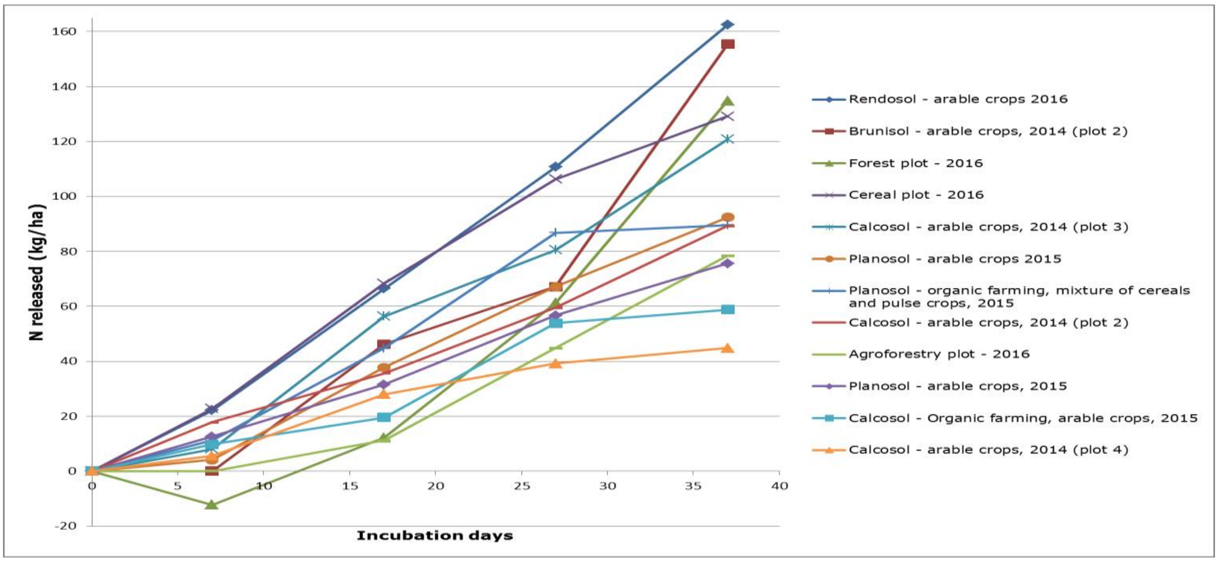


Figure 9. Soil nitrate measurement using nitrachek™ meter. Photo: Patrick Forrestal.

Prediction of N mineralisation from soils fertilised with bio-based fertilisers

When adding bio-based fertilisers the net production of mineral nitrogen is of interest and is influenced by 1) mineralization of native soil organic nitrogen, sometimes referred to as basal mineralization, 2) mineralization of organic residues, like crop residues, or organic wastes added to the soil and 3) the interaction for these two sources may have a role to play.
The mineralisation process, linked to the application of the organic materials can give varying results. During a first phase after the addition of residues net mineralization or net immobilisation can occur and the dominance of either processes can vary depending on distribution of organic components between easily degradable and more recalcitrant fractions. A second phase of mineralisation can occur by re-mineralization of the microbial biomass involved in immobilisation (Brisson *et al.*, 2008).
It is possible to simulate soil specific N mineralization using a standardized method to assess nitrogen and carbon mineralization ability of organic amendments (NF XP U44-163, last version in December 2009). The samples are incubated with a temperature of 28°C and the soil moisture is kept at field capacity. The nitrogen from mineralization is measured in samples at the 0, 7th, 17th, 27th and 37th day. The department of Charente-Maritime have shown that a crop cycle is about 15 to 30 incubation days with a median value of 24 days for the wheat and 21 days for the corn. **http://www.charente-maritime.chambagri.fr/fileadmin/publication/CA17/20_Energie_Environnement/Documents/Mineralisation_du_sol_1.pdf**
The results can be used to predict the kinetics of nitrogen release or immobilization for soils with or without organic manure addition. It is possible to assess the potential for the synchronization of nutrient release with crop development. The test shows that the nitrogen release potential and pattern of soils varies.



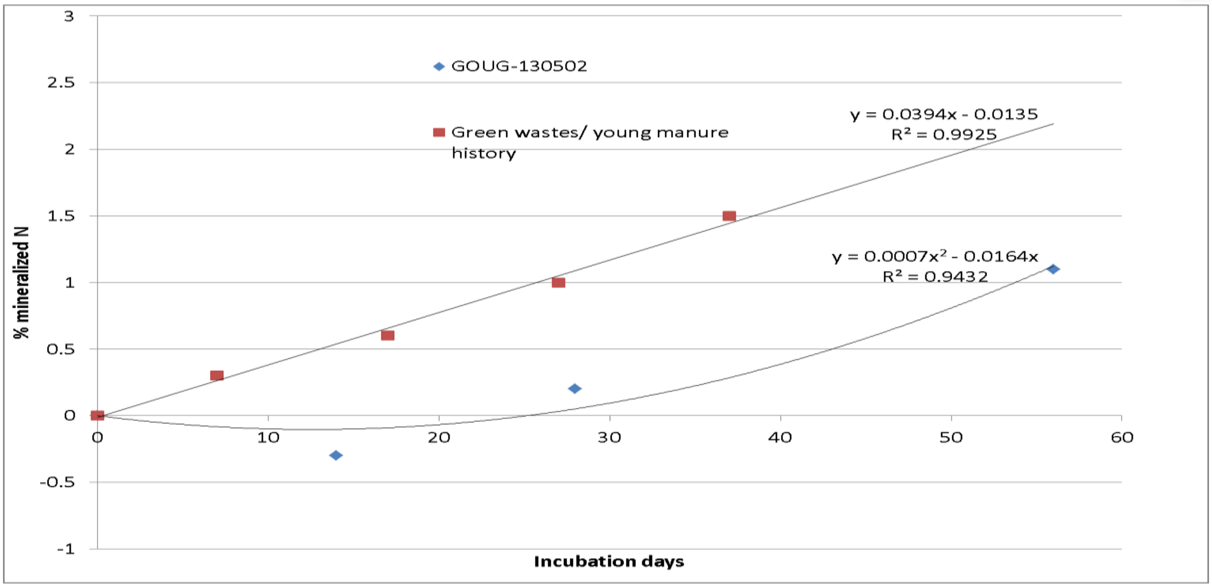


Figure 10. Examples of kinetics of nitrogen mineralization for soils of Charente-Maritime (France).

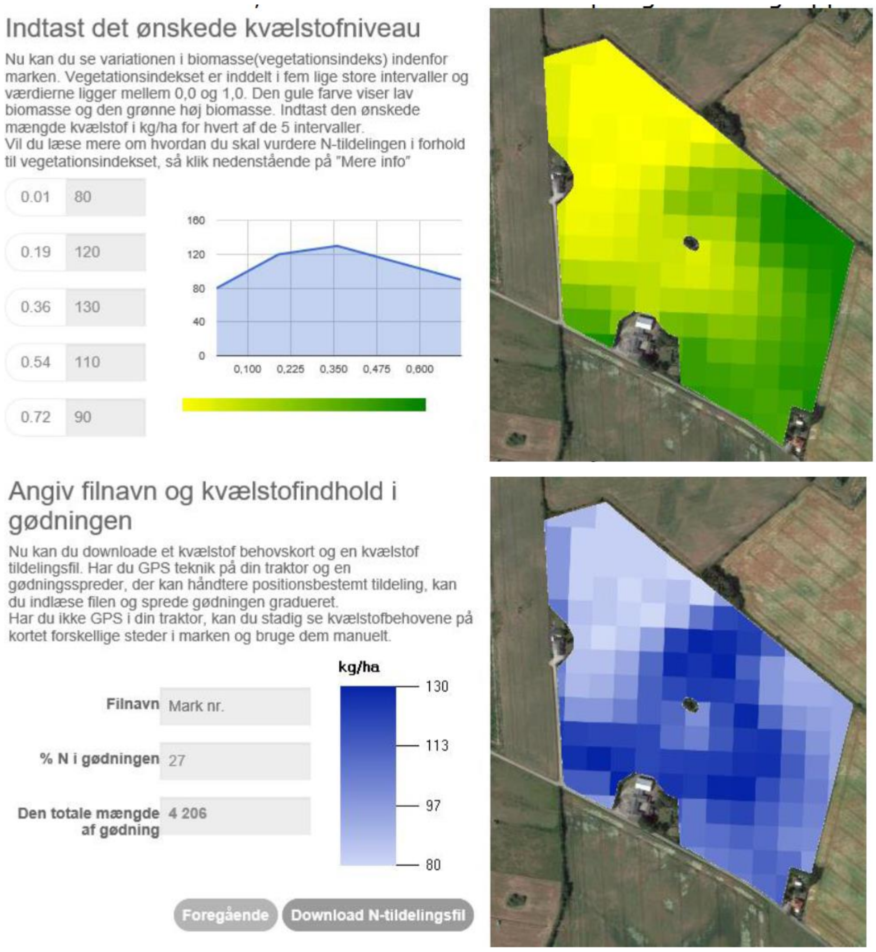
The soil nitrogen supply may be important enough because of regular organic inputs of farmers. Figure 10 illustrates contrasting kinetics of net nitrogen mineralisation between two samples. The sample indicated by the square symbols (GOUG-140519) had a history of green wastes composts and young manures application and a the net mineralisation of N is rapid and linear. In contrast for the sample indicated by the diamonds there is a period of c. 20 days of net immobilisation of nitrogen. These type of contrasting net mineralisation patterns have important implications for crop establishment and development.

Assess the site and season specific bio-based fertiliser release profile using the plant

Measurements taken from plants in the window before rapid nutrient demand commences can also be used to usefully integrate the variability in the availability of nutrients from bio-based fertiliser with site and season specific factors. Plant based measurements including visual rating, a SPAD meter (abbreviation coming from the Soil-Plant Analyses Development unit of Minolta Camera Co., who developed the first instruments to measure chlorophyll content of leaves) and NDVI (Normalized Difference Vegetation Index) have been shown to be well correlated with relative grain yield (e.g. Forrestal *et al.*, 2012).
A variety for tools are available for making measurements from crops to assess their nitrogen status. These tools include the N-tester®, N-Sensor®, Crop Sensor Isaria, GreenSeeker, CropCircle, etc. Remote sensing has become easier as drones can now carry sensors to measure canopy reflectance.

Examples in practice:

In Sweden and Denmark, a satellite based service has been provided for farmers to assess crop biomass and N uptake for their fields, based on the Sentinel-2A/2B satellites (http://cropsat.se/ & http://cropsat.dk/). This free service enables farmers to map crop status all their fields and establish graduated fertilisation maps for use with fertiliser spreaders capable of variable rate application. The example in Figure 11 shows how the map of variations in vegetation index (NDVI) for a winter wheat crop in mid spring can be used to estimate a spatially varied fertiliser N application rate to be applied as side dressing, based on a yield expectation and average N application rate (e.g. as per Figure 11 bottom).
Figure 11. Example of cropsat.dk maps of vegetation index (NDVI, top) and recommended fertiliser N application (bottom) (source www.landbrugsinfo.dk)



The corn stalk nitrate test (Binford *et al.*, 1990) has proven a useful tool for "post-mortem" identification of excess N application. In the United States it is recommended to use by many state extension services e.g. https://extension.umd.edu/sites/default/files/_docs/programs/anmp/NM-8%20Corn%20Stalk%20Nitrate%20Test.pdf

Predicting ammonia volatilisation loss in the field using modelling

Using empirical or mechanistic models to predict MFE and guide optimisation – e.g. Ammonia emission from applied manure is affected by the adsorption of ammonium in the manure dry matter, the physical processes controlling the movement of manure liquid into and within the soil, and the interaction of manure liquid with soil cation exchange complex. It has been assessed that the emission varies from 0 to more than 50% of TAN (Table 6), depending on manure type, environmental conditions (temperature, wind speed, rain), and soil properties. Biological N-transformation processes have been evaluated to be of relative minor importance due to the short duration of NH_3 emission from applied manure (Feilberg and Sommer, 2013).

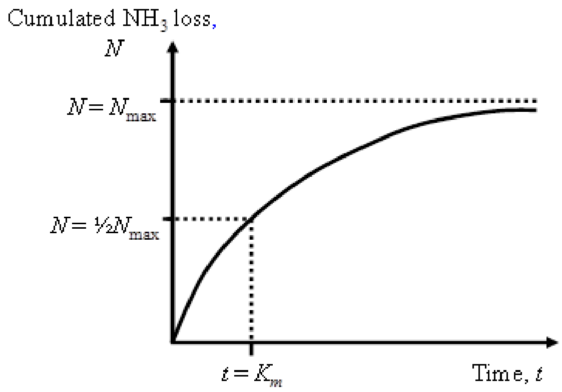
Table 6. Ammonia volatilization from surface broadcast slurry, from slurry injected into the soil and slurry that has been applied onto the soil and incorporated. Effect of incorporation varies according to time lag between application and incorporation (Adapted from Hansen et al., 2008).

Season	Soil surface and Crop	Application technique	NH_3-loss, % of applied TAN	
			Pig	Cattle
Spring	Bare soil	Trailhose	17,1	32,6
		Trailhose and incorporation	5,0	9,4
		Injection 3-5 cm bare soil	1,7	3,3
	Cereals	Trail hose	14,8	28,1
	Grass	Trailhose	17,1	32,6
		Injection 3-5 cm bare soil	12,8	24,5
Summer	Bare soil	Trailhose	22,4	42,7
		Trailhose and incorporation	6,5	12,4
		Injection 3-5 cm bare soil	2,2	4,3
	Grass	Trailhose	22,3	42,5
		Injection 3-5 cm	16,7	31,9
Autumn	Grass	Trailhose	21,8	41,6
		Injection 3-5 cm	16,4	31,2

**Incorporation by plow or rotary harrow six hours after application of manure on soil.*

Incorporating slurry into the soil is a very effective way of decreasing NH_3 volatilization. Incorporation of slurry by soil tillage or direction decreases NH_3 losses by 70-90% (Table 9.5).
e.g. **https://www.youtube.com/watch?v=p4QEsgHDqGY**

Furthermore, application of slurry with trailing hoses on the soil beneath a crop canopy may decrease NH_3 volatilization by more than 50%; the efficiency of this technique increases with increasing leaf area and height of crop (Feilberg and Sommer, 2013).
Rates of ammonia volatilization may be very high immediately after slurry application. The cumulative NH_3 loss increases hyperbolically with time (Figure 12), but the rate of ammonia volatilization from applied manure becomes very low after a few days. Such kinetics of ammonia volatilisation from a large database of European ammonia volatilization data (from Denmark, Italy, the Netherlands, Norway, Sweden, Switzerland and UK) were fitted with Michaelis–Menten-type equation and explanatory environmental factors determined. Variables significantly affecting ammonia volatilization throughout Europe are soil water content, air temperature, wind speed, slurry type, dry matter content of slurry, total ammoniacal nitrogen content of slurry ($TAN=NH_3+NH_4^+$), application method and rate, and slurry incorporation (see Table 6)(Søgaard et al., 2002). Similar findings were made by Huijsman et al (2003).



$$N(t) = N_{max} \frac{t}{t + K_m}$$

Figure 12. Schematic representation of the cumulative ammonia volatilization loss from a slurry application as a function of time following the field application of slurry. N_{max} and K_m are the parameters used in the Michaelis–Menten-type model of the rate of NH_3 loss (Søgaard et al., 2002).

Table 7. Parameterization of NH_3 volatilization from field-applied animal slurry(significant parameters, P<0.01; Søgaard et al, 2002).

Experimental factor	Effect on total NH_3 volatilisation
Soil water content	Wet soil 10% higher than dry soil
Air temperature	+2% per °C
Wind speed	+4% per m sec^{-1}
Slurry type	Pig slurry 14% less than cattle slurry
Dry matter content	+11% per % DM
TAN content	-17% per g N kg^{-1}
Application method	Not significant apart from press. injection
Band spread/trailing hose	42% less than broadcast spread
Open slot injection	73% less than broadcast spread
Slurry incorporation	No incorp. 11 times higher than shallow cultivation

D. Barriers to adoption, bottlenecks and supports for increasing nutrient use efficiency from bio-based fertilisers

Case et al. (2017) conducted an extensive survey of farmer perceptions of potential benefits and barriers to use of organic waste products on farm in Denmark. The survey received 452 responses (a 28% response rate). Of the respondents 72% used organic fertiliser/ manures. The respondents to the survey cited unpleasant odour for neighbours, uncertainty in nutrient content and difficulty in planning use as the most important barriers to use. Enhanced soil structure, low cost and ease of availability were cited as the most important advantage or reason for use. Hou et al. (2017) surveyed stakeholder perceptions of manure treatment technologies in Denmark, Italy, the Netherlands and Spain. They reported that the major barriers to processing technology adoption were related to economic factors with lack of investment capital being an issue for 60% of respondents and high processing costs and a long payback period being a concern for 52% and 45% of respondents, respectively.

Barriers to adoption include:

- Odour
- Uncertainty of nutrient content
    - Time lags in lab analysis
- Difficulty in planning use
- Cost of equipment
- Slower speed of application and increased horse-power requirements of low-emission spreaders
- Practicalities of applying high volume materials in-season
- Compaction issues for application of slurries onto the seedbed where material is near the roots vs applying before ploughing and ploughing down

Technologies and support to increase efficiency through application methodology

In Ireland the vast majority of slurry is currently spread using splash-plate spreaders. To encourage greater adoption of low ammonia loss equipment including trailing hose, shallow injection and trailing shoe spreaders grant support for equipment purchase is provided through the Targeted Agricultural Modernisation Scheme II (TAMSII) **https://www.agriculture.gov.ie/media/migration/farmingschemesandpayments/farmbuildings/tamsiisupportdocs/lowemissionsslurryspreadingscheme/TAMSIILESSSchemeTandCs040516.pdf**

In Ireland the new nutrient management online system will provide guidance on where to spread slurries based on soil test information

https://www.teagasc.ie/environment/soil/nmp/

E. Recommendations for actions needed - Conclusions

Nutrient use efficiency of crops is sensitive to the deviation in the nutrient rate from the optimum level for crop production. Nutrient use efficiency levels tend to be relatively high when nutrient availability is close to that needed to achieve the economic optimum yield. When the economic optimum yield is exceeded nutrient use efficiency tends to fall rapidly. Therefore, matching available nutrient application rates of bio-based fertilisers closely to the economic optimum requirements is a necessity for increased nutrient use efficiency of these fertilisers. As described in this paper, compared to mineral fertilisers achieving this can be more difficult as there are challenges concerning the nutrient content, nutrient availability and homogeneity of the material, setting of appropriate application rates, ammonia volatilisation and other potential loss risks (leaching or denitrification) for example.

Challenge	Potential solution (examples only)	R&D need	Implementation & knowledge transfer of available tech
Applying the target level of plant available nutrient			
Nutrient content determination	Fast, inexpensive on-farm tools[1]	Yes	Yes
Achieving target volume rate and evenness of spreading	Spreader calibration support	No	Yes
	Improved spreading technologies	Yes	Yes
	Bio-based fertilisers with improved spreading characteristics	Yes	Yes
Variable volatilisation of NH_3	Utilisation of low emission spreading technologies many already available	Yes	Yes
If the target rate of a specific nutrient application can be achieved (above) applying the optimum rate of each individual nutrient required by the crop remains challenging because			
The nutrient ratios of bio-based fertilisers frequently do not match plant requirements	Technologies that alter the available nutrient ratios in bio-based fertilisers e.g. digestion and liquid-solid separation[2]	Many developed	Yes
	Applying bio-based materials at a rate that meets the least demanding nutrient and to top the remaining nutrients up with a different source. E.g. bio-base to P removal and top-up	Yes	Yes

	with mineral fertiliser N to meet total N requirement		
Site & environment interactions on the mineralisation of organically bound nutrients causing the nutrient release profile to vary across sites and seasons	Soil based solutions to provide site specific top-dress nutrient requirements in-season. E.g. use of soil mineral N or other nutrient monitoring	Yes	Yes
	Plant based solutions to provide site specific top-dress nutrient requirements in-season. E.g. use of optical sensors, remote sensing etc.	Yes	Yes

[1]See mini-paper of Snauwaert et al.

[2] See mini-paper Fangueiro et al.

Operational groups to focus on the challenges written in italics are suggested

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