

eip-agri
AGRICULTURE & INNOVATION



EIP-AGRI Focus Group

How to improve the agronomic use of recycled nutrients (N and P) from livestock manure and other organic sources?

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1. Introduction: problem statement

In the transition from a fossil reserve-based to a bio-based economy, it has become a critical challenge to maximally close nutrient cycles and migrate to a more effective and sustainable resource management, both from an economical and an ecological perspective. The production and transport of mineral fertilisers requires significant amounts of fossil energy. For example, the production of reactive ammonium (NH_4) through the extraction of unreactive atmospheric nitrogen gas (N_2) via the Haber Bosch process amounts to a fossil energy consumption of 35.2-40.5 GJ ton^{-1} NH_4 . The total energy consumption is equivalent to $\pm 2\%$ of world energy use. Hence, the dependency of agriculture on fossil reserve-based mineral fertilisers (especially N, P, and K) must be regarded as a very serious threat to future human food security¹. Also, estimates of phosphorus reserves are highly uncertain, but based on population growth and future demand for nutrients, it is expected that depletion will occur within 93 to 291 years. Societal impact is expected to occur much sooner than the expected time of depletion, in accordance with peak theory which indicates that resource scarcity will have a major impact on product pricing and consequential social effects from the point in time onwards when the peak production has been reached and output is subsequently declining. Geopolitical moves can shift this date forward, making nutrient scarcity an imminent threat. Moreover, the quality of the remaining natural resources is declining, there is no substitute available, and to date these nutrients cannot be manufactured. Moreover, fossil phosphorus deposits are unevenly distributed in the world in which the EU depends heavily on import of phosphate rock for the production of mineral fertiliser. The European continent itself is virtually devoid of primary phosphate rock, making this dependence on import a precarious geostrategic position for the EU. Because of this, in 2014 the EC placed phosphorus on the "critical raw material list". Although vivid debates continue on calculating the exact remaining global resource availability regarding P deposits, there is consensus that the general absence of such reserves on the European continent makes this a considerable threat towards our domestic food security.

At the same time, the agricultural demand for mineral fertilisers is continuously increasing³, mainly due to the rising world population, the increasing meat consumption, and the cultivation of energy crops. In fact, the FAO reported a five-fold increase in fertiliser consumption between 1960 and 2005 (FAO, 2009) and also projects continued increase in the coming years². This tension between resource scarcity and increasing demand will continue to considerably push up the prices for nutrient resources in the near future. The increasing cost for fossil energy is another important price influencing factor, as a strong positive correlation between energy prices and fertiliser costs has been observed. Next to these economic consequences, the current use of chemical fertilisers also results in an important environmental impact.

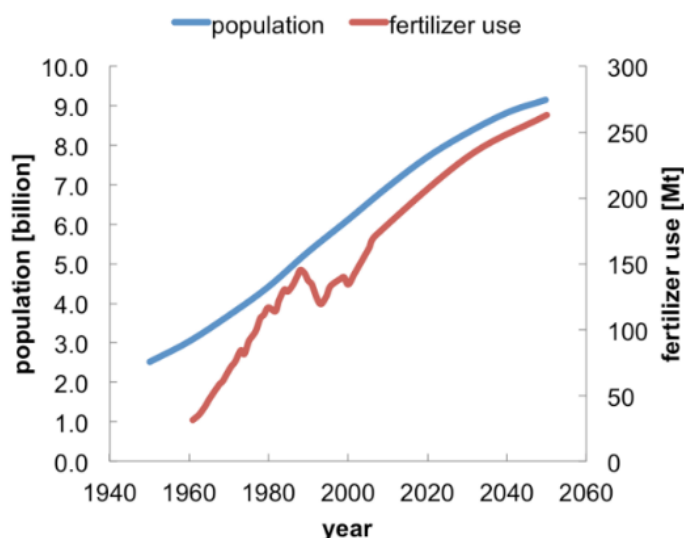


Fig. 1. Global world population and fertiliser use³

¹ Sutton et al. 2013. Our nutrient world: The challenge to produce more food and energy with less pollution. Report: Global Overview of Nutrient Management, Centre for Ecology and Hydrology, Edinburgh, UK.

² World fertiliser trends and outlook to 2018, FAO 2015.

³ N. Alexandratos and J. Bruinsma, "World Agriculture Towards 2030/2050: The 2012 Revision," Food and Agriculture Organization of the United Nations, ESA Working Paper **No. 12-03**, June 2012.

Despite these unfavorable prospects, a large amount of minerals is again dispersed in the environment through processing or disposal of waste streams, often in difficult to extract, non-bio-available form such as sewage sludge, industrial sludge, manure, household waste, incineration ashes, etc. In addition, the observed intensification of animal production and the resulting manure excesses, combined with a limited availability of arable land for the disposal of waste (manure, sludge, etc.) and the excessive use of chemical mineral fertilisers, has led to surplus fertilization and nutrient accumulation in many soils worldwide. These phenomena have caused environmental pollution. Leaching of nitrates and phosphates or runoff to water bodies has led to eutrophication of surface waters, atmospheric emissions, as well as soil erosion³. In turn, these sources of pollution have stimulated the introduction of increasingly stringent regulations for the application of nutrients to agricultural fields, and have led to more strict requirements for the quality of discharge/emission from waste(water) treatment facilities^{4,5}. A new global effort is needed to address 'The Nutrient Nexus', where reduced nutrient losses and improved nutrient use efficiency across all sectors simultaneously provide the foundation for a greener economy to produce more food and energy while reducing environmental pollution³.

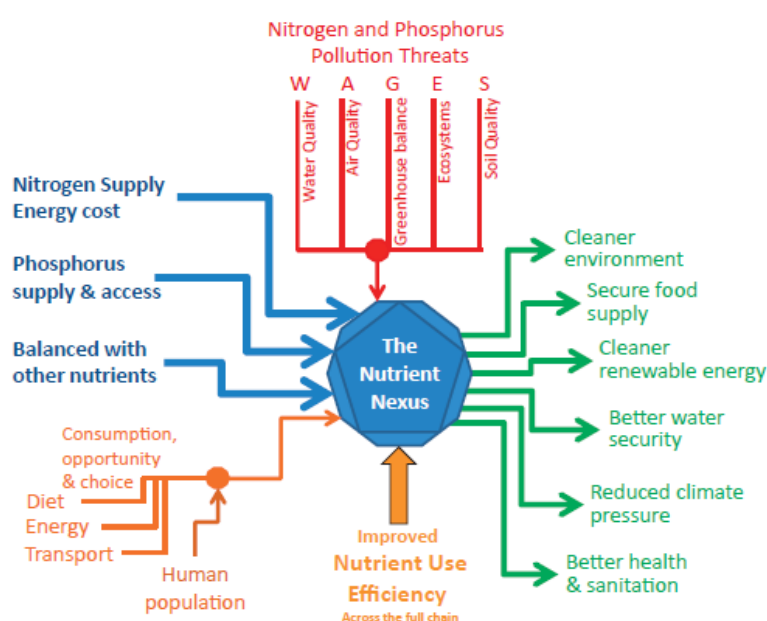


Fig. 2 The 'Nutrient Nexus' represents a key nexus point between global economic, social and environmental challenges. Improving full-chain nutrient use efficiency. Improving full-chain Nutrient Use Efficiency becomes the shared key to delivering multiple benefits (figure used from original source¹)

These abovementioned challenges are of particular interest for the EU. The EU is heavily import dependent for synthetic fertilisers such as the ore for phosphorus (P), and fossil fuel for nitrogen (N), and the provision of these results in large environmental impacts at both local, regional and global scales. It is evident from these facts, that there is an imminent need for increasing the substitution of nutrients in synthetic mineral fertiliser with waste derived nutrients originating from bio-based sources. However, current manure and bio-waste treatment technologies are costly⁶ and often not aimed towards recovery of minerals contained within, but focus on mitigating environmental pressure which often implies removal and overall loss of these nutrients. In addition to technical and cost-related issues for such recovery techniques, there also still remains a gap in knowledge and overall end-user perception for novel fertilising products recovered from biobased sources.

⁴ Kang, J et al. 2011. Phosphorus leaching in a sandy soil affected by organic and inorganic fertiliser sources. *Geoderma* 161(3-4), 194-201.

⁵ Ranatunga et al. 2013. Phosphorus distribution in soil aggregate size fractions in a poultry litter applied soil and potential environmental impacts. *Geoderma* 192, 446-452.

⁶ Velthof et al. 2013. Agronomic potential of mineral concentrate from processed manure as fertiliser. *PROCEEDINGS No: 716, Fertiliser Society*

Next to threats towards resource scarcity, there is also a nutrient flow intensity within the agricultural sector, which leads to detrimental environmental effects. The intensification of the European and global agricultural crop and livestock production is driven by the increasing demand for animal protein by a growing and wealthier world population. European livestock produces about 1,3-1,8 billion t/y of manure. Concurrently, urbanization concentrates food and biomass consumption, leading to intensified organic waste generation (estimated at around 100 million ton/year), necessitating more appropriate management and the greater recycling of valuable resources, leading to the saving of minerals and reduced energy consumption. These vast amounts of organic residues and wastes provide environmental pressure but also present an opportunity as raw resources for nutrient recovery.

As previously indicated, the production of food, feed and biomass currently relies very heavily on nutrient inputs to crops in the form of synthetic fertilisers. In the Framework 7 Project (FP7) INEMAD (www.inemad.eu), the central research idea is that in order to reconnect nutrient flows between plant production and animal husbandry, we need to invest in agro-industrial processes which can contribute in the upcycling of mineral nutrients from organic flows towards mineral fertilisers enjoying a higher nutrient use efficiency (see also picture below). Increased efficiency within agricultural system boundaries will also result in reduced dependency on the introduction of external energy and nutrients. This approach calls for the further development of a third (after crop and animal production) agro-industrial pillar to be developed in addition to and support of the two existing main pillars of agricultural activity, namely agro-residue processing and upcycling.

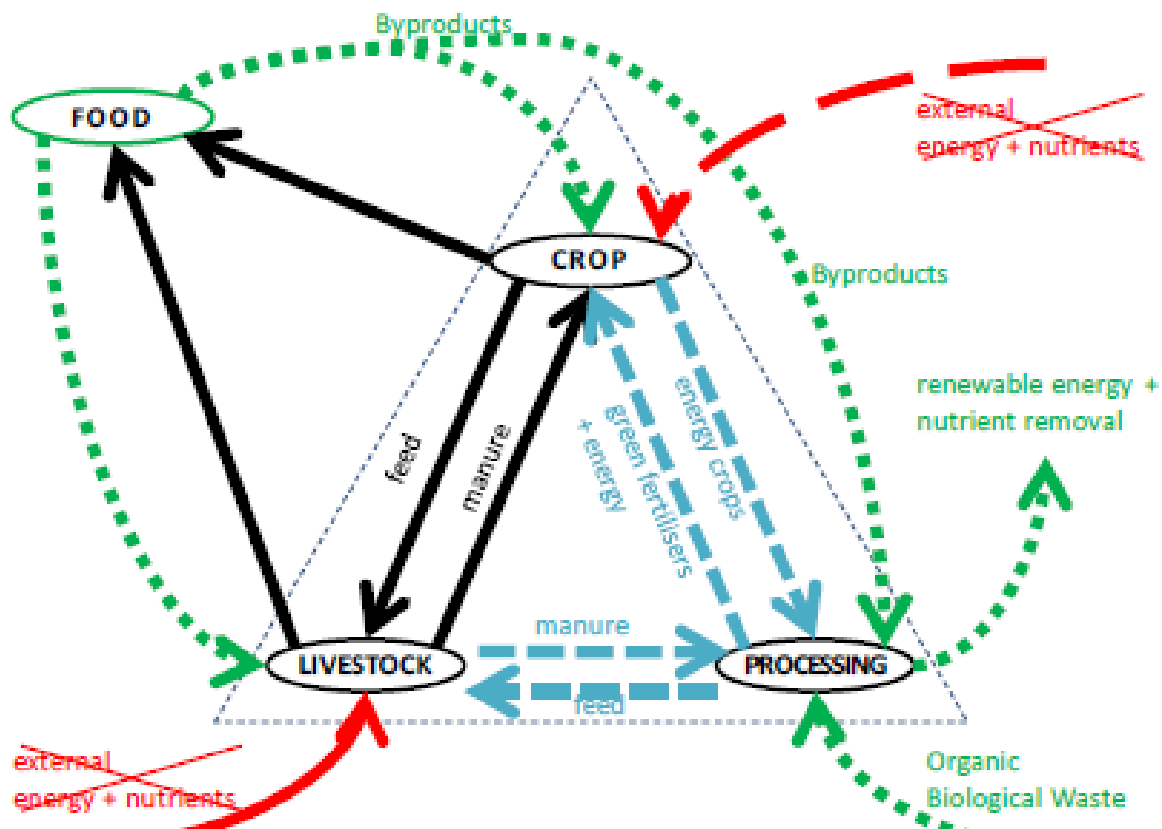


Fig. 3 Central conceptual figure of the FP7-INEMAD project, in which sustainability of the overall agricultural system is enhanced by recycling nutrients and energy via processing of manure, agro-residues and energy crops thereby reducing dependency on external nutrients and energy (www.inemad.eu)

2. Agro-processing: a third pillar in agro-industrial activities

The picture below illustrates the various process options which can 'upcycle' and recover nitrogen, phosphorus (and potassium) to higher grade end-products, characterized by higher nutrient use efficiency (NUE) in comparison to raw manure or digestates.

In this we need to add **anaerobic digestion** activities can be positioned as a key technology amongst processing systems receiving residues from agricultural activities, as digestate resulting from co-digestion of manure and/or other residues or products (e.g. energy crops) from the agro-food chain are already characterized by a higher ratio of mineral nitrogen (in the form of NH_4) in relation to total nitrogen content when comparing to the raw products. Digestate itself has already been widely described in various studies to be characterized by a higher $\text{NUE}_{\text{nitrogen}}$ than animal manure in raw form.

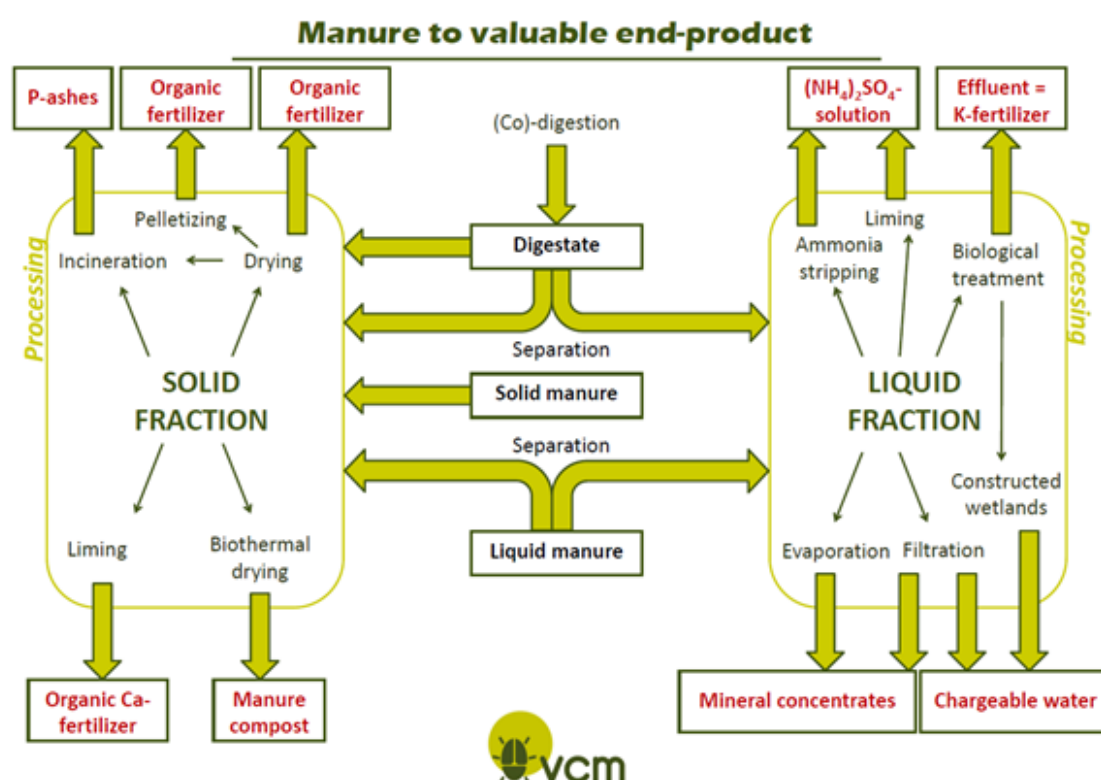


Fig. 4 Overview of manure & digestate treatment processes allowing upcycling organic residues to nutrients and organic products (www.vcm-mestverwerking.be)

Often, further product upgrading of both animal manure and digestates includes a **physical separation step** resulting in a liquid phase (80-90% of ingoing mass) and a solid phase (10-20% of ingoing mass). Dissolved nitrogen and potassium largely end up in the liquid fraction, already characterized by a higher $\text{NH}_4/\text{N}_{\text{tot}}$ ratio than the original product. Reversedly, phosphorus and organic carbon are mostly present in the solid fraction. The valorization pathways of both product fractions are described hereinafter. Liquid fraction of manure and digestate can already be considered as upgraded products from the perspective of Nutrient Use Efficiency when comparing to the raw products from which they originate. Taking this one step further, stable constructors in various EU member states have developed new animal husbandry systems in which manure and urine are already separated at the source, resulting in less emissions of methane, ammonia and odor from these stables as well as providing new products (in comparison to animal slurry) that can again act as secondary resources for organic carbon, renewable energy and nutrients.

Ammonia (NH_3) removal from nitrogen rich waste streams can be achieved via a process known as **ammonia stripping / scrubbing**, involving two steps: (i) first, the NH_3 (ammonia) is removed (stripped) by transferring volatile ammonia from the raw slurry or wastewater into the air, (ii) subsequently to be followed by recapturing this ammonia back to liquid form (ammonium, NH_4^+) by washing (scrubbing) the ammonia saturated air in a strong acidic solution. Due to economic reasons, most often H_2SO_4 is used as an acidic solution. Ammonia can also be removed with other acids such as HCl , HNO_3 and H_3PO_4 . The reaction of NH_3 with sulphuric acid (H_2SO_4) or nitric acid (HNO_3) results in ammonium sulphate ($(\text{NH}_4)_2\text{SO}_4$) or nitrate (NH_4NO_3) that can respectively be used as a N:S or N-fertilisers. This end-product of ammonia stripping and scrubbing process is already recognized in Flanders and the Netherlands as a mineral fertiliser in environmental and fertiliser legislations. This product contains around 5% of N which is completely available in $\text{NH}_4^+\text{-N}$. Next to removal of NH_3 from waste streams after stripping, NH_3 can also be recovered from airwashing linked to livestock or manure operations such as stables, separation, composting and drying units.

As compared to end-product of ammonia stripping and scrubbing where entire recovered N is available in its mineral form, the liquid fraction of animal manure or digestate still contains significant amounts of organic N. In order to further increase $\text{NH}_4^+/\text{N}_{\text{tot}}$ ratio, liquid fraction can be subjected to **membrane filtration process** where the waste stream is forced through the membrane by means of pressure. The product that is retained on the membrane is called concentrate. There are several types of membranes used in manure/digestate processing: microfiltration (MF; pores $> 0,1 \mu\text{m}$, 0,1-3 bar), ultrafiltration (UF; pores $> \text{nm}$, 2-10 bar) and reverse osmosis (RO; no pores, 10-100 bar) membranes. In a MF-concentrate suspended solids are retained, while in a UF-concentrate also macromolecules are retained. Both filtration steps can be used as a pre-treatment for RO, in order to prevent that either suspended solids or macromolecules block the RO-membrane.

Phosphorus precipitation is a reaction where phosphate salts are formed by addition of several ions to a solution containing soluble P (ortho-P). This P recovery strategy has been implemented at full-scale for wastewater, (digested) sludge and manure treatment. In conventional wastewater treatment systems, P is removed by adding soluble Fe- or Al-salts. However, Fe- & Al-phosphates are notorious for low solubility and low plant-availability and generally not seen as valuable P-fertilising products. Over recent years, more emphasis is placed on precipitate products such as struvite (MgNH_4PO_4), K-struvite ($\text{K}_2\text{NH}_4\text{PO}_4$) or Ca-phosphates as more valuable sources for secondary P.

Solid fractions of organic residues generally undergo either biothermic drying, chemical drying, thermal drying step or a chemo-thermic conversion. Under **biothermic drying** we understand conventional composting in which microbial processes heat up the substrate (also hygienising it). **Chemical drying** can be achieved by adding CaO , resulting in a temperature rise and hygienisation. The CaO is converted to CaCO_3 increasing the buffer capacity and liming potential of the end-product. Under chemo-thermic conversion processes, **incineration** is the most well-known. This will result in an ash fraction devoid of organic matter but enriched in mineral components. Depending on the nature and origin of the organic residue being processed, the incineration ashes may require additional process steps. Another type of chemo-thermic process, is **pyrolysis** which is basically the combustion of organic matter yet under oxygen deficient conditions, producing an oil (pyrolysis oil) a char product (biochar) and a gaseous phase (syngas). Finally, a third chemo-thermic conversion technique is gasification, which also takes place under oxygen deprived conditions resulting in the formation of hydrogen gas (H_2) and methane (CH_4) from organic matter rather than producing CO_2 as would be the case for oxygen saturated incineration. However, just as with incineration a mineral rich ash residue remains which can serve for nutrient recovery.

Ashes remaining after incineration or gasification of organic waste contain P-, K-, Al- and Si-compounds and possibly also some heavy metals such as Cu, Zn and Cd. **P extraction from such ashes** has been tested extensively for dried or dewatered sludge and ashes from sludge incineration. Recent research has also been focusing on extraction P from solid fractions of manure and digestate via acidification.

3. Key issues with novel biofertiliser products

Digestate, liquid fraction and solid fraction

The three tables below represent observed minimum, 10%-percentile, average and 90%-percentile values for digestate (A), liquid fraction of digestate (B) and solid fraction of digestate (C) sampled across Europe (ref. European Biogas Association, EBA). Although digestate products are in general nutrient rich, enjoying an increased nutrient availability due to mineralization within the anaerobic digester, also a high variability is observed. This applies both when we compare products within the larger population of samples but also within any given installation variability can be observed over the course of operations when fluctuating / varying in the feedstock input.

Table 1 : composition data on digestate throughout EU (Kirchmeyr, F., EBA database, 2016)

		Min	10 % quantil	average	90 % qunatil		
A	[%]	DM	0	3	6	9	
	[% of DM]	VTS in DM	1	55	69	82	
		N _{total}	0,3	5	10	18	
		NH ₄ N	0,03	2	6	13	
		K ₂ O	0,1	2	5	8	
		P ₂ O ₅	0,05	2	3	5	
	[% of FM]	C _{org}		0,6	2	3	
		N _{total}		0,13	0,3	0,5	
		NH ₄ N		0,04	0,2	0,4	
		K ₂ O		0,06	0,14	0,23	
		P ₂ O ₅		0,05	0,1	0,15	
	Liquid fraction of separated digestate n > 100						
	B	[%]	DM	0,2	1,7	5,4	8,9
		[% of DM]	VTS in DM	30	55	68	79
N _{total}			1,8	6	12	19	
NH ₄ N			0,3	3	7	14	
K ₂ O			0,9	5	10	13	
P ₂ O ₅			0,05	2	3	5	
[% of FM]		C _{org}		0,37	1,5	3	
		N _{total}		0,1	0,2	0,3	
		NH ₄ N		0,05	0,1	0,2	
		K ₂ O		0,08	0,17	0,22	
		P ₂ O ₅		0,02	0,05	0,08	
Solid fraction of separated digestate n > 100							
C		[%]	DM	9	20	39	86
		[% of DM]	VTS in DM	15	52	74	91
	N _{total}		1	2	3	5	
	NH ₄ N		0	0	0,4	1	
	K ₂ O		0,2	0,8	3	7	
	P ₂ O ₅		0,5	1	3	6	
	[% of FM]	C _{org}		4	11	31	
		N _{total}		0,35	0,6	1	
		NH ₄ N		0,01	0,1	0,2	
		K ₂ O		0,15	0,5	1	
		P ₂ O ₅		0,2	0,6	1	

The tables (Table 1) above are indicative of the potential but more so illustrate one of the biggest challenges in adopting mineral fertilising products from digestates : product variability both between different installations as well as variability observed within a single installation decrease the end-user appreciation of the produced products. This observation is also applicable to other organic raw resources such as manure and organic wastes. **One of the key challenges in the road ahead will be to be able to formulate stable products within acceptable ranges of variability.**

An old English saying states that “The proof of the pudding is in the tasting”. The same applies for assessing full potential value of biobased fertilisers. Only when the proof-of-principle is adequately provided that such products can provide (A) equal yields (~ effectiveness) with (B) equivalent nutrient losses (~ efficiency) than fossil-based mineral fertilisers, we can consider them as worthy amendments/substitutes for such products. Under the BioRefine project (www.biorefine.eu), the Ghent University (BE) published a report comparing all field trials that have taken place in Flanders over recent years, that compare novel mineral fertiliser products with conventional fertilisation scenarios. In this report, a wide range of crops was assessed (cauliflower, rye, maize, potato, lettuce, fruit orchards,...) with a wide range of products (scrubber water, digestate, liquid fractions of manure/digestate, struvite, membrane concentrates,...).

The majority of these field trials support the hypothesis that nutrients in organic matrices can be successfully upgraded to mineral fertiliser standards as based on observed yields, calculated nutrient mass balances (and nutrient use) as well as on post-harvest nitrate residues in the top 90 cm of the soil (as indication of unused nitrogen and hence risks for leaching). The future challenge for as deduced from these research trials lies predominantly in achieving stable and predictable products in regards with product composition.

Also in other EU member states considerable attention has been placed on field-scale proof-of-concept as well as demonstration fields in order to provide insights to farmer stakeholders. **There is a distinctive need to compile field experience from across the EU in a single comprehensive overview.**

In addition to quality assurances for biofertilising products, from the perspective of nutrient use efficiency perspective, there is also a pre-requisite to provide necessary guarantees towards the absence of unwanted components. For example, the absence of **viable seeds of weeds** and **potential pathogens**, allowable limits towards **trace elements** (which can be further divided into elements essential (Cu, Zn) or non-essential (Cd, Pb,...) to life), **anthropogenic organic compounds** (e.g. pharmaceuticals), and **relative ratios of chemical elements** in the products in general (e.g. Na:K:Ca:Mg and N:P:K in general; S:N in scrubber waters ;...).

Quality aspects of new products can also provide added values which need to be understood and highlighted better. For example, presence of Cd and As can play a role in conventional P fertilisers originating from phosphate rock but these problems are of less risk in P-fertilisers retrieved from manure, digestate,... Also, organic carbon in fertilising products has additional soil fertility increasing aspects on top of merely providing plant available minerals. Recent studies comparing soil organic carbon to crop response curves (yield versus soil organic carbon) have been used to put a value on organic matter. Depending on product under evaluation, the organic carbon value in fertilising products can actually surpass the value of minerals. Finally, although the mixed presence of a wider range of minerals may appear as a burden for example when formulated and predictable application of mineral nitrogen is envisaged, but considering that Cu, Zn, Na, K, Ca, Mg, S,... are also essential plant nutrients required in an equilibrated fertilisation scheme these compounds by themselves do not detract from the



value of such products. In essence also for 'extra nutrients' it all comes down to having (or creating) the right ratios in comparison to actual crop requirements and to be able to predict and guarantee product composition (stability \leftrightarrow variability).

Field scale assessments on environmental aspects have been focusing on nutrient efficiency and avoiding losses to the environment (e.g. via mass balances and nitrate residue measurements in the soil), but have also included estimations on reduced carbon footprint of arable farming when switching from fossil based mineral fertilisers to biobased products⁷.

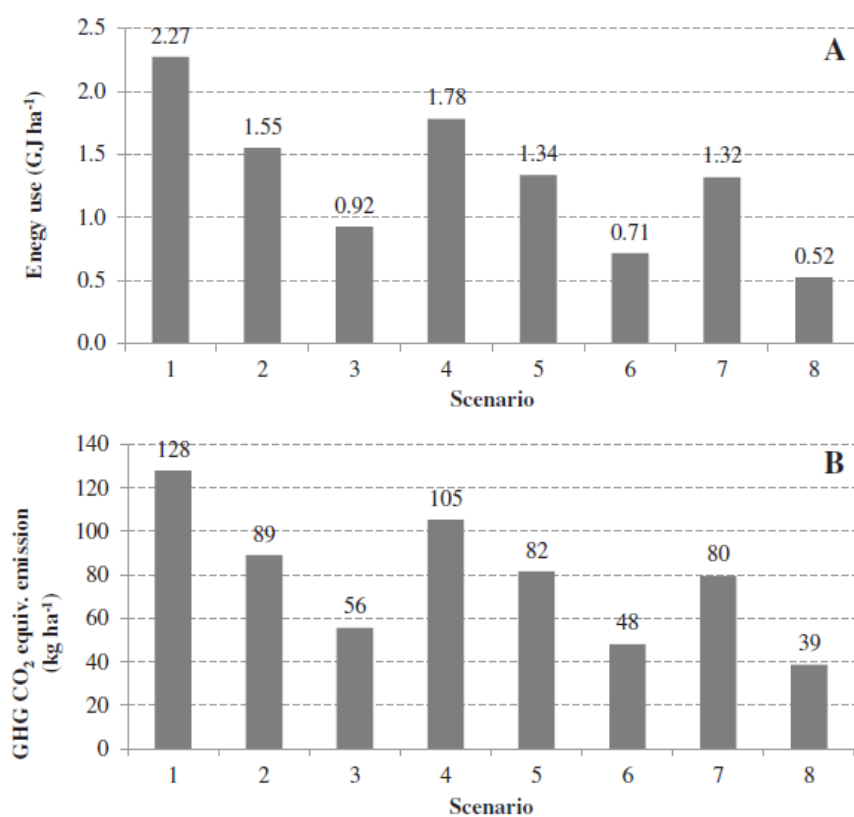


Fig. 5. Energy use (GJ/ha) and GHG (CO₂ eq ; kg/ha) for eight fertilisation scenarios under study (maize) : 1. Raw animal manure and synthetic fertiliser (conventional ; Reference treatment) ; 2-3 substitution of synthetic N fertiliser by NH₄-scrubber water from airwashing of stables (2. partial); 4. Substitution of animal manure by a mixture of digestate/liquid fraction (LF) of digestate (yet retaining mineral fertiliser) ; 5-6. Substitution with combination of NH₄ scrubber water, digestate and LF of digestate (5. Partial), 7-8. Substitution by liquid fraction of digestate⁷ (7. partial). *Note: in scenario's 2, 5 and 7 substitution of mineral fertilisers is partial, in scenario's 3, 6, 8 substitution was complete*

In addition, avoided costs for mineral fertiliser usage when switching to biobased products have been evaluated from the perspective of arable farmer as well as the owner of biobased streams such as digestate and/or manure. Under the current EU logic, manure and digestate receive a negative product value in nutrient pressure regions as stringent fertilising regulations have resulted in a scarcity of available land for applying organic fertilising products, even though in such regions fossil-based mineral fertiliser utilization is on the rise to compensate for crop requirements. Nonetheless, several studies describe positive product value of new derivatives when considering nutrient replacement value as well as impact of organic carbon on soil fertility and crop response curves.

⁷ Vaneckhaute, C., Meers, E., Michels, E., Buysse, J., Tack, F.M.G. (2013). Ecological and economic benefits of the application of biobased mineral fertilisers in modern agriculture. *Biomass & Bioenergy*, 49, 239-248.

In addition to increased environmental sustainability at the level of fertilisation, processing agro-residues enjoys significant positive effects in regards with carbon foot printing by (i) avoided methane emission from manure storage when processing manure as fresh as possible via anaerobic digestion and (ii) producing renewable energy from manure and other residues. At the COP21 event(s), the European Biogas Association (EBA) published a policy paper indicating the significant gains in CO₂ abatement that could be achieved when adopting a dedicated manure digestion policy that focuses on increasing nutrient use efficiency and therefore nutrient recycling from animal husbandry residues.

When shaping visions for biobased fertilising products for modern agriculture we will need to distinguish between (i) finding **biobased mineral fertilisers** that can act as replacements for their fossil resource based counter parts and (ii) **biobased organic fertilisers** which have the addition of organic carbon as added benefit, yet likely at the expense of lower nutrient use efficiency in comparison to products consisting solely or mainly of mineral compounds. In the end, **farmers will play a key role in the coming transition: they will need to be driver for products to comply better with crop requirements.** This may imply moving towards a market model in which biofertiliser products are tailor-made to suit specific local requirements rather than continue as bulk products with take-it-or-leave-it composition. Researchers will need to provide product effectiveness (towards crop yield) and efficiency (towards avoiding losses to the environment), whereas policy makers will need to implement frameworks that allow both market creation and market uptake.

4. Challenges in the road ahead

The text box below indicates the tasks that the AGRI Focus Group should address.

- **Identify relevant techniques** (e.g. composting, bio-digestion, etc.) to process livestock manure and other organic sources and **assess the agronomic and environmental value of the derived products** (e.g. nutrient availability, quality, impacts on soils, contaminants, etc.).
- Contextually, **identify tools and instruments** to help farmers to measure the nutrient content (and availability for crops) and recommendations for the application of these products.
- **Analyse economic and technical factors** (e.g. livestock management practices, sanitary aspects, etc.) that stimulate or limit the use of these products in agriculture and **indicate how to address them** exploring the role of innovation and knowledge transfer.
- **Illustrate possible strategies** to adapt derived products to market demands (e.g. development of quality standards) and successful business cases that exist at farm level, local and regional scale.
- **Identify research needs from practice, possible gaps** in technical knowledge, and further research work to address them.
- **Suggest innovative solutions and provide ideas** for EIP-AGRI Operational Groups and other innovative projects.

The figure below provides a holistic view on nutrient recycling within and between major agricultural activities and can function to settle thoughts and suggestions on how to acquire the goals set in front of us.

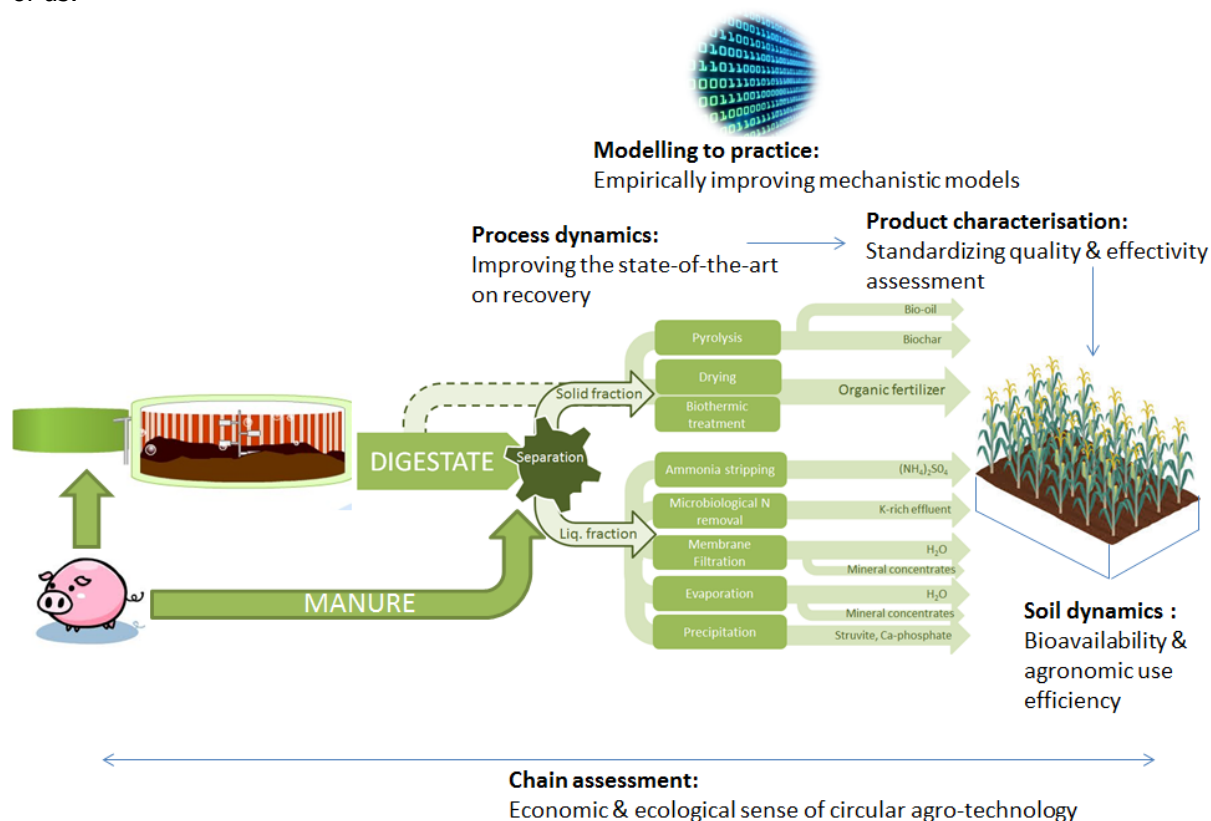


Fig. 6 Overview of the value chain of nutrient recovery from manure and digestate (also extendable to organic waste management chain) and research domains involved