EIP-AGRI Focus Group - Nutrient recycling

Assessing the environmental effects of nutrient recycling from organic materials used as fertilisers

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1. Introduction

The advances in agriculture in fertiliser use, fertiliser production and mechanisation since the late 19th century have dramatically improved crop and livestock yields, improving food security and nutrition across the globe (Cordell *et al.* 2009, Smil 2004). The increased agricultural production has been achieved largely by utilising resources which were not available for farming before, like dinitrogen, phosphate rock and fossil energy. However, the production, transport and application of these additional inputs cause wide ranging problems in the environment; climate change, acidification, eutrophication, air pollution – to mention a few. At the same time the volatility of fertiliser prices and the geopolitics of the non-renewable phosphate resources coupled with Europe's dependency on import is becoming a concern (Schoumans *et al.* 2015).

Improving the resource use efficiency of the food system can alleviate environmental and food security problems at the same time. Optimising the use of existing resources is an important goal. Just as critical is increasing the rate of nutrient – particularly nitrogen and phosphorous – and energy recycling from so far "unharvested" flows in the farm and in the wider food system. To that extent expanding our nutrient recycling rates from organic materials in agriculture and along the food chain offers opportunities to reduce the cost and mitigate the negative environmental impacts of agricultural production.

Increased recycling of these streams has its own challenges, like storage and transport of bulky material such as slurry, collection of material from dispersed sources like human urine from households, or removal of toxic materials from nutrients recovered from sewage. The environmental impacts and costs of the alternative processes and products are inherently different from each other and also determined by circumstances. For example while the additional costs and effort of introducing urine diverting toilets as opposed to traditional toilets in a rural area might be lower than the costs of retrofitting an existing urban sanitation system. The environmental impacts of plant-derived organic fertilisers (green manure) might feature a trade-off between a reduction in synthetic nitrogen use and an increase in land occupation for human purposes, while anaerobic digestion of manure emits less GHG compared to conventional storage and spreading of the manure at the expense of reduced availability of soil improving carbon in the digestate applied on fields.

To contribute to future decisions on options to recycle organic material into fertilisers this paper introduces the most important environmental effects of the recycling processes and recycled products and offers a summary of selected tools and models which could be used for the environmental assessment of these options. Relevant research and development projects are also described and ideas for research and practical implementation for operational groups are suggested. The paper focuses on processed fertilisers and soil improvers based on recovered and recycled organic materials which have the potential to become (or are already) commercial products.

2. Recycled organic fertilisers: raw materials, processing and products

Most organic materials can be considered as raw materials for nutrient recovery and recycling purposes. Livestock related raw materials include animal excreta, which has traditionally been utilised as a fertiliser in its raw or composted form. Depending on how the excreta is collected and stored (i.e. as liquid slurry or in solid form, like farmyard manure and poultry litter) it can contain additional materials, such as wastewater from the yard, bedding material or waste feed. The nutrient content and physical properties of the mixture affect how it can be further processed. Though excreta is already valuable in raw form, further processing can add value to these materials. The processing can create products which are cheaper to transport, benefiting particularly in areas of high livestock density with constrained agricultural land application. The processing can involve one or more techniques, from more traditional composting to a combination of anaerobic digestions and highly sophisticated digestate treatment.

Composting, a traditional process, can produce a stable material which can be stored for longer periods and due to its high organic carbon content is a good soil enhancer. It requires considerable fibrous material input, therefore it is used to treat farm yard manure as opposed to liquid excreta. Green manure, crop residues, food waste and animal processing by-products are often composted too.

In anaerobic digestion microbes break down the organic material and produce high methane content gas and a nutrient-rich residue called digestate. The biogas is used for electricity and heat production, while the nitrogen and phosphorous content of the digestate makes it a valuable fertiliser. However, just like slurry, digestate can be problematic to be spread in nearby agricultural land. Enhancement techniques help in adding value to the digestate via making it more transportable and/or improving its quality. Frischmann gives a detailed summary of the enhancement techniques, including composting, separation, pyrolysis and acidification (2012) (Figure 1). Most of these processes are not only applicable to digestate but also to raw forms of organic materials.

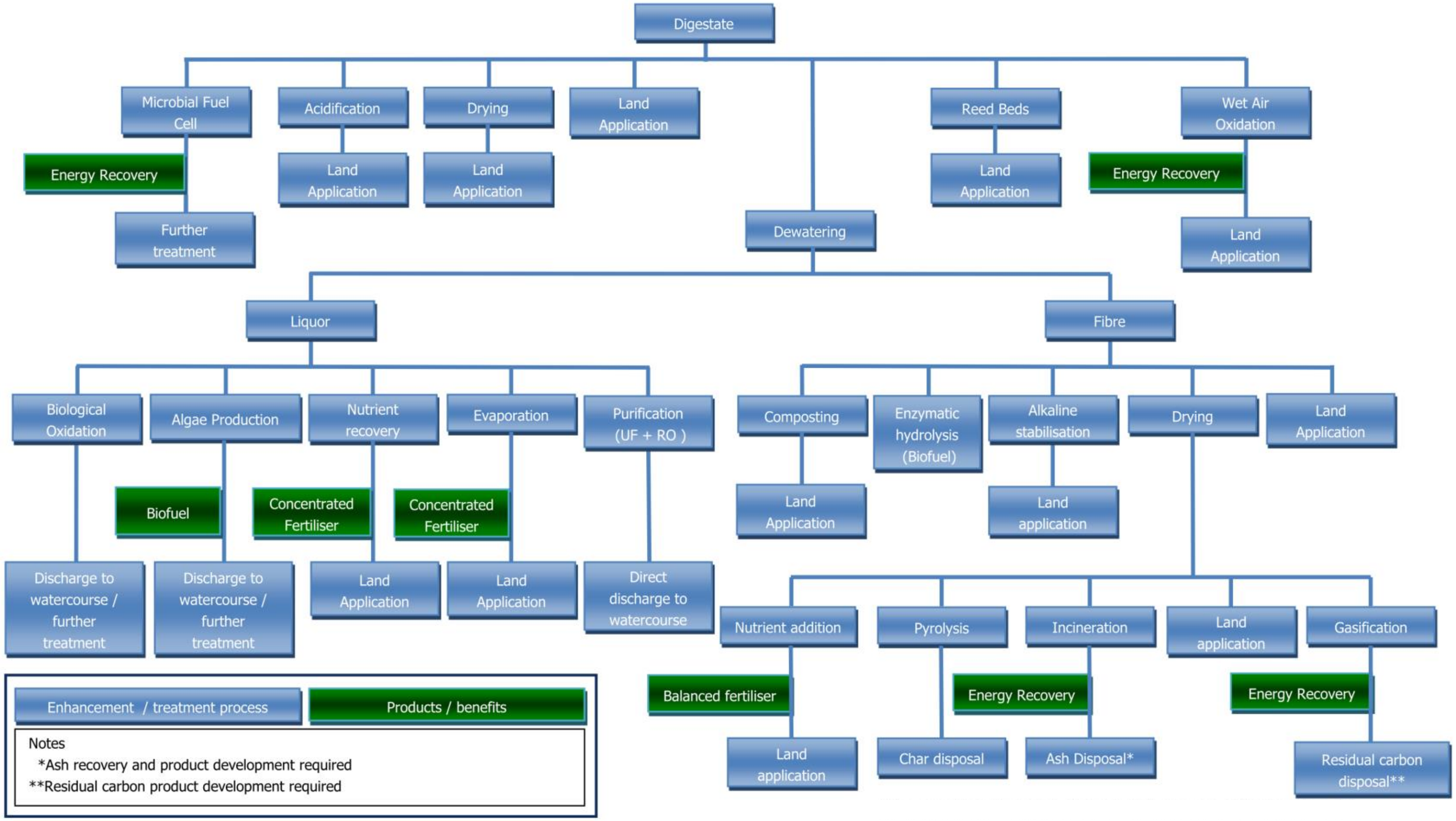

Figure 1 Overview of digestate enhancement and treatment techniques (Frischmann 2012)

A further potential nutrient source of livestock operations is the ammonia gas in livestock houses, which can be a valuable raw material for fertilisers. Air scrubbing, a commercial technology, captures ammonia in a water soluble compound form, and the resulting nitrogen rich liquid can be either used straight on the farm or in a further processed into a liquid or solid fertiliser form.

Materials of slaughterhouse origin, like bones, blood, fur and feathers have very high nutrient (mostly nitrogen) content. Materials classified as category 1 type[1] (e.g. carcasses suspected of transmissible spongiform encephalopathy infection) cannot be re-used, though the processed remains can still be utilised in energy production (BBC 2016), or alkaline hydrolysis, a new technology, can break down the material into small molecules with a potential of further processing (Franke-Whittle and Insam 2013). Low risk slaughterhouse materials are further processed, often to produce bone, meat, blood or feather meals to be used as animal feed or organic fertiliser. The nutrient content of these depends on the raw material, bone meal being very high in phosphorous, while blood meal, feather meal and meat and bone meal have high nitrogen content. The animal by-products can also be treated in composting or anaerobic digestion facilities. The energy gained from the materials can power the slaughterhouse (Biogas Research & Consulting Group 2016), while the digestate can be used as a fertiliser.

Crop residues (including harvested plant parts, like straw), are valuable source of fibre, energy and nutrients. Harvested crop residues are utilised in many different ways. If used as animal bedding or animal feed (particularly in poorer countries), eventually most of the nutrient content of the residue is added back to the soil, improving the soil quality and providing nutrients to crops in the following years. Competing for the carbon content of the residues, anaerobic digesters utilise the residues' energy content, producing nitrogen rich digestate, while cellulose-based processing turns crop residues into fuel (ethanol) or raw material for plastics. The crops residues remaining on the field are mostly ploughed in to utilise their nutrient content as fertiliser and soil enhancer.

Purpose grown biomass crops are utilised for their carbon content to produce energy or chemical feedstocks. The conversion processes are varied, and include thermo-chemical conversion (combustion, pyrolysis, gasification and liquefaction) and bio-chemical conversion (anaerobic digestion and fermentation (i.e. ethanol production)). The residues from the bio-chemical conversion processes can be further utilised, among other purposes, for their nitrogen and other nutrient content. Further sources of organic material suitable for fertiliser production include materials of aquatic source, like seaweed and fish waste, by-products from the food industry, kitchen waste, sewage sludge from wastewater treatment plants and human excreta.

As seen above, recycling organic materials as fertilisers and/or soil improvers can be a very simple process of animal excretion on fields or ploughing in crop residues, or can involve multi-step processes, often at an industrial scale. Certain organic materials can only be utilised as fertilisers if processed, like gaseous ammonia which needs to be converted to non-volatile and transportable form, or slaughterhouse waste requiring sterilisation and digestion. Others (e.g. slurry) can be used directly – however, even these can benefit from processing, improving their marketability. The conversion processes range from traditional methods, like composting, to newly developed technologies, such as air scrubbing. Processing can ensure that the material's chemical characteristics are desirable (e.g. standard nutrient content, stability over time), it does not contain pathogens, pests/weeds or toxic materials in excess of regulatory thresholds, it is easily transportable and it is easily applicable. The less processed products might be cheaper to produce and more suitable for smaller scale use, while the highly processed products could be of more reproducible quality. **Table 1** provides some examples of recycled organic fertilisers.

[1] Regulation (EC) No 1069/2009

Table 1 Examples of marketable recycled organic fertiliser and soil improver products

Product	Short description	Possible raw materials and processes	Status and examples
Compost	A mixture of organic matter that has decayed or has been digested by organisms, used to improve soil structure and provide nutrients.	Raw material: manure, crop residues, food waste, etc. Processes: composting	Commercial www.compostdirect.com biocompostajes.com
Vermicompost	Compost made through the use of worms that break down of organic material	Raw material: manure, crop residues, food waste, etc Processes: composting	Commercial Vermican Composting Solutions
Liquid phase of separated slurry or digestate	Liquid phase of animal slurry or digestate from anaerobic digestion, rich in nitrogen	Raw material: slurry / digestate Processes: solid-liquid separation	Mostly used on the same farm
Solid phase of separated slurry or digestate	Solid phase of animal slurry or digestate from anaerobic digestion, rich in carbon and phosphorous	Raw material: slurry / digestate Processes: solid-liquid separation	Mostly sold locally
Digestate from manure, herbaceous material and food waste	Material remaining after the anaerobic digestion of manure	Raw material: manure / food waste / straw, corn stover, etc. Processes: anaerobic digestion (pre-processing, like depacking, pasteurisation might be required)	Commercial pural.es www.anaergia.com/services/agri-food www.geneco.uk.com/Food-waste-recycling/Process.aspx
Nutrient-rich fertiliser from the liquid fraction of digestate	Using heat exchanger to concentrate the liquid fraction of the digestate	Raw material: food waste, animal manure, organic sludge Process: anaerobic digestion and evaportation	Commercial http://sse.com/whatwedo/ourprojectsandassets/renewables/barkip/
Granular organic fertiliser from digestate	Digestate-based organic fertiliser pellet with consistent particle size and nutrient content	Raw material: food waste, sewage sludge Process: anaerobic digestion, thermal drying, nutrient supplementation and pelletisation	Commercial MINORGA ® Bio fertiliser, Norway
Ammoninium nitrate / sulphate produced from scrubbed ammonia	Extraction of ammonia from liquid input stream in a stripping tower and its subsequent recovery through the absorption on a sulphuric / nitric acid solution in a scrubber	Raw material: liquid phase of digestate or manure Processes: ammonia desorption, ammoninium nitrate / sulphate precipitation	Commercial geostream.it/es/2014/07/ammonia-stripping-and-recovery-plant www.dvoinc.com
Bone meal fertiliser	Ground animal bones to be used mainly as a phosphorous source (also used as animal feed)	Raw material: bones	Commercial www.sinclairpro.com
Feather fertiliser	Ground poultry feathers be used mainly as a slow release nitrogen source (also used as animal feed)	Raw material: feathers	Commercial waltsorganic.com/product/feather-meal
Biochar	Biochar is charcoal made from biomass via pyrolysis and used as a soil amendment	Raw material: biomass Processes: pyrolysis	Commercial www.carbongold.com biochar.co.nz
Struvite	Phosphate mineral that can be crystallised using nitrogen and phosphorous rich liquids	Raw material: wastewater, liquid phase of digestate or manure Processes: struvite crystallisation	Commercial, but restricted in some member states Berliner Pflanze, Crystal Green from Ostara
Plant based fertiliser	Plant extracts or by-products of plants. The plants might be grown for fertiliser production	Raw materials: alfalfa, corn, etc. Processes: composting / fermentation, pulverisation	Commercial Alfalfa meal, cottonseed meal
Seaweed / microalgae based fertiliser	Seaweed extracts or by-products of seaweed /microalgae	Raw materials: seaweed / microalgae Processes: composting, / fermentation, pulverisation	Commercial www.bionova.nl/grow-products/algaemix
Human urine based fertilisers	Collected urine is used locally, but commercial product is not available	Raw material: urine Processes: collection, sanitisation	Experimental https://mysare.sare.org/sare_project/ONE13-188/?page=final
Organic waste recycling service	A service of matching waste deposit needs with nutrient needs of land	Raw material: kitchen, municipal, food industry waste Processes: might involve a variety of processes (e.g. digestion, composting, dewatering)	Commercial Veolia pandaenvironmental.com/Food-Waste-Recycling-and-Organic-Waste-Recycling.htm

3. Assessment of the environmental effects

The environmental effects of recycled organic fertilisers can be described against the counterfactual, i.e. what would have happened with the organic material otherwise and what fertiliser would have been used instead of it. For example, the nitrogen in the ammonia captured by an air scrubber would likely be discharged to the wastewater system, but often competing uses exist for raw materials, e.g. the straw used for anaerobic digestion could be used as animal bedding and eventually composted. Against this background the production processes, transport and application of the organic fertilisers need to be evaluated to obtain a full picture of environmental sustainability.

As the most important components of fertilisers and soil improvers are nitrogen, phosphorous and carbon, the environmental impacts are mostly associated to these chemical elements and their reactive forms. The effects include either improving or worsening global warming, acidification, eutrophication, soil quality, and also human health, food security and animal welfare. As organic fertilisers usually replace synthetic ones, on that account they reduce reactive nitrogen emissions and energy use associated with synthetic fertiliser production. Controlled storage of livestock manure and food waste, particularly in anaerobic digesters, greatly reduces methane emissions too. At the same time the processes involved in the recycled organic fertiliser production might be energy intensive, and purposefully grown crops would usually compete with crops grown for food and feed. Finally, especially if wastewater, slaughterhouse waste or human urine is used heavy metals, organic pollutants and pathogens can pose a risk. The direction and magnitude of these impacts at the life cycle stages of the products are different, therefore trade-offs are inevitable.

Comprehensive sustainability assessment methods and tools have been developed to deal with a large variety of impacts (Finnveden and Moberg 2005, Ness *et al.* 2007). When the interest is the impacts associated with the product itself, life cycle assessment (LCA), life cycle costing and product material/energy flow analysis are commonly used tools, looking at effects from the sourcing of raw materials to the disposal of the waste products. To estimate the environmental effects of processes and projects environmental impact assessment and sustainability impact assessment can also be used beyond LCA. Here we briefly introduce some LCA tools, as LCA methodology has well-established and widely used protocols[2] and is recommended by the European Commission for assessing the environmental footprint of products and organisations (European Commission 2013).

LCA covers environmental, human health and resource depletion, for example the environmental categories of the EC recommendation are the following: (i) climate change, (ii) ozone depletion, (iii) freshwater ecotoxicity, (iv) human toxicity – cancer effects, (v) human toxicity – non-cancer effects, (vi) particulate matter, (vi) ionising radiation, (vii) photochemical ozone formation, (viii) acidification, (ix) terrestrial eutrophication, (x) freshwater eutrophication, (xi) marine eutrophication, (xii) land use, (xiii) water resource depletion and (xiv) mineral, fossil, & renewable resource depletion. Alternative impact classification exists, for example the UNEP/SETAC framework[3]. The environmental impacts of recycled organic fertilisers affect almost all the categories mentioned above (Table 2).

[2] Guiding ISO standards: ISO 14040:2006 and ISO 14044:2006
[3] www.lifecycleinitiative.org

Table 2 Environmental pollutants and resource use as related to LCA impact categories in the EC recommendation

Environmental pollution and resource use	LCA impact category
Nitrogen pollution (including ammonia, nitrogen oxides and nitrous oxide emissions to air, nitrate leaching to water)	(i) climate change, (iv) human toxicity – cancer effects, (v) human toxicity – non-cancer effects, (vi) particulate matter, (vii) photochemical ozone formation, (viii) acidification, (ix) terrestrial eutrophication, (x) freshwater eutrophication, (xi) marine eutrophication
Phosphorus pollution	(ix) terrestrial eutrophication, (x) freshwater eutrophication, (xi) marine eutrophication
GHG (nitrous oxide, methane, carbon dioxide) emissions	(i) climate change
Toxic compounds	(iii) freshwater ecotoxicity, (iv) human toxicity – cancer effects, (v) human toxicity – non-cancer effects
Energy and resource use	(xiii) water resource depletion and (xiv) mineral, fossil, & renewable resource depletion
Land use	(xii) land use

A choice of LCA software tools are available for assessing the environmental impacts[4], some of them are widely adopted and standardised, others are more specific with better suitability for certain circumstances or questions. LCA software tools utilise either built in or stand-alone LCA databases[5]. The tools and databases normally cover all sectors, though some of them specialise in the agricultural sector, like FeedPrint (Vellinga *et al.* 2013), Agri-footprint®[6] and the GLEAM tool[7] (Gerber *et al.* 2013). The tools and datasets also differ in the impacts covered, for example the GLEAM tool estimates only greenhouse gas emissions and the USETox model focuses on characterizing human and ecotoxicological impacts of chemicals (Rosenbaum *et al.* 2008).

Impact estimates for recycled organic fertilisers and soil improvers are available only to a very limited extent in the databases (e.g. feather meal in FeedPrint). Additionally, some research has been conducted which can be accessed in scientific publications. For example, the P-REX project developed an LCA method to assess the impacts (electricity, fuel and chemical use, product yield and quality (heavy metal content), substitution of mineral fertilizer production, side effects) of nutrient recovery from wastewater and used it for ten case studies (Remy *et al.* 2015). Partially relevant LCA assessment are also available for some raw materials, seaweed being one example, as research is more abundant on its use as for biofuel production (Aitken *et al.* 2014, Langlois *et al.* 2012). Similarly, certain processes, like anaerobic digestion of organic waste materials, have been assessed in numerous projects; information from such work can help in assessing products based on digestates. However, the lack of full assessment of recycled organic fertiliser products eventually necessitates calculating the impacts of the processes and products for the individual cases.

4. Conclusions

Advancing the nutrient recycling from agricultural and food waste and by-products is an important way of improving the sustainability of our food system. Nitrogen, phosphorous and carbon are key elements in plant nutrition and soil quality and are abundant in organic waste and by-products. These nutrient sources could be utilised to a larger extent by further processing and transformation towards commercial fertilisers in circumstances where there are barriers to using the raw products as fertilisers. Nevertheless, the environmental benefits can be confounded with adverse effects, particularly if the raw materials are already utilised at a high level in the food recovery hierarchy (EPA 2016), e.g. as livestock feed, or if some of the raw materials are produced primarily for the purpose of organic fertiliser production, competing for scarce resources like land and water. Consequently, comprehensive assessment is required to estimate whether a production process and product contributes to sustainability. The LCA framework is a useful methodology in that respect; as off-the-shelf solutions do

[4] See e.g. www.buildingecology.com/sustainability/life-cycle-assessment/life-cycle-assessment-software

[5] See e.g. www.openlca.org/lca-data, http://eplca.jrc.ec.europa.eu/

[6] www.agri-footprint.com

[7] www.fao.org/gleam

not exist for the organic fertilisers discussed above, requiring assessment conducted by trained LCA specialists.

5. Examples of projects

- INEMAD project (**www.inemad.eu**) developed an environmental impact assessment of producing and using digestate in plant cropping systems. The environmental footprint of the digestate is based on LCA, starting from plant production, animal husbandry and finishing with manure processing in a biogas plant, assessing the emissions of nitrogen compounds and GHGs.
- The P-REX project (**www.p-rex.eu**) is developing guidelines for comparable assessment of phosphorous recovery options, quantifies the environmental impacts of phosphorous recovery technologies (recovery from ash, from sludge and through bio-solids), and develops recommendations for optimised recovery, use, and for legislation
- The REVAWASTE project (**www.revawaste.eu**) proposes the sustainable management of a broad spectrum of wastes (non-recyclable fraction proceeding from waste treatment plants and industrial, together with biomass, livestock and agro-food wastes) in an integrated plant. A specific part of this project is devoted to the production of struvite from digestate in a fluidized bed crystallizer. The demo plant is located in Botarell (Spain).
- The MIX-FERTILIZER project (**www.lifemixfertilizer.eu**) develops its action in the province of Soria (Spain). Here, the solid fraction of the digestate obtained at the biogas plant is composted with other organic wastes such as chicken manure and vegetable biomass. The liquid fraction is treated in a stripping prototype for the recovery of the nitrogen as ammonium sulphate. The project has produced a new type of fertiliser by the combination of the organic fraction and the ammonium sulphate previously obtained and a nitrification inhibitor to control the nitrogen release. Currently, the consortium is evaluating the effectiveness of these new fertilizers in controlled barley rainfed trials.
- The Spanish ECOVITA project, with the participation of a farmers association (with more than 13,000 members), aims to develop a production model where all the wastes generated by its members are converted into valuable products, as tailored-made fertilisers with struvite as base material.
- The Newfert project (**www.newfert.org**) is working on improving recovery of nutrients (nitrogen, phosphorous and potassium) for fertiliser production from agricultural and municipal waste. The project will design and test new recovery processes, modify existing industrial processes and scale up integrated systems to recover nutrients from solid and liquid biowaste.
- The DEMOWARE project (**www.demoware.eu**) focuses on wastewater reuse, demonstrating innovative technologies, advancing monitoring and control of wastewater reuse technologies and improving assessment methods.
- The Agrocycle project (**www.agrocycle.eu**) addresses the recycling and valorisation of waste from the agri-food sector, including agricultural waste value chain assessment, biofuel and fertiliser production from agricultural waste and agricultural wastewater utilisation.
- The Manure Knowledge Kiosk (**http://manurekiosk.info**) is a knowledge exchange, outreach and capacity building project on integrated manure management to improve the use of livestock manure and thus to enhance food security and reduce harmful emissions to air, soil and water.

6. Proposal for potential operational groups

- Business opportunity for human urine collection and delivery to farmers
- Manure and digestate processing as in the example cases in **Table 1**
- Tailor-made fertilisers from waste

7. Proposals for research needs from practice

- LCA of different groups of recycled and non-recycled organic sourced fertilisers used in plant production (following the EC recommended methodology)
- EU-wide group on plausible LCA methodologies for nutrient recycling (including monitoring for sound data on nutrient flows)
- Exploring the long-term effect of recycled organic sources fertilizers
- Assessing the trade-off between land use and GHG emission intensity of plant based fertilisers needs (in which areas and circumstances it is more optimal to grow plants for fertiliser production than as food or feed)
- Assessing the trade-off between the different uses of animal by-products (animal feed *vs* fertiliser production *vs* energy production)
- Up-to-date inventory data for business as usual technologies and processes. Data for conventional phosphorous fertiliser manufacturing based on fossil phosphorous rock are from 1992 and definitely out of date. Also nutrient flows for EU or national levels are based on many assumptions and not really reliable.
- Setting up quality assurance schemes for LCA assessors to enhance the comparability of LCA assessments

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