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Nutri2Cycle
Nurturing the Circular Economy

# Nutri2Cycle

# D.2.5 Final report on innovations across the five research lines

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# Abbreviations

C: Carbon

CAPEX: Capital Expenditure

CBA: Cost Benefits Analysis

EU: European Union

MBF: Manure Based Fertilisers

N: Nitrogen

N2C: Nutri2Cycle

$N_2O$: Nitrous Oxide

NDVI: Normalised Difference Vegetation Index

NUE: Nutrient Use Efficiency

NVZ: Nitrate Vulnerable Zones

OC: Organic Carbon

OPEX: Operational Expenditure

P: Phosphorus

PA: Precision Agriculture

RL: Research Line

SOM: Soil Organic Matter

SRL: Sub Research Line

TRL: Technology Readiness Level

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# Glossary

**Ammonium stripping/scrubbing:** Technology that aims to strip the ammonia from airflows by "washing" it with an acid solution. The result of the stripping is on one hand a filtered air flow (low in emissions) and on the other hand a liquid solution containing ammonium. Depending on the acid used ($HNO_3$ or $H_2SO_4$), this liquid solution is ammonium nitrate (AN) or ammonium sulphate (AS).

**Anaerobic digestion**: A series of biological processes in which microorganisms break down biodegradable material in the absence of oxygen and produce biogas.

**CAPEX:** Capital expenditure - funds used by a company to acquire, upgrade, and maintain physical assets such as property, plants, buildings, technology, or equipment.

**Digestate**: A nutrient-rich substance produced by anaerobic digestion that can be used as a fertiliser.

**Floating wetland** plants grown on liquid agro-residues: Recuperation of nutrients from liquid agro-residues by growing protein-rich floating wetland plants.

**NDVI** Normalised Difference Vegetation Index : graphical indicator from remote sensing measurements, assessing live green vegetation.

**Nitrification-denitrification:** Nitrification occurs under aerobic conditions and is the first step of biological wastewater treatment. Nitrification is a microbial process during which ammonium is converted to nitrite and then nitrate. Denitrification occurs under anaerobic conditions and is the second step in biological wastewater treatment. The nitrate (and nitrite) from the previous step is now reduced to molecular nitrogen ($N_2$) and nitric oxide. The objective of the couple process of nitrification-denitrification is the removal of reactive inorganic nitrogen from wastewater in a preferably harmless way.

**OPEX**: Operating expenses - costs a company incurs for running its day-to-day operations (rent and utilities, wages and salaries, property taxes).

**Precision farming:** A farming management concept based on observing, measuring, and responding to inter and intra-field variability in crops; concept of improving crop yields and assisting management decisions using high technology sensor and analysis tools.

**Struvite crystallisation:** Crystallization of nitrogen and phosphorus in the form of magnesium ammonium phosphate hexahydrate (MAP).

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# Executive Summary

This executive summary provides an overview of the main points discussed in the text. According to the GA the acquired number of longlist solutions (76) was reduced to 45 single studies, shortlisted in 24 sub-research lines (SRL) under five main research lines (RL). Each RL aimed to address specific research topics under different management practices and production contexts (i.e. soil organic matter and NP efficiency, the use of biobased fertilisers, precision agriculture and tools for sustainable husbandry). Each solution produced data, based on the objectives of the specific RL purpose. The data, from multi-year experiments, were made available in deliverable 2.6, which fed WP 3-4-5, while a summary of the solution's main findings and Research Line conclusions is proposed in this deliverable.

**RL1** "Innovative management systems, tools & practices for optimized nutrient and GHG management in animal husbandry" - producing data on 10 solutions - identified effective ways of reducing losses in carbon, nitrogen and phosphorous from European animal husbandry by an outright reduction in related emissions, improved nutrient efficiency of the associated animal waste, or by suggested novel uses for the animal waste.

**RL2** "Innovative soil, fertilisation & crop management systems & practices for enhanced N, P efficiency and increased soil OC content" verified the effectiveness of practices in building up soil organic carbon by organic input distribution, assessing at the same time that the effects on the environment (emissions ) are sustainable.

**RL3** "Tools, techniques & systems for higher-precision fertilization" demonstrated that precision fertilisation improves nutrient efficiency in livestock and arable systems, reducing chemical N fertilizer use by 20% and 23% respectively.

**RL4** "Biobased fertilizers (N, P) and soil enhancers (OC) from agro-residues" showcased the feasibility of BBFs against synthetic. The results of trials showed that these BBFs are feasible to be used as a replacement for mineral fertilisers due to their high nitrogen fertiliser replacement value (N-FRV) along with no significant negative impact on crop yield, nutrients uptake or soil properties. However, there are still a number of practical issues related to the ease of utilising these products (e.g. machinery / methods for land application, marketability) to be addressed.

**RL5** " Novel animal feeds produced from agro-residues " demonstrated the potential to replace non-sustainable protein sources in the feedstock with traditional or completely new sources. However, what emerged from the investigation, mainly for low TRL solutions, is that to really implement these solutions into practice, some extra steps are needed to increase TRL and gain insights on the business case practicability and legislative aspects.

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# Introduction

## Background in the project and objectives

NUTRI2CYCLE project has the objective of proposing and investigating solutions able to close the current gaps in the N, P and C cycles of different European agricultural systems, addressing the related environmental problems and finally proposing operative synthesis.

The phases of the **NUTRI2CYCLE project** are:

- map and comprehensively present the current flows and gaps in C, N and P cycles over three central agricultural pillars,
- find, select and prioritise innovation by the innovation funnel
- investigate prioritised solutions
- support further development and testing of innovations in demos
- implement a toolbox of comprehensible indicators to measure sustainability & evaluate trade-offs between the current practice and innovative, optimised farming systems for the investigated typologies
- impact calculation at the regional & EU level
- evaluation on how agro products obtained via more sustainable processes can aim for eco-labelling and how this could affect consumer behaviour (willingness to pay)

Deliverable 2.5 “Final report on innovations across the 5 research lines ”, aims to resume the findings of the solutions investigated and the conclusions and lessons learnt within the five research lines. This report is part of WP2 – Innovation Funnel for optimizing farm systems: reducing GHG and nutrient losses via innovative management systems and technologies to better close C, N, P cycles in the investigated farm systems.

The logic followed during WP2 was: i) to provide the rationale of the research and the experimental plans in deliverables 2.3 and 2.4, ii) to report the data collected during the investigations and needed for further elaboration in WP3, 4 and 5 (D2.6) while finally iii) in D2.5 are provided more conclusive data not only on the research and the experimental plans but more generally on the functioning of the innovations that have been investigated. To this purpose, the findings of each solution, are synthetically organised in "effects of solution on the nutrient closure" and effects of solutions on the environment", i.e. reporting the effects on GHG direct emissions and on air and water compartments. Based on the solutions findings, perspectives and lessons learnt of each research line are presented. For the solutions that were finally modelled in WP3, by LCA, and the solutions modelled at farm and wide EU level (MITERRA-Europe and Capri model), a synoptic summary is provided which highlights the different findings in terms of data collected from the experimental plan, LCA, farm modelling and finally EU level modelling. Besides transferability ranking, i.e. the potential of implementation and

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vocational geographical scope, and CBA conclusions are reported , to provide the overall picture of the data available both in terms of environmental effectiveness and real implementation capacity.

Finally the Annex 1 reports the publications arising from the investigation work of each research line, and Annex 2 the list of the PhD students involved and the title of the thesis they defended.

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# Research lines findings

## Research line 1: Innovative management systems, tools & practices for optimized nutrient and GHG management in animal husbandry

*Task 2.3.1 leader TEAGASC*

The aim of research line 1 (RL1) is to identify innovations that can contribute towards improvements in nutrient management plans and reductions in emissions within animal farming operations (cornerstone of EU production model). The research line consists of 10 innovations, which are listed in the table below, and addresses three key research questions, namely identifying ways of:

1. Reducing emissions from animal waste
2. Improving the nutrient profile of animal waste
3. Creating alternative uses for, and, adding value to, animal waste

Table 1: The ten innovations associated with research line 1 of the Nutri2Cycle project

| **Innovation** | **Partner** | **Founded by N2C** |
|---|---|---|
| LL8: Acid leaching of P from organic agro-residues in order to produce OM-rich soil enhancers and P-fertilizers | Wageningen Research, The Netherlands | |
| LL10: Small / Farm scale anaerobic digestion of agro-residues to increase local nutrient cycling & improve nutrient use efficiency | Inagro & Ghent University, Belgium | x |
| LL11: Recycling fibres of manure as organic bedding material for dairy cows | Soltub Ltd., Hungary | x |
| LL18: Slurry acidification with industrial acids to reduce $NH_3$ volatilisation from animal husbandry | University of Copenhagen, Denmark | x |
| LL19: Slurry bio-acidification using organic waste products to reduce NH3 volatilisation and increase fertiliser value | University of Copenhagen, Denmark | |

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| LL24: Adapted stable construction for separated collection of solid manure and urine in pig housing (followed by separate post-processing) | Inagro & Ghent University, Belgium | x |
| LL27: Use of an inoculate of microbiota and enzymatic pre-cursors to reduce ammonia emissions and optimize nutrient use efficiency in poultry manure. | CARTIF, Spain | x |
| LL32: Annual Nutrient Cycling Assessment (ANCA) | ZLTO & Wageningen Research, The Netherlands | |
| LL48: Recovery of energy from poultry manure and organic waste through anaerobic digestion | Czestochowa University of Technology (PCZ), Poland | x |
| LL61: Tailor made digestate products (tool development) | United Experts Belgium | |

The main topic of interest throughout research Line 1 is animal waste, with all of the 10 innovations factoring animal waste into their respective solutions to varying degrees. Eight of the 10 innovations represented ways of **reducing emissions from animal waste**, which was achieved through a diversity of approaches, such as, for example, alternative animal waste storage systems and altering certain characteristics of the animal waste to reduce its capacity to emit gases e.g. ammonia.

In addition, **improving the nutrient profile of animal waste** was also a focus of 7 of the 10 innovations. By improving the nutrient availability of animal waste, a reduced reliance on other forms of fertiliser may proffer e.g. reduced reliance on chemical fertilisers. Improving the nutrient profile was achieved by means of refining the raw animal waste to create specialised “products“ that displayed enhanced nutrient use efficiency qualities.

**Creating alternative uses for animal waste**, and, thereby, exploring ways of adding value to the waste product was investigated within 5 of the 10 innovations. By developing other uses for the animal waste, options and systems for managing large volumes or excessive quantities of localised livestock waste develop concurrently. Energy production in the form of biogas, and, the production of consumables, such as bedding from animal waste, were investigated as ways of creating new uses for animal waste.

Throughout the 10 innovations ways of reducing losses in carbon, nitrogen and phosphorous from European animal husbandry systems were identified either by outright reduction in related emissions, improved nutrient efficiency of the associated animal waste, or by suggested novel uses for the animal waste.

## Results and progress beyond the state of the art

By implementing the 10 innovations associated with research line 1 of the Nutri2Cycle project the following advancements in nutrient and GHG management within animal husbandry systems could occur:

***Reducing emissions from animal waste:*** this aspect of animal waste management was touched on by the majority of the 10 innovations including LL8, LL10, LL11, LL18, LL19, LL24, LL27 & LL48. Within these innovations it was made clear that when animal waste is left to its own devices there is no way to control and/or limit the associated gaseous emissions. Therefore, it was suggested that by managing the animal waste in a variety of ways the associated emissions can be controlled or reduced. One identified approach to reduce the current emissions associated with animal husbandry was by way of reducing the pH of the associated stored waste. Within the research carried out by two of the 10 innovations (LL18 &LL19), reducing the pH to 5.5 leads to reduced ammonia emissions, as under acidic conditions the ammonium within the animal slurry remains in a dissolved form and does not leach into the surrounding atmosphere. Acidifying livestock slurry will also lead to a reduction in methane and nitrous oxide emissions in both the storing and spreading stages. In addition, the current systems of collecting and storing animal waste from barns were highlighted within two of the innovations as sources of gaseous emissions. Within innovation LL24 it was suggested that by modifying current slatted shed designs, so that the solid fraction of the waste (dung) and the liquid fraction (urine) were collected into two separate chambers, reductions in ammonia emissions could be achieved. It was observed that by separating the solid waste fraction from the liquid fraction, the contact time between the urease enzyme, found within the dung, and the urine is significantly reduced which leads to a direct decrease in ammonia emissions. Innovation LL10, along with additional innovations where anaerobic digestion (AD) formed part of the innovation process chain (LL8, LL11, LL48), noted the ability to reduce ad-lib gaseous emissions from livestock waste by storing the waste within a controlled chamber, namely an anaerobic digester. Within an AD plant the gaseous emissions could be controlled to a degree and directed to other possible uses such as the generation of power. In addition, innovation LL27 demonstrated means of reducing nitrous oxide and methane emissions from animal manure by treating the manure with ‘effective microorganisms’, which enhances both the bio-degradation of the manure and the fixation of nitrogen and carbon within the manure.

***Improving the nutrient profile of animal waste:*** Innovation LL8 researched a means of isolating desired nutrients within livestock waste using a process termed ‘RePeat’, with particular focus on phosphorus. Isolating desired nutrients was also a benefit associated with LL24, as, by separating the waste into solid and liquid fractions, phosphorus is concentrated within the solid fraction and nitrogen

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and potassium are concentrated within the liquid fraction. By isolating nutrients, more fertiliser products become available for use in precise nutrient management plans, and more options to contend with chemical fertilisers become available. Within the innovations where anaerobic digestion (AD) formed part of the process, such as LL10 and LL48, the subsequent production of digestate was highlighted as a means of improving the nutrient profile of animal waste, as the digestate produced has a greater concentration of plant available nutrients than unrefined animal manure. Innovations LL18, LL19, LL24 & LL27 all observed that by altering the current management systems of livestock waste and reducing the associated ammonia emissions the nitrogen nutrient value of the livestock waste can be increased. In addition, innovation LL27 proposed a means of enhancing the bio-degradation and, therefore, enhancing the plant availability of nutrients contained within livestock waste by inoculating the h with chosen microbe populations.

***Creating alternative uses for, and, adding value to, animal waste:*** creating new uses for animal waste was also suggested as a means to improve nutrient cycling and reduce emissions from animal husbandry systems within Europe. Innovations LL8, LL10, LL24 & LL48 all touched on the benefits of AD technology in terms of converting animal waste to new useful by-products such as biogas, which can be passed through a combined heat & power unit to generate energy. Innovation LL11 identified a means to convert raw animal waste to a safe form of bedding, which could assist in tackling animal waste surpluses, uncontrolled emissions from stored waste, and, act as a means of returning nutrients to the soil. By replacing straw bedding with refined animal waste, a greater proportion of straw could be left as stubble within croplands and thereby return organic matter to the soil. Innovation LL8 also touched on soil organic matter, as, through its associated 'RePeat' system an organic matter rich by-product is created from livestock waste, which can be used as a new form of soil conditioner.

## Lessons learnt from solutions in RL 1

From evaluating the innovations associated with RL1, animal waste is the common point of interest across the board. Throughout the 10 different technologies, the storing and/or utilisation of animal waste was identified as key to satisfying the overall aim of RL1, with that being the development of systems to improve nutrient use efficiency and reduce emissions associated with animal husbandry systems. The main lessons observed within the RL1 technologies were as follows:

***Animal waste storage:*** presently, within livestock systems, the conventional means of storing livestock waste are a source of emissions. From the innovations within RL1 we have learned that due to animal waste characteristics such as pH value or the contact time between the urease enzyme and urine, gaseous emissions are actively released from stored livestock waste. These emissions have been shown to impact environmental conditions such as air quality and also can result in a decrease of the

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nutritional value of the stored waste; overtime, emissions of e.g. ammonia, leads to losses in the N value of the livestock waste. The innovations within RL1 propose that such issues can be addressed by modifying current livestock waste storage systems in a variety of ways, including through chemical amendments, modified housing designs and redirecting stored waste into processing systems such as anaerobic digesters.

***Animal waste refining:*** when analysing the main findings from the RL1 innovations, benefits associated with processing livestock waste were highlighted. Across innovations LL8, LL10, LL11, LL18, LL19 & LL48 four main examples as to the advantages of waste processing were provided. Firstly, through refining, the overall volume of livestock waste can be reduced. This is advantageous to farms or geographical regions with high livestock population densities and a resulting excess or surplus of animal waste. This overall reduced volume can have a positive effect on the cost feasibility of transporting the organic fertiliser from regions of production to receiving lands. Secondly, the refinement process leads to the creation of alternative nutrient rich forms of fertiliser, such as digestate or acidified slurry. Through refining, the nutrient profile of the livestock waste can be enhanced which can result in added value to the waste and the subsequent possibility of reduced reliance on synthetic fertilisers. Thirdly, in addition, reliance on synthetic fertilisers can be reduced through livestock waste refining as the process can develop specific by-products that are rich in particular nutrients such as e.g. phosphorus. Such products could be attractive on a holding with specific nutrient needs. Fourthly, when applying refined animal waste on such a holding, the animal wastes subsequent altered physical & chemical properties can also lead to a reduced risk of environmental pollution in the form of gaseous emissions or nutrient leaching.

***Development of animal waste derived products:*** the development and promotion of animal waste derived products was identified within innovations LL8, LL10, LL11, LL27 & LL48 as a way of tackling a number of current challenges within livestock production. By developing new useful by-products from animal waste or, new attractive uses for animal waste, the waste will increase in value, potentially in both an economical sense and in a nutrient profile sense. Reliance on expensive imported chemical fertilisers and soil conditioners may also decrease and there will be more options available to regions with animal waste surplus issues.

***Nutrient management planning:*** A number of the innovations within RL1 could assist in improved nutrient management planning on farms. The development of methods to isolate specific nutrients of interest, or, concentrate certain nutrients within waste fractions/ by-products, could act as an evolutionary step towards creating a livestock-waste-based-product that is as nutrient specific as current chemical fertiliser products e.g. a waste by-product that is rich in phosphorous only.

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## Solutions

### LL8: Acid leaching of P from organic agro-residues in order to produce OM-rich soil enhancers and P-fertilizers

*Chantal Hendriks, Jan Peter Lesschen, Inge Regelink, Oscar Schoumans (Wageningen Environmental Research (WR): Netherlands)*

**Aim of the solution:** to separate phosphorus from digestate material. Refining digestate results in a thick fraction with high phosphorus concentrations (20 g $P_2O_5$/kg). This product cannot be applied to fields in the region where the product is made (Groot Zevert Vergisting, an anaerobic digester in the Netherlands), because it will exceed the phosphorus application standards. Therefore, the product is commonly being exported to East-Germany (250-300 km). A new technique, called RePeat, is able to extract the P from the thick fraction. This results in a valuable OM-rich soil enhancer which can be applied locally. The P-fertiliser can be used elsewhere as a replacement for chemical P fertiliser. The solution therefore contributes to closing C and P loops.

**Key elements of innovation with respect to the state of the art:** The RePeat-system is a state-of-the-art innovation, which was built, tested and improved during the SYSTEMIC project and, since 2020, is operational in an anaerobic digester. The technique is scalable and especially of interest in areas with high P-concentrations in the soil and in areas with a surplus of organic waste. A unique aspect to this innovation is that it is purposely designed for manure processing as the majority of similar concepts in development are targeted towards sludge processing. In addition, LL8 results in the production of a phosphorous-depleted novel soil improver which is also a novel aspect to the innovation.

**Working principle:** The RePeat process separates the P from the organic matter through extraction with water and sulphuric acid followed by precipitation of released P through addition of calcium hydroxide or magnesium hydroxide. The extraction is performed in two sequential leaching steps during which 70–90% of the total P is removed from the initial solid fraction. The precipitated calcium /magnesium phosphate is recovered in a settling tank. Process water is continuously reused in the process. Per ton thick fraction, 750 kg OM-rich soil enhances was produced. The P-content in the OM-rich soil enhancer is between 1.8 and 7.4 g $P_2O_5$/kg.

Finally, the RePeat system produces a calcium phosphate and an organic soil improver with a low P content from the solid fraction of digestate. The installation has a treatment capacity of 17,000 tonnes of solid fraction of digestate per year. This is an amount equivalent to 140 kilo tonnes of unseparated digestate. The solid fraction is obtained from the liquid digestate by means of a decanter. The liquid fraction of the digestate is further processed into NK concentrate and clean water.

***Results of the solutions on nutrient closure***

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**Carbon:** The OM-rich soil enhancer is no longer exported to East-Germany and therefore transportation, emitting $CO_2$, is no longer necessary. It closes the C-loop as the poor sandy soil in the region of the anaerobic digester is now enriched by the OM-rich soil enhancer. The OM-rich soil enhancer is also used in the potting industry, replacing peat/peaty soil.

**Nitrogen:** Processing manure also enhances the closure of the N loop, but that is not investigated during this innovation.

**Phosphorus:** The P-fertiliser can be used as a replacement for chemical P fertiliser. This helps closing the P-loops, as chemical P-fertilisers are normally produced from non-renewable resources.

***Effect of solution on the environment***

**GHG:** This technique can result in extra carbon sequestration as more organic matter can be applied also in soils with high level of P. The direct GHG emissions of the application of RePEAT process were not analysed.

**Energy:** the energy needed to implement the process is equal to 57 kWh / ton thick fraction. Scaling up this technique will decrease the energy consumption to +- **20 kWh / ton** thick fraction.

**Ammonia emissions:** no data available

**Leaching to ground water:** no data available

**Final remarks:** The RePeat-system is financially most attractive for the manure processing industry when high-quality sales is possible, e.g., to the potting or mushroom industry.

**Recommendations:** This innovation has high potential in areas where the application of organic fertiliser is limited by the phosphorus application standards (north-western Europe). Scaling up this technique will result in a more stable supply and reduce the costs, which is of interest for the sales market. The market is interested in the OM-rich soil enhancer as long as the P-concentration in the product is comparable to the OM:P-ratio of compost.

**Transferability:** The present TRL of the solution is 6, as the technique is at present operational at one location. The system has high investment costs, but the currently high costs for chemical P fertiliser can be a stimulation for adoption. However, the system relies on organic waste products. Debates on the reduction of the animal density in the Netherlands might influence the stable supply of organic waste.

## LL10: Small / Farm scale anaerobic digestion of agro-residues to increase local nutrient cycling & improve nutrient use efficiency

*Sander Vandendriessche, Inès Verleden, Anke De Dobbelaere, Jan Leenknegt (Inagro, Belgium)*

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**Aim of the solution:** The solution aims to valorise agro-residues as feedstock for anaerobic digestion. More specifically, this solution is looking into the valorisation of pig manure (link with LL24) and crop residues (for example leek, a common agro-residue in Flanders), which can otherwise have negative side effects, such as ammonia and/or GHG emissions or leaching.

**Key elements of innovation with respect to the state of the art:** A unique aspect to this anaerobic digester design is its operational scale. The design represents a farm-scale digester which can be fed by a moderate herd size of at least 80 cows. By incorporating farm-scale anaerobic digestion within a working farm there will be an associated reduction in emissions emanating from the livestock waste and, in addition, a form of renewable energy will be produced. Furthermore, the digestate can be used as a fertiliser since the nutrient content of the digestate displays enhanced mineralisation and availability when compared to the raw feedstock material.

**Working principle:** The fermentation process takes place in a large reactor in the absence of oxygen. During fermentation, organic matter is converted into biogas. The biogas (mainly consisting out of methane) is subsequently burned in a combined heat and power unit (CHP) and results in a renewable energy source in the form of heat and electricity and allows to reduce methane emissions from storage tanks.

**Results of the solutions on nutrient closure**

**Carbon:** Not directly assessed

**Nitrogen:** Applying AD will not change the total amount of nutrients. However, the nitrogen will be more mineralized, so it will be more readily available for crops leading to a higher N uptake.

**Phosphorus:** Applying AD will not change the total amount of nutrients.

**Effect of solution on the environment**

**GHG:** When looking at farm scale AD of cattle slurry, it is known that GHG from storage can be reduced up to 50% in ideal circumstances (Vergote, 2020). A similar reduction is expected for pig slurry.

**Energy:** The amount of renewable energy that can be produced is dependent on the size of the AD plant. For example: a farm scale AD plant of 10 kW can produce approximately 50.000 kWh/year. The size of the AD plant is farm specific and calculated on its energy demand and available agro-residues.

**Ammonia emissions:** Due to the high N mineralization of the AD process, there is an increased risk of ammonia emissions during application of the digestate. The right timing and method of application is therefore very important. N emissions during application can be strongly reduced by performing stripping scrubbing on the digestate.

**Leaching to groundwater:** not investigated

**Final remarks:** Farm scale AD is a great technology to reduce emissions and at the same time produce renewable energy. Furthermore, the digestate can be a good fertilizer for certain crops (e.g. grass) since the N is more mineralized compared to the input feedstock and is therefore more readily available for crops.

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**Recommendations:** The profitability of farm scale AD is dependent on several factors. First of all, there should be sufficient agro-residues available all year long, since the AD plant requires a continuous feeding. Next to this, the biogas potential of these agro-residues should be sufficient. In general, it is recommended to feed the agro-residues as fresh as possible to the AD plant.

**Transferability:** The present TRL ranking of the technology is 8-9, as the technology is already existing on several farms. The technology could be widely adopted by farmers, if they have enough agro-residues available throughout the year. Therefore, there is way more potential for cattle and pig farmers compared to crop farmers. The initial investment cost can be considered as a disadvantage, but due to the current high energy prices the payback time of farm scale AD installations can be very short (3-5 years).

- Expert ranking: Within the expert evaluations, the technology was ranked fourth most transferable with a mean rank of 2, and the sixth most transferable over the medium-term with a mean rank of 3.6.
- Survey ranking: At EU level farm scale anaerobic digestion was ranked as the third most transferable over the short- term and medium-term within the survey feedback, with a mean short-term transferability rank of 2.4 (out of a maximum of 5), and a mean medium-term transferability rank of 3.4.
- Geographical scope: The results show that farm-scale anaerobic digestion could be particularly relevant for Southern and Western Europe in the short and medium term.

## CBA findings

**Croatia**: Investment in a pocket digester is economically viable with a 2-year payback period. This extends to 6.5 years if energy prices significantly decrease. Manure and digestate flows can generate equal income, influencing the investment's payback period.

**Flanders**: Pocket digesters are feasible for farms with ample land for manure disposal. However, costs for disposing of digestate at treatment facilities extend the payback period to about 7.5 years. In Flanders, a 25% increase in energy costs would make pocket digesters economically attractive for all pig farms, reducing the payback period to about 4 years.

## Producer perception of the innovation

**Barriers:** The principal innovation barriers identified by the participants were the “economic considerations” and “regulatory frameworks” (35% for each). The third barrier, specified by the participants as “other”, with 15%, included limited opportunities to use the digestate, the difficulty of obtaining permits, and the need to adapt the stable to obtain fresh manure.

**Enables**: the advantages of innovation LL10 are principally the economic benefits obtained by saving on mineral fertilizers (27%). Also, producers considered that the innovation would increase the efficient use of nutrients (19%) and bring environmental benefits by reducing nutrient loss and emission generation (19%)

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 773682.

## Synoptic table of findings across WPs

| Area | WP2: experimental data collection | wp1: modelling at farm scale | WP4: modelling at EU level |
|---|---|---|---|
| **Carbon cycle** | **Carbon cycle:** Not directly assessed | - | - |
| **Nitrogen** | **Nitrogen:** Applying AD will not change the total amount of nutrients. The nitrogen will be more readily available for crops leading to a higher N uptake. | | The use of mineral fertiliser slightly increases over the scenarios ranging between 0.5% and 0.8%, mainly caused by an increase in UAA and the mentioned shift away from affected activities to minimise income losses as a consequence of the exogenously forced adoption of the technology. |
| **P** | NO effect | NO effect | NO effect |
| **GHG direct emissions** | **GHG:** When looking at farm scale AD of cattle slurry, it is known that GHG from storage can be reduced up to 50% in ideal circumstances (Vergote, 2020). A similar reduction is expected for pig slurry. | **GHG**<br>**Housing:**<br>no effect<br>**storage :**<br>$CH_4$ Reduced by 70% compared to no digester (Biogas $CH_4$ emissions 4.4% of produced biogas $CH_4$ is assumed to be lost)<br>$N_2O$ Increased by 41% compared to no digester.<br>**Field**<br>$N_2O$ & $NO_x$ Reduced by 29% compared to manure. | The maximum application leads to the mitigation of 18.8 million tonnes (Mt) of CO2 equivalents (CO2 eq.), which reduces the agricultural GHG emissions in the EU-27 by 4.8%.<br>The reductions in GHG emissions by pocket anaerobic digestion are mainly due to changes **in CH4 emissions (-6.2%) and N2O emissions (-1.9%)** related to manure management. |
| **Ammonia emissions** | Due to the high N mineralization of the AD process, there is an increased risk of ammonia emissions during application of the digestate. The right timing and method of application is therefore very important. N emissions during application can be strongly | **storage:**<br>$NH_3$ Reduced by 75% compared to no digester.<br>**Field:** increased, the total decreased emissions of N2O and NOx were minor compared to the more abundant emissions of NH3. | |

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| | | |
|---|---|---|
| | reduced by performing stripping scrubbing on the digestate. | |
| **Leaching to groundwater:** | not investigated | No difference in surface runoff and leaching in the soil |

## LL11: Recycling fibres of manure as organic bedding material for dairy cows

*Zoltán Hajdu, SOLTUB Ltd., Hungary*

**Aim of the solution:** To recover fibre from slurry which will be utilized as bedding material. The innovation focuses on processing livestock waste material so that it can be safely used as a bedding for livestock with a quality akin to traditional bedding products, such as straw.

**Key elements of innovation with respect to the state of the art:** As the refined livestock (primarily cattle) manure can be used as a bedding material, traditional bedding materials such as cereal straw may find alternative uses other than as bedding material.

**Working principle:** The solid manure is separated from the general livestock waste by utilising a Bauer screw press separator. Often lime is added to the separated solid waste before applying the bedding material, as the lime assists in good sanitation practices. The LL11 innovation assessed many aspects to the refined livestock bedding, such as: advantages & disadvantages of thin or deep layer bedding; advantages and disadvantages of using rubber mats; optimal bedding replacement timing; impacts on livestock welfare; comparison against traditional bedding materials such as sand and straw, and, the potential environmental benefits and challenges associated with the innovation.

**Results of the solutions on nutrient closure**

**Carbon:** replacement of virgin straw

**Nitrogen:** The spent manure bedding can be applied on fields as a fertiliser, thus finally closing the N cycle

**Phosphorus:** The spent manure bedding can be applied on fields as a fertiliser, thus finally closing the P cycle

**Effect of solution on the environment**

**GHG:** The carbon footprint of the different bedding products was assessed in **D3.4.** Traditional straw bedding produced 7.9kg CO2e/ tonne; separated solid slurry bedding produced 1.13 kg CO2e per tonne, and, separated solid slurry plus dried slurry bedding produced 3 kg CO2e per tonne. Associated methane emissions were also assessed. Traditional straw bedding produced 7.8kg CH4 per tonne;

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separated solid slurry bedding produced 21kg CH4 per tonne, and, separated solid slurry plus dried slurry bedding produced 20kg CH4 per tonne.

**Energy:** Direct energy usage values for the separated slurry bedding products are not available, but it is recognised that such manure refining will consume more energy than, for example, traditional straw bedding.

**Ammonia emissions:** For traditional straw bedding, the associated ammonia emissions are 1 kg ammonia (NH3) per tonne of straw (in the global life cycle of production). For the separated solid slurry bedding the associated ammonia emissions are 2.8kg per tonne of manure, thus causing and increase in ammonia emissions

**Leaching to groundwater:** Not directly assessed.

**Final remarks:** Implementing this innovation requires operator training, relevant infrastructure such as a screw press separator, and consistent supply of livestock manure. Further aspects of the innovation assessed during the trials were the practicalities of reutilising the spent bedding as fertiliser, proper means of storing the refined manure and ensuring the refined manure is a safe form of livestock bedding. The innovation would complement a farm that has an anaerobic digester already installed as the digestate can also be refined to form a safe form of livestock bedding.

The EU Animal By-Products (ABP) Regulation (1069/2009 EC) has provisions that permit the use of manure sourced bedding materials as long as this does not pose risks to human or animal health. In the case of separated slurry for bedding, this EU requirement is applied. In the case of digestate the new 1009/2019 EC needs to be applied. The same rule is applied if the separated slurry compost is prepared for bedding.

**Recommendations:** In the utilisation of the recycled fibre technology as bedding it is recommended to assess the pros and cons of the technology. The positive impact relates to a) recycling speed of the separated slurry and digestate (depending on the amount of recycled fibre/day) b) increased animal welfare and comfort c) “reduced” environmental impact. The negative impact of the technology relates to a) the investment cost of the slurry separation technology and, in addition, biogas digestion plant (e.g. fermentation unit, storage tanks) b) the risk on animal health (bacterial counts, zoonotic pathogens) c) the energy consumption for separation

**Transferability:** The recycled fibre technology has a TRL 9 level in the HU conditions as the national legislation permits the utilisation of such materials. The applicability in other EU states depends on the national legal requirements. The technology could be widely adopted mostly in mixed farming conditions where the slurry and digestate separation technologies are available. Using the recycled fibre practices contributes to the low input farming systems. Relevant legislation to fulfill: 1009/2019 EC fertilizer regulation, which defines the end point of the utilisation of organic sourced fertilizer materials.

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## LL18: Slurry acidification with industrial acids to reduce $NH_3$ volatilisation from animal husbandry

*Miriam Beyers, Iria Regueiro Carrera, Sander Bruun, Lars Stoumann Jensen. University of Copenhagen (UCPH), Denmark*

**Aim of the solution:** The aim of slurry acidification through industrial acids is to lower the pH of the slurry and as a consequence avoid ammonia volatilization. LL18 involves livestock farmers, typically pig farmers, a service company and crop farmers. Note that in some settings pig and crop farms are run by the same person or company.

Key elements of innovation with respect to the state of the art: If applied early in the management chain, acidification also reduces emissions of methane and nitrous oxide. Slurry acidification increases the nitrogen fertilizer efficiency of slurry and may increase the availability of other nutrients, too. By decreasing slurry-related emissions, closure of nutrients loops of nitrogen and carbon can be increased. LL18 aims at such nutrient closure and at reducing the reliance on mineral fertilizers.

**Working principle:** Slurry acidification can be applied in either the animal house, the outdoor storage tank or during field application to both cow and pig slurry. The most commonly used acid is sulphuric acid ($H_2SO_4$). Hydrochloric acid (HCl) and Nitric acid ($HNO_3$) have been tested as well; however, $H_2SO_4$ has proven to be most economical.

In-house acidification - In this configuration, the slurry is pumped from below the slatted floors in the animal house to a process tank where it is acidified to pH 5.5. After the acidification process, some of the slurry is recirculated into the animal house, while the rest is transferred to the final outdoor storage. In-house acidification is the most expensive acidification technology given that animal house and process tank have to be installed accordingly. The farmer is responsible for managing the dozing of the acid, but in most commercial technology configurations, the process is automated. Given that, the acidification takes place early in the management chain, this approach results in the highest emission reductions, since emissions from both animal house, slurry storage and field application are reduced.

Storage acidification - Outdoor acidification takes place in the main storage tank. To ensure a pH below 6 during the entire storage period (usually 6 months in Central / Northern European countries and 4 months in Southern European countries), the slurry needs to be acidified about once per month (personal communication Morten Toft, Biocover Ltd.).

In-field acidification - In this configuration, an acid tank is placed in the front lift of the tractor pulling the slurry tanker from which the slurry is field applied. During application, the acid is mixed into the slurry to lower its pH to about 6 to 6.4.

**Results of the solutions on nutrient closure**

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 773682.

**Carbon:** Slight increase in soil C content

**Nitrogen:** an increase in mineral N fertilizer equivalent of acidified slurry of up to 15-20% can be achieved.

**Phosphorus:** no change in amount of P applied but the lowered pH can increase the plant availability of P as well as increase its mobility in the soil. Depending on the soil and other conditions, this can result in higher slurry-P uptake or increased P leaching.

**Effect of solution on the environment**

**GHG:** $CO_2$ not effected, $CH_4$ reduced, $N_2O$ reduced during field application.

**Energy:** negligible increase in energy consumption for the production and handling of the acid.

**Ammonia emissions:** Slurry acidification reduces $NH_3$ emissions from the animal house, during storage and field application depending on when the acid is applied.

**Leaching to ground water:** Trials on in-field acidification have shown a decrease in leaching of $NO_3^-$ . However, effects on nitrate leaching mainly depend on whether the additional N in the slurry is viewed as mineral fertiliser substitute or as a means to apply more N to the field overall – keeping mineral N fertiliser rates constant. Generally, the effect on phosphorous losses is very low. As for nitrate leaching, it also depends on the N fertilisation scheme. If due to the higher N concentration and thus a shift in the N:P ratio of the slurry towards N, less P is applied on the same area, then reductions in P leaching could be achieved.

**Final remarks:** The impacts of slurry acidification under Danish, Dutch and Spanish conditions were determined using life cycle assessment (LCA). In all three study regions, slurry acidification indicated both positive and negative environmental effects. Positive impacts are mostly achieved because of lower $CO_2$, $CH_4$, and $NH_3$ emissions during storage and field application of acidified slurry. Negative impacts were related to changes in crop productivity and the supply of the acidification technology.

**Recommendations:** The LCA results suggest that slurry acidification reduced the environmental impact of slurry management in those categories mostly related to agriculture, and that it has the potential of contributing to an overall enhanced nutrient recycling.

However, the LCA study also showed that slurry acidification can have negative impacts on those categories more related to the provision of energy (for example energy resource use) or manufacturing of inputs (for example human health effects). To justify slurry acidification on all levels, energy and material sources should be examined and carefully selected.

Because the results and recommendations vary between countries, it is also recommendable to look at the specific conditions one encounters before implementing the technology.

**Transferability:** The technology is commercially available on the market (TRL 9) but currently applied mainly in the Scandinavian countries, especially Denmark. The technology could be widely adopted by livestock farmers if legislation allows. Installing and maintaining slurry acidification will likely result in additional costs to the farmer.

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## Synoptic table of findings across WPs

| Area | WP2: experimental data collection | WP3: LCA (assessed on 3 scenarios, Denmark, Netherlands and Spain) | WP1/3: modelling at farm scale |
|---|---|---|---|
| **Carbon cycle** | Slight increase in soil C content | | |
| **Nitrogen cycle** | Increase in mineral N fertilizer equivalent of acidified slurry of up to 15-20% | | |
| **Phosphorus cycle** | No change in amount of P applied<br>The lowered pH can increase the plant availability of P | | |
| **GHG direct emissions** | $CO_2$ not effected,<br>$CH_4$ reduced,<br>$N_2O$ reduced during field application. | Significant reduction in CH4 emissions, but an increase in N2O emissions<br>**Methane**<br>DK: -206.40 kg CH4 (>-100%)<br>NL: -208.38 kg CH4 (>-100%)<br>ES: -275.10 kg CH4 (-96%)<br>**Dinitrogen**<br>DK: 1.12 kg N2O (+14%)<br>NL: 1.13 kg N2O (+5%)<br>ES: 2.95 kg N2O (+8%) | **Storage emissions**<br>$N_2O$ Increased by 12% compared to unacidified slurry.<br>$CH_4$ Reduced by 96% compared to unacidified slurry.<br>**Field application emissions**<br>Same as unacidified slurry. |
| **Ammonia emissions** | Housing: reduction of $NH_3$ emissions from the animal house<br>storage : $NH_3$reduction | **Ammonia emission to air**<br>DK: -122.15 kg NH3 (> -100%)<br>NL: -81.29 kg NH3 (-18%)<br>ES: -27.83 kg NH3 (>-100%) | **Storage emissions**<br>$NH_3$ reduced by 76% compared to unacidified slurry.<br>**Field application emissions**<br>$NH_3$ Reduction |
| **Leaching to groundwater** | Decrease in leaching of $NO_3^-$.<br>However, effects on nitrate leaching mainly depend on whether the additional N in the slurry is viewed as mineral fertiliser substitute or as a means to apply more N to the field overall – keeping mineral N fertiliser rates constant. | **Nitrate emission to water**<br>DK: -17.96 kg NO3 (-1%)<br>NL: 24.72 kg NO3 (+1%)<br>ES: 17.29 kg NO3 (+9%)<br>**Phosphorous emission to water**<br>DK: -0.14 kg P (-1%)<br>NL: -0.06 kg P (-1%)<br>ES: 0.09 kg P (+8%)<br>**Phosphate emission to water**<br>DK: 0.47 kg PO43- (+73%)<br>NL: 0.56 kg PO43- (+3%)<br>ES: 0.97 kg PO43- (+15%) | Slight increase in $NO_3$ leaching due to higher N availability |

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## LL19: Slurry bio-acidification using organic waste products to reduce NH3 volatilisation and increase fertiliser value

*Iria Regueiro Carrera and Lars Stoumann Jensen. University of Copenhagen (UCPH), Denmark*

**Aim of the solution:** Bio-acidification aims to reduce ammonia emissions to the atmosphere from slurry management, similar to slurry acidification using sulphuric acid, but without using industrial, synthetic acids. Instead, bio-acidification is based on decreasing the pH through natural fermentation in the manure.

**Key elements of innovation with respect to the state of the art:**

Bio-acidification, compared to acidification with industrial acids is relevant because:

- Although sulphuric acid is one of the cheapest industrial acids, it is still a cost to the farmer.
- Organic farms are not allowed to use synthetic industrial acids.
- Acidification with sulphuric acid increases the sulphur content of the slurry, which prohibits extensive use of acidified slurry in anaerobic digestion biogas plants, due both to the potential inhibition of the biogas process and to the cost of biogas desulphurisation.
- Concentrated sulphuric acid is a hazardous and corrosive chemical, which requires special work safety precautions.

**Working principle:** By lowering the pH of the slurry through bio-acidification ammonium stays in the dissolved form and does not volatilise to the atmosphere. Bio-acidification is based on stimulating the formation of organic acids (especially lactic and acetic acid) in the manure by fermentation. This can be done by adding simple sugars or other carbohydrates that easily hydrolyse into sugars, which promote lactic acid fermentation and a rapid pH drop, preventing methane formation and as mentioned above ammonia volatilisation.

***Results of the solutions on nutrient closure:***

**Carbon:** inorganic C may be kept in slurry, if strong acid is not added. Microbial biomass C may increase due to increase in bacteria.

**Nitrogen:** higher N retention in the slurry compared to no acidification.

**Phosphorus:** solubilisation of inorganic P by carbohydrates to reduce the pH. It is unknown how much P may be immobilized into microbial P.

***Effect of solution on the environment:***

**GHG:** Bio-acidification could replace the use of sulphuric acid to reduce methane emissions.

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**Energy:** no change.

**Ammonia emissions:** Bio-acidification could replace the use of sulphuric acid to reduce ammonia

**Leaching to ground water:** unknown.

**Final remarks:** none by now, due to the still low TRL.

**Recommendations:** none by now, due to the still low TRL.

**Transferability:** bio-acidification is currently at TRL 5 and as not be tested sufficiently to be distributed and implemented widely.

## LL24: Adapted stable construction for separated collection of solid manure and urine in pig housing (followed by separate post-processing)

*Sander Vandendriessche (Inagro, Belgium), Inès Verleden (Inagro, Belgium)*

**Aim of the solution:** The goal of an adapted stable construction in pig housing is to reduce ammonia emissions by the primary separation of pig slurry into solid manure and pig urine fractions.

**Key elements of innovation with respect to the state of the art:** The primary separation is beneficial for both the farmer and the environment: there will be less emissions coming from the manure and the resulting products have a lower disposal cost. Furthermore, these products have better valorisation options: the solid pig manure has a good biogas potential (link with LL10) and the pig urine is suitable as an NK fertilizer. In Flanders, the system is recognized as a low ammonia emitting system, which has the advantage that a post treatment technique like an acid air scrubber is not mandatory anymore.

**Working principle:** The hydrolysis of urea to carbon dioxide ($CO_2$) and ammonia ($NH_3$) is catalyzed because of urease, an enzyme which is found in solid manure. Therefore, when solid manure and urine are collected separately there are less $NH_3$ emissions because urine is less in contact with urease.

### Results of the solutions on nutrient closure

**Carbon:** separation of C and N flows can support a better management of the carbon supply to soil

**Nitrogen:** The N is mainly found in the pig urine, which can be used as fertilizer (RENURE). The total N content is 3.28-3.70 g/kg.

**Phosphorus:** The P is mainly found in the solid fraction of the pig manure, which can be used as a soil enhancer. However, this is mostly exported to France since Flanders is a P rich region. The P content is 6.33 g $P_2O_5$/kg.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 773682.

**Effect of solution on the environment**

**GHG**: The impact on GHG was not investigated, but as the solution allows a better management of nitrogen, the GHG direct emissions related to nitrogen emissions in field might be improved. The worst case is GHG emissions equal to the baseline. For sure, there will also be less GHG emissions in the stable ($N_2O$) due to the quick N removal.

**Energy:** A stable of about 2000 pigs requires 3 kWh extra/day (for the manure scraper). However, there is also a reduced need for energy because an air scrubber is no longer needed (20 kwh/ton manure) , thus the energy balance is finally positive.

**Ammonia emissions:** The primary separation will lead to a strong ammonia emission reduction, up to 60%. Therefore, the system is recognized as a low ammonia emissions stable system.

**Leaching to ground water**: not specifically investigated, but as for GHG, the solution allows a better management of nitrogen, thus at least a positive effect on N leaching is expected.

**Final remarks:** The solution is recognized as a low ammonia emitting stable system, making it interesting when building a new stable. Furthermore, the resulting products both have an added value compared to the pig slurry.

**Recommendations:** An adapted stable system might be a great choice when investing in a new stable. It will reduce emissions and is perfectly suitable in combination with a farm scale AD plant. Implementing this technology in an existing stable is difficult and will hardly be profitable.

**Transferability:** The present technology readiness level (TRL) ranking of the technology is 9, as the technology is already existing on several farms. The technology can be widely adopted by pig farmers and is independent of scale. It is not suitable to be adopted in other farming systems.

- **Expert ranking:** At EU level under the short-term transferability timeframe, the expert panel ranked the technology 11th out of the 14 technologies trialled (mean rank value of 1.3).
- **Survey ranking:** respondents ranked the technology 8th in short-term transferability (mean rank value of 1.9).
- **Geographical scope**: The adapted stable construction for manure processing is particularly relevant for Western Europe with a short-term transferability rank of 2.3 for the expert evaluation and the survey and a medium-term expert rank of 3, medium-term survey rank of 3.2.

**CBA findings:**

**Flanders:** The least favourable scenario in Flanders is a classic stable without further processing or digestion of manure. All other scenarios result in a positive impact per ton of manure.
The most favourable scenario involves treating manure in a separation system (screw press) and then digesting it. The additional investment for this scenario is recouped within 3 years.
Investing in a Vedows system combined with a digester is economically viable, with a payback period of 3.7 years. However, investing in a Vedows system without digesting the manure is less economically viable, as the payback period extends to almost 7 years.

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## Producer perception of the innovation

**Barriers:** the regulatory framework was perceived by the participants as the principal barrier for innovation adoption (36%), followed by “economic considerations” (32%).

**Enables:** better nutrient management (greater efficiency in nutrient use) and the environmental benefits (reduction in nutrient loss, reduction of emissions), both of which are linked to the efficient use of nutrients and a reduction in contamination

## Synoptic table of findings across WPs

| Area | WP2: experimental data collection | WP1/3: modelling at farm scale | WP4: modelling at EU level |
|---|---|---|---|
| **Carbon cycle** | Separation of C and N flows can support a better management of the carbon supply to soil | | |
| **Nitrogen** | The N is mainly found in the pig urine, which can be used as fertilizer (RENURE) with better efficiency | From the perspective of lowering N loss, adapted stable effectively preserves more nutrients in the system. | The use of mineral fertiliser shows no significant changes across the different implementation shares. |
| P | The P is mainly found in the solid fraction of the pig manure, which can be used as a soil enhancer. and exported | | |
| **GHG direct emissions** | Not measured | $N_2O$ Increased by 220% compared to unseparated manure.<br>$CH_4$ Reduced by 51% compared to unseparated manure. | Among the technologies considered in Nutri2cycle, the adapted stable construction has the lowest mitigation potential, reducing EU agriculture emissions by 0.7 Mt CO2 equivalents primarily due to $NH_3$ and $CH_4$ emission reductions. |
| **Ammonia emissions** | Reduction, up to 60% in housing | Average reduction by 40% | |
| **Leaching to groundwater** | Not measured | Not assessed | Not assessed |

## LL27: Use of an inoculate of microbiota and enzymatic pre-cursors to reduce ammonia emissions and optimize nutrient use efficiency in poultry manure

*Francisco Corona and Dolores Hidalgo (Fundación Cartif, Spain)*

**Aim of the solution:** The aim of this solution is to use effective microorganisms (EM) for the bio-stabilization of manure, before the manure is used as a fertilizer.

**Key elements of innovation with respect to the state of the art**: The manure is inoculated with microbes that were selected to perform specific functions. They act directly on the slurry first, and on the soil later, reducing nitrogen losses by enhancing the bio-degradation of manure. More specifically, the product under study is a liquid suspension of microorganisms based on phototropic and lactic acid bacteria and yeast in a natural environment of sugarcane molasses. Currently, in the study area (Castilla y Leon, Spain), manure is added directly to the land (soil injection) or is composted for later application (by dispersion). Nitrogen losses during the process are high. Conditioned manure is not commonly used although it can lead to improved nutrient valorisation (less losses to the environment, better assimilation by the plant) using the same application techniques. Ammonia volatilization decreases the N-nutrient value of livestock manure slurries and can lead to soil acidification and eutrophication problems. Nutrient losses to the atmosphere can be reduced by adding some key bacteria directly to the manure, so these nutrients will be available for the crop. Conditioned manure can also contribute to improvements in the properties of the soil while increasing the root system of plants. Therefore, the LL27 solution aims to show the closing of these nutrient loops and the reduction of dependency on synthetic fertilisers in a farming system, thus contributing to the objectives set out in Nutri2Cycle.

**Working principle:** In the solution LL27, 3 types of manure (pig slurry, poultry manure and horse manure) were tested on 4 types of crops (barley, broccoli, leek and cauliflower). For each type of crop, manure with EM was added to one area and manure without EM was added to the other areas. Thus, for each crop, one area was defined for each type of manure with EM and one area for each type of manure without EM. In each of the test steps, the manure and soil were characterized and finally the crop obtained was analysed. With all this information, the difference in C, N and P recovery was determined for each of the manures and the effect of the EM on them. The manure treated with EM contained more plant available nutrients than the untreated manure as it had undergone enhanced biodegradation versus the untreated manure. The microbial product converted the inert organic matter in the manure into active organic matter, due to the humic and fulvic acids. Therefore, the degradation of organic matter within the manure was avoided and, in addition, soils water retention capacity was increased.

**Results of the solutions on nutrient closure**

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 773682.

**Carbon:** After harvesting the crops, soils where manure with EM had been applied had 5% - 27% more organic matter than soils where manure without EM had been applied, when compared against pre-trial SOM values for the trial plots.

**Nitrogen:** The action of the EMs has enabled an increased recovery of between 2% - 18% of the nitrogen contained in the manure. All trial plots received the same quantity of nitrogen irrespective of manure type.

**Phosphorus:** P recovery in manure has been obtained between 8% -27%, depending on the type of manure.

**Effect of solution on the environment**

**GHG:** The fixation of N and C due to the action of EM reduced $N_2O$ and $CH_4$ emissions.

**Energy:** The only difference between the baseline and the solution is that the solution requires further mixing or stirring the manure piles periodically during the 4-6 months in which the microbial product has to be working. Energy consumption for stirring: 12 L diesel for 200 t of manure. For the same amount of manure used for fertilization, more crop production is obtained when EM is added to the manure than when it is not added. Therefore, for the same amount of crop obtained, the energy consumption will be lower in the case of manure with EM added.

**Ammonia emissions:** Between 12% - 17% of the nitrogen contained in manure is lost as emissions in manure piles where EM is added. However, emissions were always lower than those of manure piles without EM added.

**Leaching to ground water:** By incorporating effective microorganisms (EM) into livestock manure the degradation of organic matter within the manure will be avoided and the soil will retain more water. Therefore, the risk of nutrient leaching is reduced.

**Final remarks:** The use of effective micro-organisms for the stabilization of manure to be used as bio-fertilizer is a promising solution for nutrient recovery, as well as for reducing ammonia or methane emissions and for improving soil characteristics by inhibiting the degradation of organic matter.

**Recommendations:** It is necessary to determine the amount of N, P and C present in the soil and in the manure itself before dosing. In addition, it is necessary to control the addition of EM to the manure piles, not only taking into account the amount of manure, but also other factors such as the intrinsic characteristics of the manure, climatic factors, etc.

**Transferability:** due to the low technological and investment requirements, the application of the solution is very straightforward.

## LL32: Annual Nutrient Cycling Assessment (ANCA)

*Peter Paree, ZLTO, Netherlands*

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 773682.

**Aim of the solution:** ANCA connects data in the nutrient cycle, to create a comprehensive overview of all inputs and outputs of the dairy farm. This overview validates the separate datasets. With this data, farmers can optimize their nutrient management plans.

**Key elements of innovation with respect to the state of the art:** Digital sources of data are linked, using standards to ensure inter-operability. The dataset is open for decision support tool developers, so tools are developed making use of the ANCA data and advisors include it in their farm visits. Farmers are at stake to decide if tools and advisors can use their data, by the data cooperative Join-Data.nl. The application is provided via the Dutch government enterprise agency.

**Working principle:** Farmers give authorization (by Join-data) to Zuivel.nl, that manages ANCA, to collect data from milk, meat, feed, fertilizer and manure transactions. These data feed automatically in the dataset of ANCA. Scientists and farmers board members decide about presentation of data and advisory modules.

**Results of the solutions on nutrient closure**

**Carbon:** Advisory modules to decrease use of mineral fuel and fertilizer, decrease greenhouse gas emissions.

**Nitrogen:** Advice to optimize the use of fertilizer and manure allows to recover more renewable N and save chemical fertilisers.

**Phosphorus:** Advice to optimize the use of fertilizer and manure allows to recover more renewable P and save chemical fertiliser.

**Effect of solution on the environment**

**GHG**: Farmer is supported to make better decisions on feed and fertilization, thus to decrease N overapplication and GHG emissions.

**Energy:** Advice modules enhance better use of diesel and electricity.

**Ammonia emissions:** Optimize feed strategy to decrease exhaust of ammonia to the air.

**Leaching to ground water**: Optimize fertilization to decrease leaching of minerals.

**Final remarks:** ANCA provides advice from internal modules, and data for advice modules, that give suggestions to farmers to optimize their management. At the end the farmers take the decisions, that lead to concrete improvements.

**Recommendations:** Reliability of data in ANCA is better than separate data sets, but even after crosschecks in ANCA, data may differ from reality. In some sectors, like organic dairy, there is discussion about the calculation methods.

**Transferability:** ANCA relies on data sets, which can be provided in a standard way. These sets differ in each country, so adaptions on data links are necessary for each implementation.

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## LL48: Recovery of energy from poultry manure and organic waste through anaerobic digestion

*Anna Grosser and Anna Jasińska (Politechnika Częstochowska: PCz, Poland)*

**Aim of the solution:** The purpose of this line of research is intensification of methane production from poultry manure. Research focuses on the improvement of energy recovery from poultry manure and organic waste through anaerobic co-digestion and/or pre-treatment of feedstock.

**Key elements of innovation with respect to the state of the art**: Co-digestion of poultry manure (rich in ammonia) with other waste streams, in order to make more effective the AD process.

**Working principle:** Anaerobic co-digestion of different streams of organic waste, including poultry manure, contributes to energy production, while the digestate can be returned to the land as a valuable organic-mineral fertilizer, thus reducing the use of chemical fertilizers. In this context, the research planned in the last phase aims to show that anaerobic digestion of three-components can be an effective tool for closing of nutrient loops such as carbon, nitrogen and phosphorous.

### Results of the solutions on nutrient closure

**Carbon:** transformation of the organic matter into stabilised and sanitised material, i.e. effective carbon for soil.

**Nitrogen:** Nitrogen during AD is transformed from organic into readily available nitrogen (ammonia) that can increase NUE. Ammonium nitrogen content ranged from 800 to 2750 mg/l.

**Phosphorus:** transformation of organic P into mineral forms.

### Effect of solution on the environment

**GHG**: non investigated, but direct emissions are likely to be decreased if nitrogen is used more effectively.

**Energy:** Co-digestion of PM with sewage sludge allowed for a pronounced improvement in the efficiency of the process.

**Ammonia emissions:** Not assessed during trial.

**Leaching to ground water**: Not assessed during trial.

**Final remarks:** Chicken manure can be successfully introduced into digesters at a wastewater treatment plant. Such action allows for a statistically significant increase in biogas production and, also, results in a reduction in volatile solids concentration within the feedstock. Moreover, the introduction of the manure together with the feedstock does not destabilize the operation of the digesters.

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**Recommendations:** Further research is recommended to focus on the quality of the digestate and the feasibility of its management.

**Transferability:** Due to the low TRL, it is not currently possible to discuss the transferability of the technology.

## LL61: Tailor made digestate products (tool development)

*Lies Bamelis, Filip Raymaekers and Astrid Croes (United Experts: UE, Belgium) ; Ana-Marija Spicnagel and Barbara Dukic (IPS; Croatia)*

**Aim of the solution:** The aim of the solution is to give the end users (i.e. those that might be interested in investing in new technologies) a first line insight into some of the solutions that were researched in the Nutri2Cycle project. The end users will be able to fill out their local circumstances and then receive a first economical evaluation as feedback.

**Key elements of innovation with respect to the state of the art:** There is no technical innovation linked to this solution. The "innovation" lies in the extension of an existing tool (which was developed in former EU-projects) with an economic evaluation.

**Working principle:** The tool will be made available online. Stakeholders can fill out their local (economic) framework (e.g. current cost of mineral fertilizers, cost of disposal of manure, transport costs) and will receive – after filling out the different fields – a first economic evaluation. This evaluation is only an indication and cannot be used as a detailed business plan. This latter should then be further elaborated in a tailor-made way (this is not part of the Nutri2Cycle project).

**Results of the solutions on nutrient closure:** The amount of nutrients and carbon recovered is taken from the other researched innovations within the Nutri2Cycle project and is not assessed directly in this solution. The focus of LL61 is more so on the economic impacts of the innovations.

**Carbon:** not applicable.

**Nitrogen:** not applicable.

**Phosphorus:** not applicable.

**Effect of solution on the environment:** not applicable.

The focus of this solution is the design of a first-level economic screening tool. The effect on the environment is also taken from the researched solutions. Where applicable the economic impact is taken into account (e.g. the production of renewable energy, the reduction of fees that need to be paid etc.). The tool does not take into account possible fines that might be imposed when the stakeholders would not meet the legal thresholds on environmental emissions.

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**GHG**: not applicable.

**Energy:** not applicable.

**Ammonia emissions:** not applicable.

**Leaching to ground water**: not applicable.

**Final remarks:** The tool will provide a first overview and estimation of what is feasible for the end user. This way the end user can/will be triggered (or not) to move forward in the application of the researched technologies. This makes the project results easily accessible and lowers barriers for actual implementation of the project's results.

**Recommendations:** The online tool is being expanded through several European projects so far. It would be nice to further elaborate the tool to make it a very good and decent overview (and 1st line evaluation tool) for nutrient recovery.

**Transferability:** The tool will be made in a way that the expansion of it will be continuously possible.

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# Research line 2. Innovative soil, fertilisation & crop management systems & practices for enhanced N, P efficiency and increased soil organic carbon content

*Task 2.3.2 leader ISA*

Research line 2 aims to test and demonstrate agronomic practices that can be implemented to improve nutrient use efficiency, reduce nutrient losses to the environment, and increase soil organic matter content.

This research line is divided into two sub-research lines and has, in total, three individual solutions: two solutions focus on means to increase soil organic matter content and the potential use of organic materials as alternatives to mineral fertilizers, while one solution looks at the potential of catch crops to reduce N losses.

Two solutions with TRL ≤ 6 are in tier 1, while the other two solutions with a TRL 7-9 are in tier 2.

Table 2: The three innovations associated with research line 2 of the Nutri2Cycle project

| Solution | Partner | Founded by N2C |
|---|---|---|
| LL 16 Using digestate, precision agriculture and no-tillage focusing on OM stocking in an area characterized by the lack of it (TRL 9) | UMIL, Italy | x |
| LL 17 Crop farmer using a variety of manure and dairy processing sludge to recycle and build soil C,N,P fertility (TRL6) | Teagasc, Ireland | x |
| LL 21 Catch crops to reduce N losses in soil and increase biogas production by anaerobic co-digestion (TRL 9) | IRTA, Spain | |

## Sub-research lines:

1) Practice for increasing soil organic matter content (SRL1):

Two individual studies are included in this sub-research line. The first solution (LL16) entitled “Using digestate, precision agriculture and no-tillage focusing on OM stocking in an area characterized by the lack of OM in sandy soil” is coordinated by UMIL and aimed at replacing mineral fertilizers by digestate for rice and maize fertilization while simultaneously increasing soil organic matter content. Any risk

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of pollution swapping (i.e. gaseous emissions and leaching) is fully evaluated to ensure a full NPC closed cycle.

The second study (LL17) entitled "Crop farmer using a variety of manure and dairy processing residues to recycle and build soil C, N, P fertility" is coordinated by Teagasc and aims to assess agronomic benefits (build soil C, N, P fertility) of different bio-based recycling derived fertilisers at field-scale for increasing nutrient recovery and recycling from different agri-food processing waste resources, and thus facilitating farmers' understanding of how best to incorporate such alternative fertilisers into their respective nutrient management plans.

2) Catch crops to reduce nitrogen losses in soil and increase biogas production by anaerobic co-digestion (LL21): this sub-research line (SRL 2) is coordinated by IRTA and aims to investigate the nutrient extraction efficiency from soil of three different catch crops species, as well as the viability of using them as co-substrates for the anaerobic co-digestion with dairy manure.

## Results and progress beyond the state of the art

All the solutions proved to be effective in:

- replacing chemical fertilisers,
- supporting yield,
- increasing carbon content and improving soil quality,
- Attention must be paid to the P budget and reduction of ammonia emissions.

For LL16 results indicated that the use of digestate **increased the carbon stock** in soil and can fully replace mineral nitrogen fertilizer with no decrease of crop yield. However, this solution did not close the P cycle since the digestate contains a larger amount of P than the one required by the crops used within the solution. The solution LL16 does not lead to increases in nitrogen and carbon losses (i.e. GHG and ammonia emissions, $NO_3$ leaching) to the environment when compared to the use of chemical fertilizers (urea). Furthermore, the anaerobic digestion aspect of LL16 allowed not only to recycle animal manure but also to produce renewable electricity.

The results of solutions LL17 have indicated that bio-based fertiliser options can be integrated into farmers' nutrient management plans for sustainable crop production, leading to chemical fertilisers replacement and increase in organic carbon in soil. Finally, this practice enhance soil health by increasing soil organic carbon and organic matter content. The results from both grassland and arable land trials indicate that fertiliser efficiency of a number of selected bio-based fertiliser products is statistically similar to chemical fertiliser in terms of achieving similar dry matter yield. The results from

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this study indicated that the selected bio-based fertilisers can supply up to 60% of the plants N requirement and between 60 and 100% of the plants P requirements. Nevertheless, the use of these bio-based fertilizers might lead to an increase in associated ammonia emissions if no mitigation strategies are implemented. Further data analysis is required to highlight the positive effect of such solution on the soil carbon content. The outcome would inform the different stakeholders (farmers, advisors, recycling-based SMEs) about the potential scope of increasing nutrient recovery and recycling from different agri-food processing based waste streams and thus facilitate displacing current chemical fertiliser needs.

The last solution (LL21), the production of catch crops for use in anaerobic digestion, showed to be a good strategy to reduce nitrogen leaching and increase C accumulation in soil. However, it is not as efficient in closing the P cycle since the amounts of P applied to comply with plant N requirements led to an overapplication of P. Anaerobic co-digestion of ensiled ryegrass and cow manure improves process stability and methane yield (43% and 47% in terms of $m^3$ $CH_4$ $t^{-1}$ waste for ryegrass and oilseed rape, respectively) in comparison with a conventional anaerobic mono-digestion of manure.

Overall, the production of catch crops can be seen as an efficient solution to minimize nutrient losses and the use of catch crops for anaerobic digestion of manure might result in a digestate able to replace a large amount of mineral N fertilizer.

## Lessons learnt from solutions in RL2

In the present research line, three different approaches showed to be efficient in closing the NPC cycle. The first was to consider the use of organic materials that can be used as a source of NPC for soil and plants. The second approach focused on reducing nutrient losses by leaching by using catch crops, and, finally, the last approach combined both by adopting strategies that reduce losses and considering some new soil inputs.

Overapplication of P when application is based on N needs and the increase of ammonia emissions are the two main challenges associated with the application of organic materials. Hence, the management of these organic materials (from storage to soil application) have to ensure that all these potential risks are minimized.

Anaerobic digestion appears as a key technology since it enables the production of energy and simultaneously a new fertilizer that can efficiently replace mineral fertilizers.

All the solutions tested here have a high TRL value indicating that they can right now be used by farmers. It can then be concluded that the solutions proposed in RL2 might provide a readily available answer to problems related with the NPC cycles at farm scale.

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## Solutions

### Using digestate, precision agriculture and no-tillage focusing on OM stocking in an area characterized by the lack of it (SRL1-LL16). (TRL 9)

*Fabrizio Adani, Massimo Zilio, Fulvia Tambone, Giuliana D'Imporzano, Axel Herrera, Ambrogio Pigoli, Bruno Rizzi (University of Milan: UMIL, Italy)*

**Aim of the solution**: The solution has the aim to recover nutrients (N, P macro and micronutrients) and carbon from sludge and wastes in a nutrient and carbon depleted area and to deliver the nutrients to soil in an effective way. The solution integrates anaerobic digestion (AD) of sludge and wastes, production of energy, production of digestate and ammonium sulphate (AS), injection of digestate and practices of precision agriculture (PA).

**Key element of innovation respect to the state of the art:** the solution effectively closes the NPC cycle, recovering from waste streams in an area where nutrients are not available. The solution put in line innovations to make the recovery effective (recovery of energy) and environmentally sound (injection of digestate, PA, minimum tillage, decrease of leaching and associated emissions).

**Working principle**: the system consists of an AD plant paired with a stripping system. The AD takes place in three reactors in a series at a size of 4500 $m^3$ each, under thermophilic conditions (55°C). The biogas produced by the plant is fed to a CHP (combined heat & power) unit in order to recover heat and electrical energy, primarily consumed on-site, while the excess is sent to the national grid. The stripping system decreases the Total Ammonia Nitrogen (TAN) level in the reactor, avoiding ammonia inhibition during the AD process while at the same time producing ammonium sulphate $(NH_4)_2\ SO_4$. Digestate and ammonium sulphate are used to fertilize rice and wheat fields, integrating PA practices (e.g. digestate injection, top dressing of the recovered AS, minimum tillage).

**Results of the solution on nutrient closure**

**Carbon**: based on the results collected during N2C, the solution contributed to an increase in soil carbon stock (2.1 g/kg in 4 years) thanks to the input of stabilized organic matter into the soil (average 7.5 tons Carbon/ha year).

**Nitrogen**: the solution enabled 100% replacement of chemical nitrogen fertilizer needs, without impacting crop yield.

**Phosphorus**: the solution did not close the P loop, as P was delivered in excess with respect to the plant's needs (54 kg/ha as P).

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## Effect of solution on environment

**GHG**: based on results collected the solution proved to cause the same direct emissions on fields ($N_2O$ and $CH_4$) as the use of chemical fertilizers (urea).

**Energy:** Thanks to AD the solution allowed to produce renewable electricity fed to the grid (65kwh/ton of sludge, or 8.5 kwh/kg of recovered nitrogen)

**Ammonia emissions:** based on results collected, the solution was associated with the same extent of ammonia emissions on fields as the use of chemical fertilizers (urea).

**Leaching to groundwater**: based on results collected the solution proved to cause the same $NO_3$ leaching as the use of chemical fertilizers (urea). P leaching was not measured.

**Final remarks**: the recovery of nutrients from sewage sludge represents, for carbon and nutrient-depleted areas, a way to close the C N P nutrient loop in crop production and increase the carbon stock in the long term. Therefore, anaerobic digestion represents a key technology to producing renewable fertilizers, thanks to both energy production and the modification that occurs to waste during the biological process, producing a material (digestate) with high amending and fertilizing properties.

**Recommendations**: according to data collected during N2C the following recommendations about the solution can be proposed: 1) use of nitrification inhibitor, as digestate is injected in pre-sowing, would further decrease $N_2O$ emissions (Herrera et al., 2022); 2) in P saturated soils, the separation of P from digestate, via struvite precipitation, would allow a better environmental outcome.

**Transferability**: The whole system has a TRL 9. Because of the combination of different technologies and practices, its transferability/applicability into other farm systems is more suitable towards medium to a larger scale companies, as the initial investment and later operation management can demand high cost.

- **Expert ranking:** At the EU level this technology is ranked as the 9th most transferable within the expert evaluations (transferability rank 2),
- **Survey ranking:** this technology is ranked as 7th within the survey feedback (1.9) evaluations in the short-term. For the medium-term timeframe, transferability rankings are slightly higher (6th rank).
- **Geographical scope:** the solution could be particularly relevant for Northern and Southern Europe in both the short and medium-term.

## CBA findings

The total variable costs in standard wheat production amount to 601,92 €/ha in Croatia and 675,00

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€/ha in Belgium. On the other hand, if innovative production principles are being used, total variable costs amount to 769,28 €/ha in Croatia and 829 €/ha in Belgium.

Gross margin (balance) calculation for Croatia amounts 238,08 €/ha in standard, and 70,72 €/ha in innovative scenario. In Belgium, gross margin calculation amounts 1.091,57 €/ha in standard and 832 €/ha in innovative scenario.

If analysing the N2C case scenario, but also several other research papers, it can be concluded that combining no-till and using digestate as main source of N for wheat production has a positive short- and long-lasting effect on OM in soil and can be a sustainable way of wheat production as it has no negative effects on yield quality as well as quantity.

## Producer perception of the innovation

**Barriers:** regulatory framework, (38%), followed by the difficulty of use (23%), and the need for training in how to use the innovation (23%)

**Enables**: better nutrient management (33%) and environmental benefits such as the reduction of greenhouse emissions and the reduction of nutrient loss (33%), followed by the economic benefits of saving on mineral fertilizers (17%)

## Synoptic table of findings across WPs

| Area | WP2: experimental data collection | WP4: modelling at EU level |
|---|---|---|
| **Carbon cycle** | increase in soil carbon stock (2.1 g/kg in 4 years) thanks to the input of stabilized organic matter into the soil | |
| **Nitrogen cycle** | the solution enabled 100% replacement of chemical nitrogen fertilizer needs, without impacting crop yield. | |
| **Phosphorus cycle** | the solution did not close the P loop, as P was delivered in excess with respect to the plant's needs (54 kg/ha as P). | |
| **GHG direct emissions** | based on results collected the solution proved to cause the same direct emissions on fields ($N_2O$=10.3 ± 6.8 kg/ha and $CH_4$=0.053 ± 0.04kga/ha) as the use of chemical fertilizers (urea) ($N_2O$=7.59 ± 3.2 6.8 kg/ha and $CH_4$= 0.036 ± 0.03 ) | $N_2O$ emissions show an increase as the total N application increases, thus the modelling give higher results.<br>However, this is compensated by a reduction in GHG emissions related to the production of mineral N fertilizer and additional soil organic carbon sequestration.<br>The application of digested sludge at maximum implementation share could reduce agricultural GHG emissions by 1.5 Mt $CO_2$ equivalents, implying a reduction of 0.34% of total EU agriculture emissions compared to the reference.<br>The potential GHG savings due to the anaerobic digestion of the sewage sludge was not considered, as that is not part of |

| | | |
|---|---|---|
| | | the agriculture sector, but this would increase the GHG mitigation potential of this solution. |
| **Ammonia emissions** | Based on results collected, the solution was associated with the same extent of ammonia emissions on fields (25.6 ± 9.4 kg/ha) as the use of chemical fertilizers (24.8 ± 8.3 kg/ha) (urea). | Decrease in $NH_3$ emissions.<br>The application of digested sludge at maximum implementation share could reduce ammonia emissions by 4.7 kt, implying a reduction of 0.18% of total EU agriculture $NH_3$ emissions compared to the reference. |
| **Leaching to groundwater** | Based on results collected the solution proved to cause the same $NO_3$ leaching as the use of chemical fertilizers (urea). P leaching was not measured. | According to EU level modelling increase in N leaching (2.6% at maximum implementation share), as total N input increases. If farmers would adjust the mineral fertilizer application in following crop, this could be reduced. |

## Crop farmer using a variety of manure and dairy processing sludge to recycle and build soil C,N,P fertility (SRL1-LL17) (TRL6)

*Patrick Forrestal, Elizabeth O’Carroll (Teagasc, Johnstown Castle, Ireland)*

**Aim of the solution:** Return nutrients to croplands by various organic manures and sludges. Demo LL17 was selected to be one of the fourteen lighthouse demonstration trial sites within the Nutri2Cycle project. LL17 involves a crop farmer, their agricultural advisor and agricultural researchers working together to return nutrients to croplands by trialing various organic manures and sludges which will lead to data collection and an understanding of C, N, P nutrient loop closures within the crop system, contributing to the overall aim of the Nutri2Cycle project.

**Key elements of innovation with respect to the state of the art:** replace chemical fertilisers by the correct application of local available by-products. By utilizing available by-products of the food industry, such as dairy processing sludges, and organic fertilisers, such as animal manure and slurry, the closure of nutrient loops such as carbon, nitrogen and phosphorous can be achieved within arable systems. Lighthouse demo LL17 aims to display such nutrient loop closures and reduced reliance on synthetic fertilisers within an arable system, thus contributing to the goals set within Nutri2Cycle.

**Working principle:** Since 2019, the lighthouse demo has been established on a private arable farm and consists of a trial site of 28 plots, which represent 7 fertiliser types over 4 replications. In 2022, the fertiliser products trialed were cattle slurry, poultry manure, pig slurry solids, calcium participated dairy processing sludge (dissolved air floatation sludge), and aluminium participated dairy processing sludge (activated sludge). Two further fertiliser types were trialed, which were chemical fertiliser and zero fertiliser (control) references. The crop type, along with known soil P and K levels, determined how much applied fertiliser the given crop required in order to promote optimal yield. Once this

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fertilizer value was determined, the known nutritional value of the various bio-based fertilizers was incorporated into the required fertiliser rate. Therefore, all plots received the same fertiliser rate, but, the cattle slurry, poultry manure, pig slurry solids, and dairy processing sludge plots received less chemical fertiliser, particularly less mineral phosphorus fertiliser, due to the delivery of nutrients from the bio-based fertiliser products. Crop yield and soil analysis has been undertaken throughout the trial, and, to date, the yields from the majority of the bio-based fertiliser plots are either comparable or superior to the yield from the chemical fertiliser only plots.

### Results of the solutions on nutrient closure

**Carbon:** Analysis of soil from the trial site displayed an increase in soil organic matter of, on average, 0.30% as % of DM from 2019 to 2021 within the bio-based fertiliser trial plots.

**Nitrogen:** The amount of recovered nitrogen supplied by the 5 trialled bio-based fertilisers in 2022 varied from 2% to 64% of the crop's needs.

**Phosphorus:** The amount of phosphorus supplied by the 5 trialled bio-based fertilisers in 2022 varied from 66% to 100% of the crop's needs.

### Effect of solution on the environment

**GHG**: No data available.

**Energy:** This lighthouse demo does not lead to additional energy production and energy production is not a by-product of this solution.

**Ammonia emissions:** No data available.

**Leaching to groundwater**: Not assessed during trial.

**Final remarks:** Trialing such bio-based fertilisers within an arable system will allow for a data bank to be created indicating, for given crops under given soil conditions, which bio-based fertilisers perform best and at what rate should the products be applied. During the trial an increase in soil organic matter (SOM) content was observed within the bio-based fertiliser trial plots, with the plots returning an average SOM content of 4.2% (as % of DM) at the end of 2019, which increased to an average SOM content of 5.2% (as % of DM) at the end of 2022. However, further soil analysis is required to determine at what depth(s) the SOM is concentrated within the soil profile as the farmer converted from conventional till to minimum till during the course of the field trial and this change may have impacted the observed increase in SOM. In addition, the trial showcased the possibilities of reducing mineral fertiliser dependency, in particular phosphorous, as the cattle slurry provided 44-66% of the crops P needs, the poultry manure provided 46-100% of the crops P needs, the pig slurry solids provided 63-100% of the crops P needs, while the two dairy processing sludge products provided the crop with all its P needs over the duration of the trial. By collecting information over such a time frame (2019 to 2022) data can be gathered that may be accessible to other farming groups and generate interest in the possible value of bio-based fertilisers on their respective arable farms.

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**Recommendations:** It is critical to know soil P and K levels along with the nutrient content of the bio-based fertilisers prior to calculating fertiliser application rate, as the majority of the trialed bio-based fertilisers are high in phosphorus and some are also high in potassium, particularly the pig slurry solids and cattle slurry.

**Transferability:** The present technology readiness level (TRL) ranking of the technology is 7, ''system prototype demonstration in operational environment'' as the technology involves an active demo site on a working arable farm. The technology could be widely adopted by arable farmers if availability and access to the bio-based fertilisers were secured. Investment in equipment for applying the bio-based fertilisers may be an additional cost (affordable) on farms unfamiliar with using sludges and slurries.

- **Expert Ranking**: the technology is ranked as the third most transferable technology in the short-term (transferability rank 2.7) and the second most transferable in the medium-term (transferability rank 4.4).
- **Survey ranking**: at EU level in the short-term (transferability rank 2.8) and the medium-term (transferability rank 3.6) it is ranked as the most transferable technology within the survey feedback.
- **Geographical scope:** The technology was ranked in the top three technologies for the Northern and Southern Europe conditions.

## CBA findings

Large quantities of by-products produced on farms need to be disposed of somewhere, and transport is quite expensive. Utilizing OM would greatly reduce the costs of disposal and purchase of mineral fertilizers.
Depending on the treatment used and the fertilization program, the cost varies. The use of chemical fertilizers involves the highest cost (453 €/ha), while the lowest cost is when using poultry manure (285 €/ha). There are no significant differences in the cost of implementation of broiler manure, cattle slurry, DAF sludge and activated sludge.

## Producer perception of the innovation

**Barriers**: "Economic considerations (too expensive, investment is not worth it since no economic return is expected)", "Regulatory framework that makes it difficult (building permits, resulting product not classified as fertilizer)" and other, each with a rate of 22%, followed by the "absence of economic subsidies or economic incentives"
**Enables:** the most important advantage is the economic benefit through savings on mineral fertilizers (31%). The second best advantage is the better nutrient management (19%), followed by "better compliance with the legislation" and "environmental benefits", and the reduction of emissions and of nutrient loss (both 17%).

## Synoptic table of findings across WPs

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| Area | WP2: experimental data collection | WP3: LCA |
|---|---|---|
| **Carbon cycle** | increase in soil organic matter of, on average, 0.30% as % of DM from 2019 to 2021 within the bio-based fertiliser trial plots. | no variation |
| **Nitrogen cycle** | recovered nitrogen supplied by the bio-based fertilisers varied from 2% to 64% of the crop's needs. | no indicators |
| **Phosphorus cycle** | phosphorus supplied by the bio-based fertilisers varied from 66% to 100% of the crop's needs. | no indicators |
| **GHG direct emissions** | Not measured | no variation |
| **Ammonia emissions** | Not measured | no variation |
| **Leaching to groundwater** | Not measured | $NO_3$ (kg)<br>Ca-DPS: 103 (+37%)<br>Al-DPS: -2.6 (-2%)<br>Phosphate emission to water (kg)<br>Ca-DPS: -6.2 (-37%)<br>Al-DPS: -19.5 (-116%) |

## Catch crops to reduce N losses in soil and increase biogas production by anaerobic co-digestion (SRL2-LL21).

*August Bonmatí[1], Erica Montemayor[1], Laura Burgos[1], Francesc Camps[2], Francesc Domingo[2], Marta Torrellas[1], Assumpció Antón[1], Victor Riau[1] ([1]Sustainability in Biosystems, [2]Sustainable Field Crops, IRTA, Spain)*

**Aim of the solution**: The solution has the aim to extract excess nutrients from soil by means of the inclusion of different catch crops species in the crop rotation. Catch crops are then used as co-substrates in the anaerobic digestion of cow manure to optimize biogas production.

**Key element of innovation respect to the state of the art:** The solution effectively closes NPC cycles by recovering nutrients from waste streams and limiting the leaching of excess nutrients to groundwater (catch crops extract the remaining NPK in the soil). The solution also optimizes the biogas production of cow manure using catch crops as co-substrate.

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**Working principle**: The technology consists of a biogas plant that processes cow manure. Digestate is used as organic fertilizer on a maize crop, the harvested maize then feeds livestock and the catch crop harvested post maize is used as co-substrate in the biogas plant. The valorisation of manure as fertilizer means recovery of nutrients, and the use of catch crops as co-substrate means an energetic valorisation.

## Results of the solution on nutrient closure

**Carbon**: the solution allowed to **increase the carbon stock** in soil thanks to the input of stabilized organic matter to soil (digestate).

**Nitrogen**: the solution enabled the replacement of 100% of the crops' chemical nitrogen fertilizer needs, and the crop yield was not negatively affected by this.

**Phosphorus**: the solution did not close the loop, as P was delivered in excess with respect to plant needs.

## Effect of solution on environment

**GHG**: The biogas plant indirectly reduces GHG as the use of biogas as an energy source reduces the use of fossil fuels.

**Energy:** Thanks to AD, the solution produced renewable electricity which was fed to the grid. An increase of 40-50% of $m^3$ $CH_4$ $t^{-1}$ waste of the co-digestion of manure and catch corps has been reported in comparison with a conventional anaerobic mono-digestion of manure system.

**Ammonia emissions:** Ammonia emissions increased to values of 4.59 kg N/ha when applying the digestate for maize fertilization compared to 0.63 kg N/ha with the use of mineral fertilizers.

**Leaching to groundwater**: Based on results collected, the use of catch crops showed to be a good strategy to reduce nitrate leaching to 4.55 kg N/ha instead of 12.76 kg N/ha observed with baseline solution (application of mineral fertilizers). Cu and Zn extraction by plants are also relevant, with values between 26 – 55 g/ha and 147 – 184 g/ha, respectively.

**Final remarks**: The inclusion of catch crops in crop rotation is a good solution to limit leaching of nutrients, and therefore recover and close nutrient loop. At the same time, the use of catch crops as co-substrate optimized energy recovery of manure increasing biogas yield.

**Recommendations**: according to data collected the following recommendations about the solution can be proposed: 1) Ryegrass, rapeseed and black oat are crops that showed good results in Mediterranean conditions. Nevertheless, it is necessary to select catch crop species according to pedoclimate conditions and growing periods; 2) The making of silage from catch crops , before their use as co-substrate in biogas plants, is a good practice to preserve their properties and maximize biogas production.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 773682.

**Transferability**: The system has a TRL 9. Because of the combination of different technologies (anaerobic digestion) and practices, its transferability/applicability into other farm systems is more suitable for medium to large farms, as the initial investment for anaerobic digestion is high.

## Research line 3. Tools, techniques & systems for higher-precision fertilization

*Task 2.3.3 leader WR*

Precision fertilization aims to fertilize the right type, at the right time, in the right place, and with the right rate (Reetz et al., 2015). This stimulates the efficient and effective use of nutrients, which has environmental, economic and societal benefits. All land-bound farming systems can benefit from precision fertilization. The focus of this research line is to test the environmental benefits that can be obtained by using the latest precision fertilization tools, techniques and systems. For example, the potential of using near-infrared sensors, soil scans, N-sensor, and drone techniques were tested. Precision fertilization contributes to closing nutrient loops by increasing the nutrient use efficiency. The nutrient use efficiency (NUE) is the ability of crops to take up and utilize nutrients for maximum yields (González-Fontes et al., 2017). Precision fertilization is dominantly used in combination with chemical fertilizer with a focus on nitrogen. However, the use of biobased fertilizers instead of chemical fertilizer was also investigated by this research line, including the potential of closing N, P, and C loops. The list of solutions included in this research line is shown in the table below.

The research questions that were investigated were: i) can higher nutrient use efficiencies be obtained by using higher-precision fertilization tools, techniques, and systems, ii) can biobased fertilizer be used for precision fertilization just like chemical fertilizer, and iii) how practitioners receive these innovative tools, techniques and systems in terms of implementation.

In table 3 are reported the solutions included in the RL3 .

Table 3: The six innovations associated with research line 3 of the Nutri2Cycle project

| Solution name | Partner | Founded by N2C |
|---|---|---|
| LL30 Precision farming coping with heterogeneous qualities of organic fertilizers in the whole chain | Thunen Germany | |
| LL28 Precision farming and optimised application: under-root application of liquid manure for maize and other row crops | Thunen Germany | |

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| | | |
|---|---|---|
| LL63 Use of organic materials for fertilization of maize grown on conventional or soil conservation practice | ISA Portugal | x |
| LL73 Field assessment of precision arable farming using bio-based fertilizers in potato growing | WR, the Netherlands | x |
| LL68 Integration of UAV/Drone and optical sensing technology into pasture systems | TEGASC Ireland | x |
| LL13 Sensor technology to assess crop N uptake | 3-R-Biophosphate, Hungary | x |

## Results and progress beyond the state of the art

The solutions are very different, but they all aim to increase the nutrient use efficiency.

This research line showed that precision-fertilization can result in higher nutrient use efficiencies in livestock systems (LL68) as well as in arable systems (LL13). Both solutions showed a reduction in the use of chemical N fertilizer, 20% reduction in the case of the livestock system, and 23% in the case of the arable system. LL13 assessed a reduction in N leaching and emissions of approximately 25%. The yield was not negatively nor positively affected by precision-fertilization, but the yields became more homogeneous across the field. Under-root application of liquid manure stimulated a steady early plant growth (LL63).

Besides chemical N fertilizer, bio-based fertilizers are also suitable to use for precision-fertilization. Using sensors to detect the variable composition of slurry manure (LL30) or changing from homogeneous application to variable application of slurry manure (LL73) can help the efficiency of nutrient application during the growing season. LL63 showed that variable rate application is also possible with slurry manure in European farming systems, and it has the potential to reduce the nutrient losses to the environment.

The success of innovative technologies and new bio-based fertilizer types depends on the support of and adoption by practitioners. The safe use of organic fertilizer instead of chemical fertilizers was demonstrated by LL63 and the benefits of precision fertilization were demonstrated by LL13. Although LL63 has very low investment costs, replacing chemical fertilizer for organic fertilizer will most likely only be implemented in areas with manure surplus. The Yara N-sensor (LL13) has high investment cost and will therefore more likely be implemented by large farms.

Precision agriculture with manure using the NIRS technology to assess the heterogeneity of an organic fertilizer results in quick, cheap and spatial exhaustive insights in the nutrient applicability (LL30). The result of classical chemical analysis used for analytical determination of plant-available nutrients in organic fertilizers is imprecise and also costly and time-consuming. Additionally, the analysis refers to a bulk sample. The sampling error and the analytical error accepted in fertilizer legislation are often exceeded. To obtain a representative sample, liquid manure or digestate has to be mixed thoroughly. Besides, mixing manure provokes climate-relevant aerial emissions, which can be avoided by this technology (LL30).

## Lessons learnt from solutions in RL3

Although the innovations tested by RL3 are very different, the main lessons learnt from RL3 are:

- Precision fertilization often results in a win-win situation as it increases the nutrient use efficiency and reduces the use of chemical or organic fertilizers.
- Precision fertilization using biobased fertilizer instead of chemical fertilizer contributes to closing N, P and C cycles. The adoption is currently most dominantly hampered by (national and European) policies. There is only a limited number of biobased fertilizers that meet the criteria of being referred to as recovered nitrogen from manure (RENURE). These are often the most refined biobased fertilizers, while the use of less refined biobased fertilizers in combination with precision fertilization also showed potential.
- The more efficient use of chemical and organic fertilizer results in a reduction in leaching of nutrients to ground- and surface water, and a reduction in GHG emissions. An exception is the trade-off between a reduction in $NH_3$ emissions due to manure injection and an increase in $N_2O$ emissions.
- Investment costs of precision fertilization tools, techniques and systems are often high, which makes precision fertilization techniques dominantly applicable for large(r) farms.

## Solutions

### Precision farming coping with heterogeneous qualities of organic fertilizers in the whole chain (SRL19-LL30). (TRL 9)

*Jörg Rieger, Bernhard Osterburg, Susanne Klages, Mareike Söder, Alexander Gocht (Thünen Institute: Germany)*

**Aim of the solution**: The main purpose of using near-infrared sensor (NIRS) is to cope with heterogeneous nutrient contents of liquid manure, to **optimise nutrient supply** according to plant needs and site-specific conditions. NIRS provides on-the-fly detection of nutrient contents of liquid manure which allows for precise application rates. Applying liquid manure to precisely meet the plant needs can **reduce the risk for N and P overapplication**, and therefore it can reduce N and P leaching to ground -or surface water.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 773682.

**Key element of innovation respect to the state of the art:** Near Infrared Spectroscopy (NIRS) for precision agriculture is dominantly used for estimating soil and crop properties (Mulla, 2013), and less for precision fertilisation. However, Ng et al. (2020) acknowledges the potential of NIRS sensors for precision fertilisation. Nutrients can more precisely be applied to the plant needs due to this innovation. This will increase the nutrient use efficiency of organic fertilisers and reduce the use of mineral N and P fertilisers.

**Working principle**: NIRS sensors operate with the principle of reflection and absorption of constituents in liquid manure within certain wavelengths. Nutrient sensing with NIRS can be done stationary and/or on-the-go rapid measurement. It is commonly employed during manure filling from storage into application tank or during mixing of manure in the application tank but can also be mounted to a tractor for real-time measuring nutrient composition of slurry during manure spreading. NIRS sensors can detect dry matter, total nitrogen, ammonium nitrogen ($NH_4$-N), potassium oxide ($K_2O$), and phosphorus pentoxide ($P_2O_5$). On-the-go detection of nutrient content of slurry allows employing different algorithms in variable rate fertilization such as setting a target application rate for a nutrient (e.g. N) and at the same time limiting application rate for another nutrient (e.g. P). Overall, this aids to optimize nutrient supply according to plant needs and site-specific conditions. Furthermore, by using NIRS sensors, tracking of manure transport and documentation of application rates help to improve nutrient management at farm level and to comply with legal frameworks.

**Results of the solution on nutrient closure**

**Carbon**: the variable application of organic fertilizers will result in a variable application of carbon. However, this solution focused on optimising macro- and micronutrient application.

**Nitrogen**: due to better information regarding N content in liquid manure, application rates can be more precisely adapted to plant needs and mineral N input can be reduced.

**Phosphorus**: due to better information regarding P content in liquid manure, application rates can be more precisely adapted to plant needs and soil P content.

**Effect of solution on environment**

**GHG**: A reduction in N application rate can lower $N_2O$ emissions. However, measurements of GHG emissions were not part of the experimental setup of this solution.

**Energy:** the NIRS sensor is mounted on the tractor and therefore no change in energy use is expected. Indirectly, the reduced use of organic fertilizer or chemical fertilizer can change(reduce) the energy consumption.

**Ammonia emissions:** Direct NIRS measurements can reduce manure storage time because there is no need to wait for laboratory results. This can reduce ammonia emissions during storage.

**Leaching to ground water**: Based on a literature study, this innovation reduces the risk for N and P overapplication, and therefore it can reduce N and P leaching to ground -or surface water.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 773682.

**Final remarks**: the main obstacle at present is that the NIRS manure sensor technology has been recognized as a nutrient quantification tool by very few federal states of Germany. In the remaining regions, where this technique is not acknowledged, farmers who export manure should still go through the conventional lab analysis to determine the nutrient content, which results in additional costs for farmers and no incentive for technology implementation.

**Recommendations**: This innovation can reduce the use of mineral fertilisers, but the purchase of the NIRS sensor requires an investment. After the investment, this technology will produce a large amount of data which can be used for the optimisation of the application of (organic) fertiliser. Conclusions on the beneficial effect of this innovation should be drawn with caution, because studies claim that economic and statistical analyses over a period of ten years showed no statistically significant economic advantage of precision fertilisation (Boyer et al., 2011; Liu et al., 2006; Anselin et al., 2004). An explanation of the small benefits can be that the application rate is already near optimum (Pannell, 2006). Economic margins of precision fertilizer applications will increase with increasing fertilizer and crop prices (Biermacher et al., 2009).

**Transferability**: The whole system has a TRL 9. At the moment, the innovation is applicable for larger farms or contractors due to investment cost. The larger the farm, the shorter the payback period.

- **Expert Ranking** "The use of sensor technologies in plant cropping systems is one of the most transferable technologies across Europe. This technology ranked 2nd most transferable in the short-term and 3rd most transferable in the medium-term European wide expert evaluation."
- **Survey Ranking** The technology ranked 4th most transferable in the short-term and 5th in the medium-term European wide NTF survey evaluation."
- **Geographical Scope:** the transferability of the application of sensor technologies in plant cropping systems is highest in Northern and Southern Europe in both the short and medium-term."

### CBA Findings

Standard production of potatoes includes mineral fertilisation, while production under innovative conditions includes the use of bio-based fertilisers.
The total variable costs in standard potato production amount to 3.501 €/ha in Croatia and 2.112 €/ha in Belgium, while in innovative production they amount to 4.409 €/ha in Croatia and 2.943 €/ha in Belgium.
Gross margin calculation for Croatia amounts 2.199 €/ha in standard, and 1.291 €/ha in innovative scenario. In Belgium, gross margin calculation amounts 5.238 €/ha in standard and 4.407 €/ha in innovative scenario. It can be seen from the above that the total variable costs of potato production are higher in the innovative than in the reference case scenario in both countries.

### Synoptic table of findings across WPs

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 773682.

| Area | WP2: experimental data collection | WP3: environmental modelling | WP4: EU level |
|---|---|---|---|
| **Carbon cycle** | variable application and increase in carbon | | |
| **Nitrogen cycle** | application rates can be more precisely adapted to plant needs and mineral N input can be reduced. | | Reduction in mineral fertiliser use ranges between 0.04 and 0.24 million tonnes (Mt).<br>The lower use of mineral fertiliser can be explained by a substitution effect with manure which is assumed to have a higher efficiency with NIRS (see chapter 3.2) and the decrease in UAA due to enforced technology implementation.<br>The direct effect of NIRS on manure use ("Tech only") is relatively high, ranging from 0.1 to 0.4 Mt which is equivalent to an EU-wide reduction of 1.9% and 7.4%, respectively. |
| **Phosphorus cycle** | application rates can be more precisely adapted to plant needs and soil P content. | - | |
| **GHG direct emissions** | Not measured | Where over-application is common, precision slurry application can markedly reduce the risk of over-application and hence emissions to the environment, without compromising crop yields. | The solution could reduce GHG emissions by 3.2 Mt $CO_2$ equivalents (0.8%), which is mainly due to the mitigation of $N_2O$ emissions (-1.6%) and NH3 emissions (-4%).<br>The N-Sensor at maximum implementation share could reduce agricultural GHG emissions by 1.9 Mt CO2 equivalents, implying a reduction of 0.4% of total EU agriculture emissions compared to the reference. |
| **Ammonia emissions** | Direct NIRS measurements can reduce manure storage time thus reduce ammonia emissions during storage. | | Reduced $NH_3$ emissions by 4%. |
| **Leaching to groundwater** | Based on a literature study, it can reduce N and P leaching to ground | | |

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 773682.

## Precision farming and optimised application: under-root application of liquid manure for maize and other row crops (SRL20-LL28). (TRL 8)

*Jörg Rieger, Bernhard Osterburg, Susanne Klages, Mareike Söder, Alexander Gocht*

*(Thünen Institute, Germany)*

**Aim of the solution**: This solution aims to replace mineral N and P fertilizers for under-root application around maize seeds by liquid manure. In oversupplied soils of intensive livestock production areas, this solution can contribute to replacement of mineral N and P fertilizers to increase the nutrient use efficiency and, thus, contribute to closing the nutrient loops.

**Key element of innovation respect to the state of the art:** this innovation ensures that nutrients are available to the crop right after germination below the soil surface near roots, so roots can grow better towards them, especially in dry periods of the growing season. Optimizing the nutrient uptake can reduce the loss of nutrients to the environmental. This is the first type of precision application technology for under-root fertilisation in maize with manure.

**Working principle**: a precise deposition of the manure close to the seed (in the seeding lines and in a precise soil depth) is necessary. Normally, the manure is applied before seeding the crop. The technology consists of a precise application technique in terms of positioning of manure and seeds, making use of GPS information, and in terms of dosage.

### Results of the solution on nutrient closure

**Carbon**: More C in manure will be returned to the soil compared to current practice of using mineral fertiliser for under-root fertilizer application in maize.

**Nitrogen**: using liquid manure for under-root fertilizer application replaces mineral fertiliser input, improves N use efficiency of manure and reduces N surplus.

**Phosphorus**: using liquid manure for under-root fertilizer application replaces mineral fertiliser input and improves P use efficiency of manure and reduces P surplus.

### Effect of solution on environment

**GHG**: slurry injection substantially reduces $NH_3$ emissions, but it can increase $N_2O$ emissions ( Velthof and Mosquera, 2010; Hou at al., 2015; Flessa and Beese, 2000) compared to broadcast application. By increasing the N and P use efficiency, the carbon footprint is lowered.

**Energy:** Experts stated that there is significant higher energy use (fuel) compared to broadcast application.

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**Ammonia emissions:** slurry injection substantially reduces $NH_3$ emissions, but it increases $N_2O$ emissions compared to broadcast application (Velthof and Mosquera, 2010). Reduced $NH_3$ emissions also decrease the formation of secondary particulate matter and indirect $N_2O$ emissions.

**Leaching to ground water**: the reduced use of N/P-fertiliser and the increased nutrient use efficiency have a positive effect on the N and P leaching to ground -and surface water. To increase the P use efficiency, Federolf et al. (2016) recommended injecting the manure prior planting.

**Final remarks**: The combination no-till and injection substantially reduces sediment-bound P losses and $NH_3$ volatilisation (Dell et al., 2011).

**Recommendations**: On one hand, this innovation reduces the use of mineral fertilisers, but on the other hand the purchase of machinery for under-root application of slurry brings investment costs.

**Transferability**: The whole system has a TRL 8. This technology is only applicable to maize or similar row crops. It is unknown whether the investment cost will pay back in the decreased chemical fertilizer costs.

### Use of organic materials for fertilization of maize grown on conventional or soil conservation practice (SRL20-LL63). (TRL 4-5)

*David Fangueiro (Instituto Superior de Agronomia: ISA, Portugal)*

**Aim of the solution**: This solution aims to use manure and compost for maize fertilization in combination with soil conservation practices (no-tillage). The use of organic fertilisers decreases the use of mineral fertilisers like rock phosphate. Besides, the application of organic fertiliser helps to sequester carbon in the soil and close the N, P and C cycle.

**Key element of innovation respect to the state of the art:** this solution introduced a more sustainable way of farming in a region that normally heavily relies on chemical fertilizer. This solution combines the use of composted chicken manure or slurry manure with no-tillage.

**Working principle**: this solution uses composted chicken manure or slurry manure in combination with no-till to improve circularity and soil quality. The use of composted chicken manure and pig slurry as substitute of mineral fertilizer for basal fertilization is studied in three different soils. This aims as an example to neighbouring farms to show the safe use of organic instead of mineral fertilizers.

**Results of the solution on nutrient closure**

**Carbon**: manure returns to the soil instead of being exported. Manure contains carbon and therefore this solution will increase the soil organic carbon content.

**Nitrogen**: the use of organic fertilizer will reduce the use of chemical N fertilizer.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 773682.

**Phosphorus**: the use of organic fertilizer, which also contains significant amounts of P, results in a significant application of P which has to be considered in the fertilization plan.

**Effect of solution on environment**

**GHG**: No significant differences in terms of $N_2O$ emissions with the use of organic fertilizers relative to mineral fertilizers in conventional tillage farming. However, the use of compost in no tillage led to a significant increase of $N_2O$ emissions relative to mineral fertilizer.

**Energy:** NA

**Ammonia emissions:** Although no measurements were performed in this experiment, the use of organic fertilizers, namely pig slurry, can result in significantly higher ammonia emission if a proper application technique is not used. Nevertheless, the use of band application or pre-treatment by acidification might minimize such impacts.

**Leaching to ground water**: NA

**Final remarks**: this technique reduces the use of chemical N and P fertilizer and also improves the soil organic carbon content. In combination with no-tillage, this solution has potential for increasing soil organic carbon even further.

**Recommendations**: partial replacement of mineral fertilizers with organic material to supply N, P and C to soil. In some cases the amounts of organic fertilizer to be applied have to be limited by the resulting P inputs in order to avoid any environmental issue.

**Transferability**: the technique has TRL 4 “Technology validated in the lab” to 5 “Technology validated in relevant environment”. Low investment costs (50 euros/ha for application of compost and slurry and acquisition of compost) makes this technique attractive for adaptation. However, the applicability of this technique is limited to the areas with compost or manure surplus.

### Precision arable farming using bio-based fertilizers in potato growing (SRL21-LL73). (TRL 5)

*Chantal Hendriks[a], Niels Kanters[b], Peter Paree[b], Rembert van Noort[b], Erik Meers[c], Ivona Sigurnjak[c], Vaibhav Shrivastava[c], Jan Peter Lesschen[a] ([a]Wageningen University & Research: WUR, Netherlands; [b]Southern Agriculture and Horiticulture Organization: ZLTO, Netherlands; [c]University of Ghent: UGent, Belgium)*

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 773682.

**Aim of the solution**: The solution has a double aim; closing nutrient loops and increasing the nutrient use efficiency, by replacing chemical fertilizers by biobased fertilizers, using precision fertilization.

**Key element of innovation respect to the state of the art:** The application of biobased fertilizers with different refinement levels using precision fertilization has not been done before. Precision fertilization is commonly carried out using chemical fertilizer or highly refined biobased fertilizers.

**Working principle**: The mineralisation rate of different biobased fertilizer products, the fertiliser replacement value and the large-scale application of these biobased fertilizers in the field was tested. The effect on potato yield (qualitative and quantitative characteristics) was analysed. Besides, the precision application of manure and plasma treated manure (reducing $NH_3$ emissions) was tested based on spatial maps of the electrical conductivity of the soil.

**Results of the solution on nutrient closure**

**Carbon**: Other products resulting from the digestion plant are OM-rich soil enhancers. This product was not tested in this trial. Precision fertilisation using manure or plasma treated manure can have an effect on the soil organic carbon content in the long-term.

**Nitrogen**: Stimulating the use of bio-based N fertiliser using precision agriculture will enhance the recycling of N and reduce N losses. Refinement level of two nitrogen bio-based fertilisers (liquid fraction of digestate (LFD) versus ammonium sulphate (AS)) did not impact the potato production when it is combined with manure application at the beginning of the growing season (common practice in the Netherlands). The N release rate is slightly higher for AS (142±19%) compared to LFD (113±24%) and the nitrogen fertiliser replacement value is slightly higher for AS (1.13) compared to LFD (1.04). The incubation experiment (Hendriks et al., 2022) showed comparable $N_2O$ emissions after application for AS (0.02 g of $N_2O$ per 100g N applied) and for LFD (0.03 g of $N_2O$ per 100g N applied).

**Phosphorus**: The soil has a high phosphate status, P will therefore not be limiting, no additional P fertilizer products were therefore used.

**Effect of solution on environment**

**GHG**: Compared to mineral fertiliser, biobased fertilisers showed lower GHG emissions because of the rapid hydrolysis of mineral fertiliser products, resulting in increased $NH_4^+$ availability (Hendriks et al., 2022). The incubation experiment (Hendriks et al., 2022) showed comparable $N_2O$ emissions after application for AS (0.02 g of $N_2O$ per 100g N applied) and for LFD (0.03 g of $N_2O$ per 100g N applied).

**Energy:** Large amounts of product need to be applied when the less refined biobased fertilisers (LF) had to be applied. Therefore, the application of liquid fraction of digestate cost more energy (fuel) compared to the other biobased fertilisers.

**Ammonia emissions:** NA, this could not be measured in the laboratory.

**Leaching to ground water**: N leaching was not determined directly, but nitrate was measured in the subsoil after the potato harvest (Hendriks et al., 2022). $NO_3$-N residue in the subsoil was higher than

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the threshold value during the experiment where all fields received equal amounts of fertiliser (310 kg N/ha). The $NO_3$-N residues in the soil were 264±64 kg N/ha for fields that received AS and 205±85kg N/ha for fields that received LFD. For the fields that also received manure at the beginning of the growing season the $NO_3$-N residues were 245±10 kg N/ha for AS and 258±56kg N/ha for LFD. This means that the biobased fertilizers have a higher risk on leaching of nitrate after the growing season.

**Final remarks**: adoption of this technique is hampered by current national and European policies. BBF products that meet the RENURE criteria have the biggest chance for being adopted as a replacement for chemical fertiliser.

**Recommendations**: in areas with a manure surplus, it is recommended to replace chemical fertilizer for biobased fertilizer by potato growers. The nutrient use efficiency can probably be increased when variable amounts of pig slurry and/or biobased fertilizers are applied and catch crops are used after the potato harvest. Allowing the use of biobased fertilisers as RENURE products will boost the adoption of this innovation.

**Transferability**: The present technology readiness level (TRL) for the technology is 5,''technology validated in relevant environment''. This solution is applicable on a wider scale, but especially in regions with manure surplus. The larger the farm size, the more likely farmers adopt precision fertilization techniques. The use of bio-based fertilisers is independent of farm size.

- **Expert Ranking: the solution** is ranked 10th in short-term transferability by the expert panels (rank of 2). The technology improved in ranking over the medium-term within the expert evaluation to 5th place (rank of 3.7)."
- **Survey Ranking solution** is ranked 10th in short-term transferability (rank of 1.7), but within the NTF survey participant's evaluation the technology fell further to 11th place (rank of 2.5) over the medium-term."
- **Geographical Scope:** with regard to expert evaluations the transferability of potato growing with refined pig manure fractions is highest in Northern Europe, whereas the transferability is highest in Southern and Northern Europe within the survey feedback.

**Producer perception of the innovation**

**Barriers:** The main disadvantage perceived was that a regulatory framework makes adoption difficult, making it challenging to obtain construction permits and, above all, it means the resulting products cannot be classified as fertilizers.

**Enables:** The main benefit perceived was the reduction in both emissions and the loss of nutrients, which is closely related to greater efficiency in nutrient management.

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## Integration of UAV/Drone and optical sensing technology into pasture systems (SRL22-LL68). (TRL 4-5)

*Elizabeth O'Carroll, S.M. Ashekuzzaman, Patrick J Forrestal (TEAGASC, Ireland)*

**Aim of the solution**: LL68 formed part of the longlist of technologies at the initial stages of the Nutri2Cycle project. LL68 involves the use of optical sensing technology to tailor nitrogen rates on grazed grassland before further nitrogen fertiliser is applied onto the grassland by the farm manager. The urine/dung patches typically display excessive N loading, Therefore, by identifying these areas before applying any N fertiliser, the risk of nitrogen losses from the system is reduced. Additionally, the N loop can be closed further as, by using spatial maps generated by the technology, N fertiliser products are applied where specifically needed within the pasture and at the correct rate, as opposed to the traditional approach of homogeneous application throughput the pasture.

**Key element of innovation respect to the state of the art:** It has been shown that N loading within urine patches can exceed 700 kg N/ha equivalent, with such patches becoming hotspots for N losses within the system in the form of ammonia, nitrous oxide and N leaching. It is estimated that when using the Teagasc dairy farm at Johnstown Castle as a trial site approximately 20% of the recently grazed paddock area will be allocated to urine/dung patches. This will result in a 20% reduction in applied N fertiliser but no expected reduction in grass yield. By avoiding N application onto urine/dung patches, N nutrient loops are closed further as less N fertiliser is applied and the risk of N losses from the paddock reduces, i.e. reduced risk of excessive N loading.

**Working principle**: Optical sensing technology such as the 'Spikey' instrument can detect urine patches within the pasture. This detection can be combined with precision agricultural technology where further sensors can prevent the application of nitrogen fertiliser from a fertiliser spreader when passing over these identified urine patches.

### Results of the solution on nutrient closure

**Carbon**: Effect on the soil C stock has not been measured. However, no direct effect is expected, as grass yield is not reduced.

**Nitrogen**: The technology could potentially result in up to a 20% reduction in applied N fertiliser.

**Phosphorus**: NA

### Effect of solution on environment

**GHG**: By preventing N fertiliser application onto urine/dung patches where the N load is already high, the risk of N losses from the grassland system in the form of GHG nitrous oxide reduces. Reduction in fertilizer N application will reduce mineral fertilizer associated $N_2O$ emissions. The emission factor for CAN fertiliser in Irish grassland is 1.49%.

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**Energy:** No energy is produced from implementing the technology although it may lead to a reduction in energy consumption along the production chain as it results in reduced need of N fertiliser.

**Ammonia emissions:** By preventing N fertiliser application onto urine/dung patches where the N load is already high the risk of ammonia emissions from the grassland system reduces.

**Leaching to ground water**: By preventing N fertiliser application onto urine/dung patches where the N load is already high the risk of N leaching from the grassland system reduces.

**Final remarks**: If equipment cost and operator skillset were not an issue such a technology could be highly applicable throughout grass based grazing systems that are prevalent in certain countries across the E.U., including Ireland.

**Recommendations**: Due to the novelty of such technologies within the Irish dairy industry further exposure to and training in operating the optical sensing technology and interrupting spatial mapping findings is necessary in order to determine how likely uptake of such a technology would be.

**Transferability**: The present technology readiness level (TRL) for the technology is 4,''technology validated in lab''. The technology is transferable to grassland based farms, of which there are many across Europe. However, factors such as the cost of the optical sensing technology and skillset to either operate the devices or interpret the spatial findings may be a barrier to transferability at present.

### Sensor technology to assess crop N status (SRL23-LL13). (TRL 9)

*Zoltán Hajdu (SOLTUB, Hungary)*

**Aim of the solution**: This solution aims to improve the precision application of N by using the YARA N-sensor and GreenSeeker instead of conventional mineral N application without using sensors for different agronomic crops.

**Key element of innovation respect to the state of the art:** this study introduces variable mineral N application in areas where the soil is heterogeneous and so the N application should be heterogeneous. The sensor will help apply the N fertilizer in the right amount and at the right place within a field, which results in a higher nutrient use efficiency of crops.

**Working principle**: Both technologies, the YARA N-sensor and the GreenSeeker, measure the Normalised Difference Vegetation Index (NDVI), by capturing light reflectance at specific wave bands that are related to the crop's chlorophyll content and biomass. Crop N uptake can be estimated from this information. From the collected raw field data, the NDVI maps are prepared and used to create the fertilisation maps. The optimum application rates are sent to the controller of the variable rate spreader or sprayer, which will adjust the fertilizer rates accordingly. The whole process of

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determining the crop's nitrogen requirement and application of the correct fertilizer rate happens instantaneously, with no time delay. This enables "real time agronomy" to be possible.

**Results of the solution on nutrient closure**

**Carbon**: NA, this solution only focuses on mineral N.

**Nitrogen**: reducing excessive N fertiliser application will result in reduced GHG emissions and N leaching to ground- and surface water.

**Phosphorus**: NA, this solution only focuses on mineral N.

**Effect of solution on environment**

**GHG**: Prevention of excessive N fertiliser application will reduce $N_2O$ emissions, however, these have not been measured in this research.

**Energy:** Diesel fuel consumption was two times 3 l/ha; one for scanning the field and the other for fertilizer application. However, at the moment the scanning is done in parallel with the crops spraying so farmers only need to drive one time. This is done in autumn with liquid fertilizers (head fertilizer application).

**Ammonia emissions:** NA.

**Leaching to ground water**: It is expected that N leaching to ground- and surface water can be reduced due to increased nutrient use efficiency.

**Final remarks**: Precision agricultural technologies such as the tractor mounted N- sensor help farmers in preventing nutrient losses and reducing soil heterogeneity, in terms of nutrient the right amount of fertilizers at the right place. The technology has several benefits. It improves nitrogen use efficiency, crop productivity, reduces costs of fertilizer inputs. On the other hand, the technology requires investment costs and labour skills.

**Recommendations**: with enthusiasm this technique is adopted by Hungarian farmers, because the application rate of N fertilisers is adapted to soil and crop’s specific requirements, creating more homogeneous crop yields with agronomic and environmental benefits.

**Transferability**: The present technology readiness level (TRL) for the technology is 9, ‘’actual system proven in operational environment’’. Especially larger farms buy the YARA N-sensor and GreenSeeker sensor, due to the relatively high investment costs. However, the Hungarian state supports precision agriculture technologies. The technique can be adapted for different crops in the plant cropping systems.

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## Research line 4. Biobased fertilizers (N, P), soil enhancers (OC) from agro-residues

*Task 2.3.4 leader UGENT*

Research line 4 (RL4) aims to investigate various nutrient recovery and recycling solutions to produce bio-based fertilisers (BBFs), namely N- fertilizers, P-fertilizers and organic C-rich soil enhancers derived from agricultural secondary raw materials. The substitution of mineral fertilizers with bio-based alternatives is crucial in materials and energy recovery, since the production of fertilizers is highly energy and resource consuming as they are based on fossil fuels (e.g. N-fertilizers on Haber–Bosch process) or fossil ore deposits (e.g. phosphate rock). When developing a new fertilizer technology through valorization of waste streams, it is important to maintain the balance of nutrients, along with undertaking economic and environmental assessments. In addition, impact on crop yield and soil quality should be considered, as should the CNP nutrient use efficiency of the bio-based fertilisers when compared against commercial reference products. This particular research line is therefore the heartfelt centre of Nutri2Cycle containing n. 17 of the shortlisted solutions (see D2.2 for all short-listed solutions). These solutions address both innovative and farm-level practical nutrient recovery technologies and / or recovered products. For the majority of these solutions, agronomic tests (field trials and / or pot experiments) were conducted to showcase the agronomic performance of these recycling derived fertilizers against synthetic fertilizers. In addition to agronomic performance, economic aspects and environmental impacts of the selected solutions have also been reported in associated deliverables, i.e. D3.3 and D3.4, respectively. The outcomes of the solutions under RL4 bring together valuable information for farmers who are interested in replacing their reliance on synthetic fertilizers and present evidence-based support for policy makers at national and EU levels to further improve existing regulations and applications for alternative fertilizing products.

In table 4 are reported the solutions investigated in RL4.

Table 4: The seventeen innovations associated with research line 4 of the Nutri2Cycle project

| Solution | Partner | Founded by N2C |
|---|---|---|
| LL 23 Pig manure refinery into mineral fertiliser using a combination of techniques applicable at industrial pig farms | UMIL, Italy | x |
| LL14 Substituting mineral inputs with organic inputs in organic viticulture | CIA 1779, France | |
| LL6 Concentrate from vacuum evaporation/ stripping as nutrient-rich organic fertilizer | UGent, Belgium | |

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| | | |
|---|---|---|
| LL47 Production of growing substrates for horticulture application from poultry manure, solid state digestate and biochar through composting | PCz, Poland | x |
| LL62 Blending of raw and treated organic materials to produce organic fertilizers (NPC) | ISA, Portugal | x |
| LL49 Nitrogen and phosphorus recovery from pig manure via struvite crystallization and design of struvite based tailor-made fertilizers | CARTIF, Spain | x |
| LL52 Pilot-scale crystallizer for P recovery | UMIL, Italy | |
| LL65 Struvite as a substitute of synthetic P fertilizer | UGent, Belgium | x |
| LL20 Low temperature ammonium-stripping using vacuum | IRTA, Spain | x |
| LL15 Closing the loops at the scale of farm : using the livestock manure to fertilize the feeding crop on agroforestry plots | CIA 1779, France | x |
| LL57 Recovered animal manures for precision fertilization of apple orchards and vineyards | ISA, Portugal | x |
| LL66 Application of digestate in large scale orchards | IPS, Croatia | |
| LL1 Ammonium stripping / scrubbing and $NH_4NO_3$ as substitute for synthetic N fertilizers | Inagro/UGent, Belgium | x |
| LL2 Ammonium stripping / scrubbing and $NH_4SO_4$ as substitute for synthetic N fertilizers | Inagro/UGent, Belgium | x |
| LL9 Liquid fraction of digestate as a substitute for mineral N & K fertilizer | Inagro/UGent, Belgium | x |
| LL55 Manure processing and replacing mineral fertilizers in the Achterhoek region | WR, the Netherlands | |
| LL22 BIO-PHOSPHATE: high temperature reductive thermal process recovery of concentrated Phosphorus from animal bones | 3-R-Biophosphate, Hungary | |

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## Results and progress beyond the state of the art

The solutions under RL4 showcased the feasibility of BBFs against synthetic fertilizers on agricultural lands in a holistic approach, with some solutions optimising the recovery of energy and nutrients (e.g., solutions under RL1) in a closed cycle and further supported with field trials as a complementary investigation under RL4 with solutions LL1-2-9. For instance, the field trials were conducted directly on either manure, slurry, digestate or recovered products from these materials, such as ammonium salts. The results on the field trials / pot experiments showed that these BBFs are feasible to use as a replacement for mineral fertilisers due to their high nitrogen fertiliser replacement value (N-FRV) along with no significant negative impact on crop yield, nutrients uptake or soil properties.

However, there are still a number of practical issues related to the ease of utilising these products (e.g. machinery / methods for land application, marketability). When field trials were not performed in solutions, then more technical insights on the nutrient recovery technology and quality of the recovered products have been reported.

Overall, we can conclude that agricultural circularity can be stimulated by (i) solving the practical issues that occurred during the application of BBFs, (ii) making sure that these BBFs are on the component material category (CMC) list of the Fertilising Products Regulation (EU) 2019/1009 so they can legally replace mineral fertilisers, and (iii) reducing the surplus of slurry (export or treatment) manure to stimulate the use and fair pricing of fertilising products. There are also some additional factors to convince farmers to use BBFs, such as national policies, subsidies, creating infrastructure for collection, handling, storage, distribution and sanitation of the BBF products.

## Lessons learnt from solutions in RL4

The BBFs recovered from agro-residues are **good candidates to replace synthetic fertilizers** by the technical, environmental, agronomic and economic point of views.

The optimal use of BBFs, according to crop requirements in different growing conditions, increases the economic return of agricultural production and provides farmers with the most efficient BBFs for a given farm / region. In this aspect, field trials using a variety of BBFs were established under RL4 in order to assess the **food and feed safety** along with the human health safety aspects of incorporating BBFs into a crop nutrient management plan.

The recovered nutrients from agricultural waste and / or agricultural by-products perform equally well when compared against the baseline scenarios of commercial synthetic chemical fertilisers, and, in

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most cases, are associated with similar environmental impacts in terms of emissions. For instance, the results of LL55 suggest that digestate treatment producing a RENURE (Recovered Nitrogen from Manure) displays the same profile in terms of environmental impacts of fertilisation as the use of conventional chemical fertilisers considered as baseline (e.g., N-leaching grassland: baseline: 27.2 kg N/ha/yr, solution: 22.3kg N/ha/yr; $N_2O$ emission grassland: baseline: 8.36 kg N/ha/yr, 13.11 kg N/ha/yr). Findings from solution LL6 demonstrates that 90% of N in the evaporator concentrate was found in the organic form, which, if optimised, could reduce the associated $NH_3$ volatilization during product storage and application. Approximately 43% of the organic N in this product could become available for plants within three weeks post land application.

However, development of innovations in agriculture also involves product and market development which is a key component of a successful business model.

## Solutions

### Pig manure refinery into mineral fertiliser using a combination of techniques applicable at industrial pig farms (SRL7-LL23). (TRL 9)

*Fabrizio Adani, Giuliana D'Imporzano, Fulvia Tambone, Ambrogio Pigoli, Bruno Rizzi, Axel Herrera (University of Milan: UMIL, Italy)*

**Aim of the solution:** The solution aims to reduce pig slurry volume to allow better management of nutrients, both for exporting or easing its management on site (top dressing with readily effective nitrogen). The products are a solid fraction (19% wet weight (ww)), a concentrate (a RENURE like material, 33% ww) and clean water (48% of mass).

**Key elements of innovation with respect to the state of the art:** The process produces a concentrate that can be labelled as RENURE (e.g., recovered $NH_4$-N/Total Nitrogen >90%). It uses optimized sequential Reverse Osmosis (RO) steps and a continuous remote monitoring system to allow better control of processing fluxes (e.g. pressures), prevent fouling and provide maintenance of membranes when needed. The energy needed and costs are quite low for the type of process (7 $kwh_e/m^3$ of slurry, compared to 11-30 $kwh/m^3$ of other equivalent system (Samanta *et al.,* 2022)).

**Working principle:** The system starts with mechanical separation via a screw-press, followed by a vibrating screen to separate the main solid fractions (19% of the global mass), and then the liquid fraction coming from the last separator enters through the first stage of RO able to process a high content of total solids by using Vibratory Shear Enhanced Processing (VSEP) system. The VSEP allows to retain most of the nutrient content in a concentrate fraction (33% of the global mass), then the subsequent RO steps (2nd and 3rd) use extra-fouling resistant membranes to produce the permeate i.e. clean water that can be safely used as industrial water or released into the environment representing the 48% of the global mass slurry treated.

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## Results of the solutions on nutrient closure

**Nitrogen:** The solution reduced the total volume of the liquid nutrient-rich fraction by 50%; this facilitated its management on-site and future exportation. The produced concentrate allows the use of top dressing in place of mineral fertilizers. Because of its RENURE characteristics (e.g., recovered $NH_4$-N/Total Nitrogen >90%), it could be used in a Nitrate Vulnerable Zone (NVZ) instead of chemical fertilizer. Field trials demonstrated the refined product has the same nutrient use efficiency as that of chemical N fertiliser.

**Phosphorus:** As for nitrogen, the solution reduces water content, thus allowing export and easing the management of nutrient distribution. P can be exported, following N export, in the ratio of 42% of the total content in the slurry.

## Effect of solution on the environment:

**GHG:** Ammonia and $NO_3$ leaching were not measured in-field, as field trials mainly focused on the productivity and substitution value of the exported of concentrate. However, as the amount of N delivered to soil is equal to the one of the control (chemical fertilizers) and the yields are equal, it could be estimated that $N_2O$ emissions might be equal to chemical fertiliser treatments.

**Energy:** The solution demands 7 $kwh_e$ for processing $1m^3$ slurry (25 MJ as electricity).

**Water:** The solution allows the recovery of clean water (48 % of initial mass)

**Ammonia emissions:** not investigated.

**Leaching to ground water:** not investigated.

**Final remarks:** The membrane filtration technology represents a solution for producing recovered fertilizers (e.g. mineral concentrates) with RENURE characteristics to be exported or used in NVZ as a substitute for synthetic fertilizer.

## Transferability:

- **Expert and survey ranking:** At the EU level the pig manure refinery into mineral fertilisers technology is ranked in the short-term as the 5th and 9th most transferable technology within the expert evaluation (averaged transferability rank 2) and the survey feedback (averaged transferability rank 1.8) respectively. In the medium-term this technology is ranked as the 8th most transferable innovation for both the experts and the NTFs.
- **Geographical scope**: high potential for this technology is in Eastern Europe, whereas, when evaluating the NTF survey data, the technology received the highest transferability rank for Southern Europe.

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## Substituting mineral inputs with organic inputs in organic viticulture (SRL3-LL14). (TRL 6)

*Jean-Philippe Bernard, Mathilde Blanc, Corinne Lombard (Chambre interdépartementale d'agriculture 17-79 (CIA 1779), France)*

**Aim of the solution:** The proposed solution has the aim to substitute completely or in part commercial fertilisers for organic agriculture with BBFs produced on site, while maintaining the previous level of fertilization and keeping in line with the organic standards. Products are sunflower oil-cake produced on the farm, and a commercial compost specific for organic agriculture.

**Key elements of innovation with respect to the state of the art:** In organic agriculture, in general, it is essential to monitor the amount and timing of applied fertilisers to ensure they are used as efficiently as possible within the system in order to limit NP losses. The farm that is part of the study, "EARL Le Petit Bois", produces its own organic sunflower oil-cake and implements a follow-up system together with the CIA 1779 in order to monitor the NP intakes from the vine with the use of precision agriculture farming tools.

**Working principle:**

Replace organic commercial fertilisers with BBF. Two trials were undertaken over two years

The first year, three modalities were tested on the vineyards: a) 100% oil-cake; b) 50% oil-cake and 50% commercial compost; c) 100% commercial compost

The second year, only two modalities were tested: a) 100% oil-cake and b) no fertilization.

The question of crop nutrition in organic farming is usually dealt with by taking the soil fertility into account. The latter can be improved thanks to organic soil improvers.

Depending on the soil analysis, the amount of organic amendments in variable quantity can

be made:

- on the plots traditionally provided with organic materials (and not having undergone too deep recess): from 2 to 5 tons of humus, i.e., 20 at 50 tonnes of farmyard stock or 8 to 20 tonnes of industrial stock,
- on the plots with low organic matter or having been deep-shattered: 5 to 15 tonnes / ha of humus, i.e. 50 to 150 tonnes of farm compost or 20 to 60 tonnes of industrial compost.

The inputs must be made with well decomposed products, being low in nitrogen, rich in waste of plant origin, ligneous and buried superficially (maximum 15 cm deep) at least 3 to 6 months before planting. It is possible to spread them one year before, and to cultivate a cereal or other annual crop in the meantime. Soils should be regularly worked superficially (i.e. incorporation of cover crop) between the crop and the plantation to facilitate the decomposition of organic matter. The ideal is to divide the inputs into 2 or 3 annual spreads, interspersed with cereals-type annual crops. Placing cereals with buried straw is a good way to correct the humus rate of a soil (1 ha cereals produces 1 ton of humus,

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more if the straws are incorporated; moreover, the aceramic system favours the maintenance of the soil structure).

But, the transition from conventional farming to organic farming needs to rely on bio-based fertilizers whose efficiency is comparable to synthetic fertilisers in order to avoid significant decreases in yield. The encountered problem then is to find bio-based products authorized by organic standards at an acceptable price.

Therefore, the solution for this kind of farming is to build a fertilization pathway combining the recycling of the on-farm crop residues with other external sources of organic fertilizers. In the present case, the farmers have to choose to use their main farm residue, the oil cakes issue from the production of seed oil, as a livestock food or as bio-based fertilizer.

It will be necessary:

- to rely on tools to assess the good synchronization between NP inputs from organic fertilizers, soil participation and needs of grape vine in nutrients
- to select the practices to optimize the balance between carbon storage and organic fertility in soil of grapevine plots.

**Results of the solutions on nutrient closure**

**Nitrogen:** replacement of synthetic N fertiliser . Oil-cakes' total N = 37 kg/ton of raw matter

**Phosphorus:** A reduced consumption of phosphate rock is expected because of the supply of organic P from oil-cake instead of extraction material: oil-cake's $P_2O_5$ = 19 kg/ton of raw matter

**Carbon:** an increase in soil quality and recovered nutrients is predictable because of the supply of organic matter for vineyard: oil-cake's OM = 68.2 % fresh matter and its use of oilcake as a fertilizer, that is taken into account in the fertilization plan.

**Effect of solution on the environment:**

**GHG**: not investigated.

**Energy:** Not applicable.

**Ammonia emissions:** not investigated.

**Leaching to ground water:** not investigated.

**Final remarks:** This demonstration aimed to conduct the farmers to a recycling practice of the own residuals as fertilisers by proving the objective agronomic effects of oil-cake. The feedback of the farmers we got was quite good.

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## Concentrate from vacuum evaporation/ stripping as nutrient-rich organic fertilizer (SRL4-LL6). (TRL 4)

*Hongzhen Luo, Ivona Sigurnjak, Ana Roble-Aguilar, Evi Michels, Erik Meers (Ghent University: UGENT, Belgium)*

**Aim of the solution:** This solution aims to close the N loop in agriculture by promoting the complete substitution of synthetic mineral N fertilizers using the novel product, i.e. evaporator concentrate (EVA) recovered from manure processing via an integrated anaerobic digestion-centrifugation-evaporation process. The agronomic value of the novel product was evaluated at full-scale field trial by testing the effect on crop growth and yields as well as the soil properties as compared to synthetic fertilizers.

**Key elements of innovation with respect to the state of the art:** The evaporator concentrate (EVA) was recovered from an integrated nutrient recovery cascade consisting of anaerobic digestion, centrifugation, evaporation and reverse osmosis membrane filtration. The resulted concentrate is only 14% of the fed volume, showing high priority in reducing the cost for transportation and storage. The EVA is also characterized as an organic-rich solution (organic matter content 46% on dry matter basis) containing multiple plant-essential nutrients (N, P, K, S) and trace elements (i.e. Ca, Fe, Mg, Mn, etc.). Moreover, 90% of N in the evaporator concentrate is in organic form, which can reduce the $NH_3$ volatilization during storage and application. However, 43% of the organic N in this product can become available for plants within three weeks after soil application, as indicated by a soil incubation conducted at laboratory controlled conditions. Therefore, this product can be used as good substitutes for synthetic fertilizers meeting the nutrients demand of plants while reducing the N loss to environment. However, little has been reported about the agronomic performance of this product in field application settings.

**Working principle:** The agronomic value of the evaporator concentrate (EVA) was evaluated in a full-scale field trial under maize cultivation. The growth of maize shoot and root, the N uptake in the aboveground biomass and the soil N dynamics after fertilization was monitored during the growing season. The applied rate was set as 105 kg N $ha^{-1}$ according to a pre-test on the soil. This led to 65 kg $P_2O_5$ $ha^{-1}$ and 259 kg $K_2O$ $ha^{-1}$ supplied by EVA, thus no extra mineral P or K fertilizer was applied. The results were compared with a synthetic fertilizer reference using calcium ammonium nitrate (CAN) at the same N rate, and a control treatment without any N fertilizer. The P and K rate in control and synthetic reference were compensated by triple superphosphate (TSP, 40% $P_2O_5$) and potassium chloride (60% KCl) at the same NPK rate to be the same as EVA.

Results of the solutions on nutrient closure

**Nitrogen:** Application of evaporator concentrate resulted in the complete replacement of synthetic mineral N fertilizer, with no significant difference in the maize biomass yield, crop N uptake or soil nitrate residue compared to the synthetic reference using calcium ammonium nitrate. The N fertilizer replace value of the evaporator concentrate was calculated as 65 %.

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**Phosphorus:** Application of evaporator concentrate also achieved complete replacement of synthetic mineral P fertilizer, with no significant difference in the maize biomass yield, crop P uptake or soil total and extractable P content compared to the synthetic reference using triple superphosphate.

**Effect of solution on the environment:**

**GHG**: Not determined.

**Energy:** processing (Reverse osmosis and evaporation) requires significant amount of electricity (D3.4).

**Ammonia emissions:** not investigated.

**Leaching to ground water:** groundwater was not investigated, but the soil nitrate residue was analogous to that of the chemical fertiliser.

**Final remarks:** The evaporator concentrate recovered from evaporation process can be used as an organic-rich fertilizer in crop production. It also has high potential to be used as substitute for synthetic NPK fertilizers with no significant impact in crop yield, nutrients recovery or soil properties.

**Transferability:**

- **Expert ranking:** Growing with refined pig manure fractions is ranked 10th in short-term transferability by the expert panels (rank of 2). The technology improved in ranking over the medium-term within the expert evaluation to 5th place (rank of 3.7)."
- **Survey Ranking** In the survey participants' evaluation solution is ranked 10th in short-term transferability (rank of 1.7), but within the NTF survey participant’s evaluation the technology fell further to 11th place (rank of 2.5) over the medium-term."
- **Geographical Scope:** with regard to expert evaluations the transferability is highest in Northern Europe, whereas the transferability is highest in Southern and Northern Europe within the survey feedback.

**Synoptic table of findings across WPs**

| Area | WP2: experimental data collection | WP4: EU level |
|---|---|---|
| **Carbon cycle** | complete replacement of synthetic mineral N fertilizer, with no significant difference in the maize biomass yield, crop N uptake or soil nitrate residue compared to the synthetic reference using calcium ammonium nitrate. The N fertilizer replace value of the evaporator concentrate was calculated as 65 %. | |
| **Nitrogen cycle** | Application of evaporator concentrate also achieved complete replacement of synthetic mineral P fertilizer, | The reduction in N mineral fertilizer use for the manure treatment options is relatively low, |

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| | | |
|---|---|---|
| | with no significant difference in the maize biomass yield, crop P uptake or soil total and extractable P content compared to the synthetic reference using triple superphosphate. | with a reduction of 0.45% (mineral concentrates), as only the Netherlands, Belgium and one region in Germany have a pig manure surplus. |
| **Phosphorus cycle** | Not measured | - |
| **GHG direct emissions** | Not measured | Pig manure processing to mineral concentrates has a potential GHG reduction of 0.23 Mt (0.05% of EU total emissions in the agricultural sector). |
| **Ammonia emissions** | Not measured | Pig manure processing to mineral concentrates has a potential reduction in $NH_3$ emission by 13.4 kton (0.49%). |
| **Leaching to groundwater** | The soil nitrate residue was analogous to that of the chemical fertiliser. | Pig manure processing to mineral concentrates has a potential reduction in N leaching by 2.2 kton (0.1%). |

## Production of growing substrates for horticulture application from poultry manure, solid state digestate and biochar through composting (SRL5-LL47). (TRL 3)

*Danuta Dróżdż, Krystyna Malińska, Katarzyna Wystalska, Jolanta Sobik-Szołtysek (Politechnika Czestochowska: PCz, Poland)*

**Aim of the solution:** The main goal of this work is to close C, N, and P loops by converting biodegradable material, mainly poultry manure, into organic soil enhancers and growing media, such as dry poultry manure, poultry manure-derived biochar, compost, in order to enhance soil properties and increase the plant yield. Conversion of poultry manure into organic soil enhancers includes composting, pyrolysis and drying. In the case of composting, the analysis of C, N, and P was performed in a laboratory composting set-up with a particular focus on ammonia emissions and nitrogen losses.

In Poland, most of the poultry manure is used as fertilizer for crops, especially root crops (i.e. beets and potatoes), corn and canola. These plants are tolerant to high levels of nitrogen more than other crops. Their yield is also highest when chemical fertilizers are applied (Agroprofil, 2020). Poultry manure contains about 15 kg/t N, 15 kg/t P, 4 kg/t K, and 24 kg/t Ca. Farmers apply raw poultry manure and liquid fraction from poultry manure mainly in the autumn and spring (IUNG, 2000; Agroprofil, 2020). According to data from 2020, 35% of soils in Poland are dominated by very acidic and acidic soils (pH below 5.5); 37% by slightly acidic soils (pH 5.6- 6.5) and 28% by neutral and alkaline soils (pH> 6.5) (Statistical Yearbook of Agriculture, 2020). However, it is more common for soils to become acidified through the use of mineral fertilizers. However, the use of organic fertilizers, for example,

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based on poultry manure (i.e. compost, diluted poultry manure) makes it possible to raise the soil pH, which is important for plants.

**Key elements of innovation with respect to the state of the art:** The overall goal of this work was to investigate the potentials of poultry manure as a source of organic soil enhancers, such as dried poultry manure, poultry manure derived biochar and poultry manure derived compost, and, to determine their respective physicochemical properties, effects on soil properties and impacts on the growth of cherry tomatoes.

**Working principle:** The proposed solution aims to maximize the closing of the carbon, phosphorus, and nitrogen cycle loops during the processing of poultry manure. A novelty in this solution is based on the concept of poultry manure biorefinery where different processes, i.e. thermal and biological, are used to convert poultry manure into added value products that can be applied as soil enhancers for improving soil properties and increasing the plant yield.

In a poultry manure biorefinery, poultry manure will be converted through a) pyrolysis into biochar, b) composting into composts, c) drying to produced dried poultry manure.

**Results of the solutions on nutrient closure**

**Nitrogen:** The amount of input nitrogen in the compost mix (before composting began, fresh mix) was 395 g N in dry weight. In the mature compost, 121 g N in dry weight was observed. The mass of nitrogen decreased by 69%-72% in the compost from the composting reactor.

Dach et. al., (2012) composted animal manure in the laboratory reactors and reported that the content of nitrogen which decreased by 7-9% and $NH_4$ emissions by 92.72% in comparison to the initial values. Ogunwande et al. (2008), who also composted poultry manure, obtained similar results. They reported nitrogen losses of 60-80%. Awasthi et al., (2021) composted poultry manure with the addition of biochar which reduced nitrogen losses by 10%. Only 38-41% was emitted from the composting reactors in the form of ammonia.

**Phosphorus:** The amount of input phosphorus in the compost mix (before composting began, fresh mix) was 0.27 g P in dry weight. In the mature compost, 0.06 g P in dry weight was observed. The content of phosphorus in the final mass of the composting mixture from the composting reactor decreased by 77.78%-84%. Some of the phosphorus was converted by microorganisms during the composting process, while approximately 22% of the phosphorus was lost via leachate and during the evaporation process in the composter. Similar results were also obtained by Tiquia et al, (2002) who composted animal manure in a windrow, and phosphorus losses were 53%. High phosphorus levels were observed by Ogunwande et al. (2008) who composted poultry manure. The phosphorus losses ranged from 40-67% during composting of poultry manure. In the study of Zhang et al., (2021) it was confirmed that phosphorus can be characterized in animal manure-based composts in the form of struvite crystals ($MgNH_4PO_4$- $6H_2O$). The different forms of phosphorus in compost have an impact on the microbial population structure during composting. Therefore, phosphorus losses can be

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associated with intensive phosphorus utilization by microorganisms.

**Effect of solution on the environment:**

**GHG:** Not measured.

**Energy:** Not determined.

**Water:** The initial mass of the composting mixture decreased by 64.29%-73% from the composting reactor. The weight loss was significant because compost was matured for 5 months under laboratory conditions, and the water loss during this time was 81%-88%. However, the loss of organic matter was 43%-60% for the compost from composting reactor. Tiquia et al., (2002) composted animal manure in a composting windrow and reported a compost mass loss of 57%. Composting in a windrow is slower and there are lower mass losses compared to composting in composting reactors under controlled conditions. Similar results were obtained by Petric et al., (2009) in which the mass of poultry manure compost after the process decreased by 62% and the loss of organic matter was estimated at 40-45%. Dach et. al., (2012) also investigated the mass balance of animal manure mixtures during composting. They observed a decrease in the mass of the compost mixture between 38 and 47%. Water losses from compost prepared from poultry manure, estimated by Ahn et al. (2007), reached about 40-65%. The increased aeration of the compost, the higher the water losses.

**Final remarks:** Processing methods which allow conversion of poultry manure to value added products with high fertilizing potential can include drying, composting and pyrolysis. These methods allow conversion of raw poultry manure into stable materials which can be easily stored, transported, mixed with soil, and distributed in the agricultural fields. With the introduction of new legislation on fertilizing products (i.e., Fertilizing Product Directive from July 16, 2022) it is expected that the interest in such resources as poultry manure to be used as substrates to obtain e.g., soil organic enhancers will increase. Poultry manure-based soil enhancers could – after fulfilling the conformity assessment – become available on the EU market. This opens more possibilities for the countries with high poultry production, and thus significant quantities of poultry manure to be managed.

Therefore, the results from this research work can contribute to the advancement of the state of the art by providing a better understanding of the properties of soil enhancers derived from poultry manure, in particular biochar derived from poultry manure, and their effects on soil properties and plant growth.

**Transferability**

**Expert and survey ranking:** : Across Europe the solution  is listed as one of the most transferable technologies throughout the evaluations.
within the expert evaluation

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**Survey ranking**: within the survey feedback in both the short and medium-term timeframes it is ranked as the second most transferable
**Geographical scope:** the highest potential of using poultry compost & pig slurry to replace mineral fertilisers is in Northern Europe

### Blending of raw and treated organic materials to produce organic fertilizers (NPC) (SRL5-LL62). (TRL 4)

*Joana Prado, David Fangueiro (Instituto Superior De Agronomia: ISA, Portugal)*

**Aim of the solution:** To produce manure-based fertilizers (MBF) with specific N:P ratios to substitute mineral fertilizers for basal fertilisation. The production can be done by combining the manures between them or by adding small amount of mineral fertilizers to each manure.

**Key elements of innovation with respect to the state of the art:** The use of manures with the common ratios found in the mineral fertilizers, to valorise the use of manure and avoid the over-application of P, as result of fertilization planning be firstly conducted accounting the N vehiculated.

**Working principle:** Blending manures or manures with mineral fertilizers, without many techniques in order to keep the production prices low. In some case it was necessary to use low technology treatments, such as, solid-liquid separation, to produce the intended N:P ratio. For instance, the liquid fraction was used to produce the N enriched manure-based fertilizer.

**Results of the solutions on nutrient closure**

**Nitrogen:** in general, the N-enriched solutions did improve the N mineralization and nitrification rate compared to the raw manures, and in some cases were equivalent to the rates observed for the mineral fertilizers. In a pot experiment the solutions were identical in terms of N uptake compared to mineral fertilization, thus obtaining equivalent NUE.

**Phosphorus:** improvement in N/P ratio allows to better close CNP cycles at once.

**Effect of solution on the environment:**

**GHG**: In an incubation experiment, the greenhouse gases (GHG) emission was measured to compare the environmental impacts of using MBF. Two baselines were used: the exclusive use of mineral fertilisers and use of the raw organic materials (manures or slurries).

Comparing to the mineral fertilisers, the MBFs had higher GHG emissions, due to the incorporation of organic matter that stimulates microbial activity and consequently $CO_2$ emission.

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Comparing to the raw organic materials, some MBFs were able to decrease GHG emissions, whereas others were not. For instance, poultry manure with urea and poultry manure with superphosphate emitted less GHG than poultry manure used exclusively. However, only half of the MBFs were compared to the corresponding raw materials. Further studies of these MBFs are required.

**Energy:** increase for distribution of manure mixes is compensated by the saving of synthetic fertilisers.

**Ammonia emissions:** not investigated.

**Leaching to water:** In a leaching experiment, various manure-based fertilisers (MBF) were created with different N:P ratios and were compared to chemical fertilisers. The P leaching potential was considerably higher with the exclusive application of mineral fertilizers, in contrast to these MBF (comparing the treatments with the same N:P ratio), indicating that blending of animal manures or slurries with mineral fertilisers decreased nutrient solubility and consequent losses of P.

**Final remarks:** Further assessments are required, but the preliminary results show that the MBFs created in this work demonstrated a high potential to substitute mineral fertilizer in basal fertilization. The most successful MBFs depended on the N:P ratio tested: for the 0.5:1 ratio, blending of poultry manure with superphosphate showed the highest potential, whereas for the 2:1 ratio, it was pig slurry blended with the liquid fraction of pig slurry that showed more favourable results, and for the 1:1 ratio, it was poultry manure blended with pig slurry.

## Nitrogen and phosphorus recovery from pig manure via struvite crystallization and design of struvite based tailor-made fertilizers (SRL6-LL49). (TRL 6)

*Francisco Corona, Francisco Verdugo, Dolores Hidalgo (Fundacion Cartif: CARTIF, Spain)*

**Aim of the solution:** Separation and recovery of P and N from slurry in the form of struvite fertilizer. The crystallisation of N and P in the form of magnesium ammonium phosphate hexahydrate ($MgNH_4PO_4{\cdot}6H_2O$) also known as MAP (magnesium ammonium phosphate) or struvite, is one of the possible techniques used to recover nutrients from the digestate, obtaining a product that can be used as a base for high quality organic fertilisers.

**Key elements of innovation with respect to the state of the art:** The recovery of P from agro-livestock wastes as well as from wastewater effluents in the form of struvite has a number of advantages: it provides a slow-release fertiliser that improves the agronomic properties of the waste, reduces pollution caused by the generation of agro-livestock wastes, can help to solve and prevent fouling problems in wastewater treatment plants and reduces pollution related to excessive discharge of nutrients (N and P) in wastewater effluents.. Conventional mineral P fertilisers are readily soluble and can cause high P concentrations in overland runoff when rain falls shortly after fertiliser application, leading to an increased risk of eutrophication of receiving water bodies. Struvite, being a less soluble

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and "slow-release" fertiliser, can provide a longer-term source of P for crop growth than readily soluble forms of P, resulting in a better match to plant P demand in the growing season and increasing its use efficiency (Withers et al., 2014).

**Working principle:** Ammonium and phosphate can be removed from the digestate by precipitation of a phosphate and ammonium salt called struvite. The reaction that takes place is described below:

$$Mg^{2+} + NH_4^+ + PO_4^{3-} + 6H_2O \rightarrow MgNH_4PO_4 \cdot 6H_2O$$

In practice, excess magnesium (Mg) is used to improve the reaction yield and thus the efficiency of nutrient recovery. As the concentration of N is usually much higher than the concentration of Mg and P in the digestate, a source of Mg and a source of P can be added to the digestate externally. The operating pH is usually between 8.5 and 9.0. The resulting struvite is a good slow-release fertiliser. The chemical addition of the reagents and the precipitation of the struvite crystals can be carried out in the same reactor or in different stages.

Experiments for the study of struvite crystallisation at pilot scale were carried out in batch mode in a 50 L volume fluidised bed reactor (FBR).

Before crystallisation, the samples were subjected to a solid-liquid separation step by centrifugation, in order to eliminate the solids that the digestate might contain, and thus favour the mixing of the reagents to produce the struvite crystallisation and avoid fouling and blockages in the reactor.

A FBR of own design was used for the pilot scale tests of the study carried out in this chapter. It is a 50 L working volume reactor made of borosilicate glass with a cylindrical shape. The reactor has an internal diameter of 20 cm and a total height of 2 m, so that the L/D ratio = 10 recommended for FBRs is achieved.

Once the sample was centrifuged, the digestate and the necessary amount of Mg salt was added to the reactor, so that each sample had its corresponding Mg/P molar relationship. The Mg salt used was $MgCl_2 \cdot 6H_2O$. Finally, the pH of the samples was around 8.5, so the addition of a concentrated alkali (50 % w/w NaOH solution) was necessary to raise the pH value to 9.0.

After the reaction time had elapsed, the crystal harvest was collected by means of the solids discharge valve and the sample was concentrated by centrifugation to obtain the struvite crystals formed. The sedimented phase (crystals) was subjected to a drying process in an oven at 40 ºC for 48 h, to remove moisture. Moreover, the supernatant obtained from centrifugation (crystallisation mother liquor) was removed for subsequent analysis of N, P and Mg concentration.

## Results of the solutions on nutrient closure

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 773682.

**Nitrogen:** As P acts as a limiting reagent in the reaction to obtain struvite (1 mol of P, 1 mol of N and 1 mol of Mg to obtain 1 mol of struvite), therefore the amount of N recovered in the form of struvite will depend on the amount of P present in the liquid phase of digestate.

**Phosphorus:** Under optimal operating conditions, about 90% of the P contained in the liquid phase of the digestate used as raw material is recovered in the form of struvite. This alternative can allow the transportation of organic phosphorous fertilizer (in a solid and concentrated form) and its application in fields located far away from the production place, as assessed in deliverable D3.4.

**Effect of solution on the environment:**

**GHG**: direct emissions were not investigated but a separation of N/P /C flows can generate a better management of all the nutrients and thus decrease direct emissions

**Energy:** As well as previous parameter, N and P struvite content avoid the energy consumption of the production of this same amount of nutrient in a traditional way i.e. mineral fertiliser production. Thus, the energy consumption would be lessened due to the application of both nutrients in one organic product.

**Leaching to water:** The liquid stream obtained in the struvite crystallization process (mother liquor) will contain a small amount of nutrients and organic matter, which can be used for fertigation.

**Final remarks:** The crystallization of N and P in the form of struvite is a nutrient recovery technology with great potential, so that the digestate streams obtained in anaerobic digestion processes of organic waste can be valorised, with good prospects from a technical and economic point of view.

## CBA findings

For the current market prices (i.e. situation 2019) the farmer should not pay more than 0.175 €/kg in Croatia or 0.108 €/kg in Flanders.
The research showed as well that the price for struvite can be up to 62% higher in Croatia (i.e. region with nutrient shortage) then in Flanders (i.e. region with the nutrient excess).

## Synoptic table of findings across WPs

| Area | WP2: experimental data collection | WP3: LCA |
|---|---|---|
| Carbon cycle | Separation of carbon and P allow a better management of flows and cycle closure | Effective SOM decrease |
| Nitrogen cycle | struvite can act as N fertiliser | No circularity indicator in LCA |

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| | | |
|---|---|---|
| **Phosphorus cycle** | Under optimal operating conditions, about 90% of the P contained in the liquid phase of the digestate used as raw material is recovered in the form of struvite. This alternative can allow the transportation of organic phosphorous fertilizer (in a solid and concentrated form) and its application in fields located far away from the production place. | No circularity indicator in LCA |
| **GHG direct emissions** | not measured<br>but a separation of N/P /C flows can generate a better management of all the nutrients and thus decrease direct emissions | Increase<br>In conclusion, considering the whole life cycle (direct emissions and upstream process), the transport of struvite to fields located less than 200 km away is less impactful for 13 of 16 impact categories that the transport of digestate<br>Thus, this practice can be a sustainable management option that contributes to addressing the main challenges such as nitrogen over-fertilisation of crop fields, resource use, the environmental pollution or the transport of untreated digestate over long distances |
| **Ammonia emissions** | not measured | increase |
| **Leaching to groundwater** | The liquid stream obtained in the struvite crystallization process (mother liquor) will contain a small amount of nutrients and organic matter, which can be used for fertigation. | increase |

## Pilot-scale crystallizer for P recovery (SRL6-LL52). (TRL 4)

*Fabrizio Adani, Giuliana D'Imporzano, Tommy P. Sciarria, Ambrogio Pigoli, Bruno Rizzi, Axel Herrera (University of Milan: UMIL, Italy)*

**Aim of the solution:** To separate and recover P from other nutrients in the form of struvite, using an alternative low-cost magnesium (Mg) source, i.e. seawater bittern (SWB), which is a by-product of sea salt processing.

**Key elements of innovation with respect to state of the art:** The reuse of by-product of sea salt processing (i.e. Seawater bittern (SWB)) as an alternative use of low-cost magnesium. The simple design of the device requires just the electricity input due to mixing and allows, as a result, recovery of 70% of P.

**Working principle:** An air-lift reactor was differentiated into three zones: riser, clarifier and collector. The supersaturated condition of the riser zone ensured the struvite growth, enhanced by the recirculation and up-flow of small particles (centres of nucleation). The clarifier section consisted of a

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quiet zone where these particles rise and fall. In the collector, the nuclei settled once their settling velocity was higher than the up-flow velocity. The inputs are the liquid fraction of digestate (fed continuously at 0.29 L $h^{-1}$) and a seawater bittern solution as Mg source (fed continuously at 0.02 L $h^{-1}$), added to allow struvite precipitation at different $Mg^{2+}/PO_4^{3-}$ molar ratio for each test.

## Results of the solutions on nutrient closure

**Nitrogen:** The crystallizer allowed the recovery of 46% of the N in the raw digestate.

**Phosphorus:** The crystallizer allowed the recovery of 70% of the P present in the raw digestate into the struvite flux. Struvite obtained can replace 100% mineral P fertilizer.

**Carbon:** thanks to the separation of the flows of organic carbon and phosphorus, it is possible to better manage the supply of organic matter to the soil, even in  soils saturated with phosphorus

## Effect of solution on the environment:

**GHG**: direct GHG emissions related to struvite application are not reported.

**Energy:** The energy required for the system was not calculated, but according to the results reported in the literature, the energy required for the crystallization process is negligible since the process takes place at room temperature and is due only to the mixer.

**Leaching to water:** Based on the results collected, the solution does not affect N or P leaching in the soil.

**Final remarks:** The solution shows the possibility of P recovery from digestate up to 70% from the initial concentration by struvite crystallization, even using digestate at high total solids concentration (TS>4%). Furthermore, the results indicated that sea-water bittern could be a low-cost alternative Mg source, leading to a high P and N recovery efficiency. Agronomic tests with *Brassica rapa chinensis* confirmed the possibility of using the struvite produced as a competitive alternative to conventional chemical phosphate fertilizers.

Struvite recovery using low-cost magnesium sources could be a way to mitigate future runoff due to the slow-release and lower water dissolution properties of this natural product

**Transferability:** Seawater bittern is a low-cost alternative compared to the conventional Mg source for struvite precipitation, even using digestate at a relatively high solid content.

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The simple design of the lab-scale crystallizer could be easily upgraded to a real-scale reactor that could work together with a biogas plant to recover the P present in the outflow digestate. The device is suitable to be operated at each company scale due to its simplicity.

### Struvite as a substitute of synthetic P fertilizer (SRL6-LL65). (TRL 4)

*Aleksandra Bogdan, Ana Robles Aguilar, Ivona Sigurnjak, Evi Michels, Erik Meers (Ghent University: UGENT, Belgium)*

**Aim of the solution:** To investigate the feasibility of alternative and **low-cost cation sources** to recover struvite via precipitation and to determine the potential effect of struvite as a P source in three contrasting soils.

**Key elements of innovation with respect to the state of the art:** Although the bioavailability of novel secondary P fertilizers has been examined in previous studies, insufficient attention has been paid to defining optimal plant growth duration and monitoring conditions to assess the dynamic changes in P. In this sense, these elements have been investigated in this particular solution. Furthermore, for controlled phosphorus precipitation/recovery, it is usually necessary to supplement $Ca^{2+}$ or $Mg^{2+}$ ions; this represents more than 75% of the total operational costs and, as a result, hinders a more extensive application of this process. Therefore, we have also investigated alternative and low-cost cation sources (seawater and limestone) to recover struvite by precipitation.

**Working principle:** Struvite is an ammonia and magnesium phosphate hexahydrate ($NH_4MgPO_4 \cdot 6H_2O$). Therefore, when ammonia and phosphate are found in solution, they can be removed by adding a magnesium salt, under controlled conditions. That means that either in urban WWTP centres, specially WWTP where anaerobic digestion is combined with biological P removal, in manure digestates or in WWTPs effluents, where ammonia and phosphate are found at high concentrations, struvite can be recovered. One of the main advantages of recovering struvite from waste flows is the high selectivity of the reaction. That means the recovered product will be free of contaminants and will not contain heavy metals either organic residues at significant concentrations. Struvite has low solubility in water but a high solubility in acidic solution. This characterizes it as a slow release fertilizer that will prevent P losses due to filtrations or runoffs. The majority of struvite is produced following the same reaction with differences centred on, the only difference is the feedstock used, the source of Mg and the reactor used.

**Results of the solutions on nutrient closure**

**Nitrogen:** The struvite usually contains 4.7-5.6% N (w/w). This makes it not suitable for a N fertilizer, still, the solution still contributes to the recovery and export of N.

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**Phosphorus:** Struvite usually contains 28-29% P2O5 (w/w). The product is very suitable for top-dressing application and can be blended with other solid fertilisers but, it can also be dissolved in a slightly acidic solution, making the P available to the plants. Therefore, traditional agricultural machinery can be used for the application and it is recommended to be applied before seeding/planting. Phosphorus availability from struvite is profoundly influenced by soil pH and/or processes in the rhizosphere. Root exudates (e.g., organic anions) and root morphology affect fertilizer bioavailability. Also, related to pH, the soil or substrate use will affect the P availability from struvite.

## Effect of solution on the environment:

**GHG**: direct emissions were not measure in this solution, as P is not involved in direct GHG emissions.

**Energy:** The energy required to produce the struvite will depend on the type and volume of the reactor. This was not measured directly in this solution.

**Leaching to water:** Struvite allows the cleaning of wastewater. Direct leaching tests were not performed.

**Final remarks:** The potential effect of struvite as a P source has been analysed in three contrasting soils. The effectiveness of struvite as a P source for ryegrass was compared to TSP and was found to be soil specific. It was most effective on the sandy soil that had low extractable Fe and Al, and a low P sorption maximum. It is clear from the current study that struvite will be most effective in soils with low initial P, and neutral to acidic pH values.

To recover struvite using low-cost sources, it was shown that **limestone powder and seawater** have a great potential to be used partially or totally as ion source for industrial recovery of P. The recovered struvite could potentially be used as soil amendment and/or as phosphate rock substitute for fertilizer production. Finally results suggests equal crop effectiveness of P in struvite and mineral fertilizers.

## Synoptic table of findings across WPs

| Area | WP2: experimental data collection | WP3: LCA |
|---|---|---|
| **Carbon cycle** | not relevant | |
| **Nitrogen cycle** | The struvite usually contains 4.7-5.6% N (w/w). This makes it not suitable for a N fertilizer, still, the solution contributes to the recovery and export of N. | |
| **Phosphorus cycle** | Struvite usually contains 28-29% P2O5 (w/w).<br>The product is very suitable for top-dressing application and can be blended with other solid fertilisers but, it can also be dissolved in a slightly acidic solution, making the P available to the plants. | |

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| | | |
|---|---|---|
| **GHG direct emissions** | Direct emissions were not measure in this solution, as P is not involved in direct GHG emissions. | Direct $N_2O$, $CH_4$ emissions unchanged<br>Struvite recovery slightly improved the environmental performance of a WWTP in Flanders. The hotspot analysis identified that, albeit marginal, reduced polymer use, improved dewaterability and avoided imports of synthetic P fertiliser resulted in a net benefit to the system as a consequence of the struvite precipitation. To further enhance the sustainability of WWTPs, plant operators may wish to focus on optimising polymer usage and at identifying sustainable substitutes. |
| **Ammonia emissions** | not measured | LCA indicated reduction in $NH_3$ emissions, considering both direct and upstream process emissions |
| **Leaching to groundwater** | Direct leaching tests were not performed. | |

## Low temperature ammonium-stripping using vacuum (SRL7-LL20). (TRL 4)

*Miriam Cerrillo, Miguel Moreno, Adrian Carrascosa, Laura Burgos, August Bonmatí (Sustainability in Biosystems, IRTA, Spain)*

**Aim of the solution**: The objective of this solution is to recover ammonia from livestock manure by means of a low temperature vacuum evaporation. The ammonia salt recovered can be used as a fertiliser and close nitrogen cycle.

**Key element of innovation respect to the state of the art**: Compared to conventional ammonia stripping / absorption, vacuum stripping operates at a lower temperature, because of a lower heating requirement. Ammonia recovery from livestock manure can produce marketable products, such as fertilisers, and allows for nitrogen loop closure.

**Working principle**: When a vacuum is applied to an enclosed reactor, boiling point temperature decreases to below normal boiling point, thus reducing energy costs because of lower heating requirements. In addition, gas-phase ammonia mass transfer is boosted by the suction effect of the applied vacuum. A lower alkalinity requirement is also reported, as pH is adjusted to a lower value. The recovered ammonia can be in the form of ammonium sulphate, nitrate or lactate salt solution, among others. This technology can be applied directly to raw livestock manure or as a subsequent step of an anaerobic digestion process to produce a nitrogen fertilizer. It also prevents ammonia gas emissions into the atmosphere during storage.

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## Results of the solution on nutrient closure

**Carbon**: the solution allowed to increase the carbon stock in soil thanks to the input of organic matter to soil (processed pig slurry).

**Nitrogen**: the solution allowed to replace 100% mineral nitrogen fertilizer, as an ammonia salt (sulphate, nitrate, lactate, etc.) is produced.

**Phosphorus**: the solution allowed to replace phosphorus as it is precipitated as calcium phosphate during pH adjustment. It is recovered around 58% of P in the solid fraction, and the remaining 30% can be found in the processed slurry. Total nitrogen (TN) is recovered in the form of ammonia lactate (13-27%) and solid fraction (1-16%). The remaining part is either emitted (13%), present in the processed slurry (around 40%) or accumulated in the system (precipitate).

## Effect of solution on environment

**GHG**: direct emissions of the use of the produced RBFs were not measured.

**Energy:** Processing plant presents an energy consumption of 3,2 kWh/$m^3$ (electricity). Thermal energy is recovered from the heating system of the farm (The demand of thermal energy is 2,92 kW/$m^3$).

**Ammonia emissions:** Based on results collected the solution cause some direct ammonia emissions during operation (0,14 g/$m^3$).

**Leaching to ground water**: The solution may cause the same $NO_3$ leaching as the use of chemical fertilizers (urea).

**Final remarks**: The processed livestock manure, with lower nitrogen content, should be managed as fertilizer accordingly to its composition (e.g. new N/P ratio) or further processed. On the other hand, an ammonium salt solution is produced, which can be used as a fertiliser. With this processing plant it is expected to recover more than 40% of the nitrogen content of the pig slurry to reuse it as a fertiliser and close nitrogen cycle.

**Recommendations**: According to the data collected during Nutri2Cycle the following recommendations about the solution can be proposed:

- Absorption process with acid should be adjusted and operated correctly to optimize ammonia absorption and reduce losses.
- An efficient treatment of the exhausted gases is necessary to minimize ammonia losses and other gases (e.g. $H_2S$) is required

**Transferability:** The whole system has a TRL 6-7. Due to the plant simplicity, since it is easy to place within a 20-foot sized container, and the complete automation of the process, it is suitable to become an on-farm treatment for decentralised pig slurry management. Nevertheless, its

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transferability/applicability is more suitable to medium or larger sized farms, as the initial investment and later operation management can be expensive.

## Producer perception of the innovation:

**Barriers**: the principal innovation barrier identified by participants was “economic considerations” (35%), followed by the “regulatory framework” (18%) and the “absence of economic subsidies or other economic incentives” (15%).

**Enables:** The main advantages identified by the FG participants were related to environmental and governance aspects. They suggested that the innovation principally helps to make the use of nutrients more efficient and reduces contamination.

## Consumer perception of the innovation:

## Synoptic table of findings across WPs

| Area | WP2: experimental data collection | WP3: LCA |
|---|---|---|
| **Carbon cycle** | The solution allowed to increase the carbon stock in soil thanks to the input of organic matter to soil (processed pig slurry). | |
| **Nitrogen cycle** | The solution allowed to replace 100% mineral nitrogen fertilizer, as an ammonia salt (sulphate, nitrate, lactate, etc.) is produced. | mineral fertiliser replacement |
| **Phosphorus cycle** | the solution allowed to replace phosphorus as it is precipitated as calcium phosphate during pH adjustment. It is recovered around 58% of P in the solid fraction, and the remaining 30% can be found in the processed slurry. Total nitrogen (TN) is recovered in the form of ammonia lactate (13-27%) and solid fraction (1-16%). The remaining part is either emitted (13%), present in the processed slurry (around 40%) or accumulated in the system (precipitate). | mineral fertiliser replacement |
| **GHG direct emissions** | Not measured | Increased considering background process |
| **Ammonia emissions** | Based on results collected the solution cause some direct ammonia emissions during operation (0.14 g/m$^3$). | reduction |
| **Leaching to groundwater** | Not measured | Field application not considered in the study boundaries |

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## Closing the loops at the scale of farm : using the livestock manure to fertilize the feeding crop on agroforestry plots (SRL3-LL15). (TRL 7)

*Jean-Philippe Bernard, Mathilde Blanc, Corinne Lombard (Chambre interdépartementale d'agriculture 17-79 (CIA 1779), France)*

**Aim of the solution:** Substituting external mineral nutrient input from synthetic fertilisers by recycled organic based fertilizers in orchards & agroforestry.

**Key elements of innovation with respect to the state of the art:** Within the N2C project, the CIA 1779 has been commissioned to demonstrate the situation and the possible evolution of the nutrient cycling in a farm associating crop farming, livestock farming and agroforestry.

This demonstration has several ambitions:

i) Understanding the fertilizing effect of effluents, in particular the nitrogen effect, on a agroforestry plot

ii) Appreciating the effect of agroforestry implantation on carbon storage

**Working principle:** using the livestock manure to fertilize the feeding crop on agroforestry plots and monitoring productions. An agroforestry plot was investigated (Saint Martial sur Né, in the department of Charente-Maritime), by a monitoring protocol on different areas selected according to the effluent spreading and the agroforestry situation.

**Results of the solutions on nutrient closure**

**Nitrogen:** synthetic N was partly replaced by manure. Manure N content ranged from 1.5 to 4.5 kg N/ton of effluent.

**Phosphorus:** partial replacement of conventional P fertiliser: solid manure's P2O5 = 2.4 g/kg fresh Matter and Slurry's P2O5 = 1.1 g/kg fresh matter.

**Carbon:** increase in carbon supply and circular valorisation of internal carbon flows

**Effect of solution on the environment:**

**GHG**: not measured.

**Energy:** no variation respect to baseline.

**Ammonia emissions**: not measured.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 773682.

**Leaching to water:** not measured.

**Final remarks:** The agroforestry system enables soil carbon stocks to increase as pruning residues, roots and perennial aerial plant debris is incorporated into the soil. The supply of organic matter (manure) for arable plot provides improves the carbon profiles.  Finally, an increase or renewable energy because of the wood production in agroforestry for energy and heat production is achieved in this scheme.

## Recovered animal manures for precision fertilization of apple orchards and vineyards (SRL3-LL57). (TRL 7)

*Catarina Esteves, David Fangueiro (Instituto Superior De Agronomia: ISA, Portugal)*

**Aim of the solution:** the objective is to enhance soil fertility and plant nutrition in orchards and vineyards by recovering nutrients from animal manures and slurries. This approach aims to reduce reliance on mineral fertilizers within European agriculture. Precision Agriculture techniques will also be employed to ensure smart and efficient utilization of both organic and mineral nutrients. The overall goals include optimizing resource use efficiency in crop and soil fertilization, sustaining high crop productivity, and minimizing agricultural impacts.

**Key elements of innovation with respect to the state of the art:** The existing literature lacks sufficient studies on the replacement of chemical fertilizers with animal manures under permanent cropping systems.  Additionally, the utilization of animal manure in permanent crops, such as orchards, holds significant potential, particularly due to the decline in organic matter content as orchards age. This practice is particularly important in Mediterranean regions, where organic matter depletion poses a pressing concern. It is also important to incorporate available techniques and technologies, such as variable-rate application of fertilizers. This approach enhances fertilizer efficiency, reduces resource consumption, promotes homogeneous crop productivity, and minimizes environmental impacts.

**Working principle:** In an apple orchard, a three-year experiment was conducted to replace mineral nitrogen (N) with organic N sourced from animal manures and slurries. The replacement rate progressively increased each year, reaching 57% by the third year. Throughout the experiment, the effects of this practice were assessed on various aspects, including crop productivity, nutrient uptake in leaves and fruits, selected fruit quality traits, and soil fertility. Additionally, environmental impacts were evaluated by measuring greenhouse gas emissions, such as carbon dioxide ($CO_2$), nitrous oxide ($N_2O$), and methane ($CH_4$).

In the vineyard trial site, the focus was on precise nutrient application. To achieve this, understanding of the spatial variability within a 6.7-hectare vineyard was necessary. This was accomplished by utilizing satellite imagery to obtain the normalized difference vegetation index (NDVI) and proximal

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sensors to measure apparent soil electrical conductivity (ECa). Based on this information, three management zones were delimited within the vineyard. Soil samples were collected from each zone for incubation experiments. In these experiments, pig slurry was applied at variable rates, adjusting the application rate to match the specific soil and crop requirements in each zone, and the effects were measured on soil nutrient dynamics, greenhouse gas emissions, and the potential for nutrient leaching. The fertilisation plan was outlined to fulfil soil phosphorus (P) needs.

## Results of the solution on nutrient closure

**Nitrogen:** In the apple orchard, a total of 80 kg N per hectare was applied to fulfil crop N requirements. In the organic treatments, more than half of this amount was substituted with organic N obtained from animal manures and slurries.

After three years of experiment, soil N content significantly increased in the organic treatments (43% mineral N + 57% organic N), with an increase ranging from 40 (acidified cattle slurry) to 100% (cattle manure), when compared to the control (100% mineral N).

**Phosphorus:** In the apple orchard, after the three-year experimental period, soil extractable P content was higher in the cattle manure treatment. In the incubation experiments conducted with vineyard soil, the effects of organic P from pig slurry were compared to a mineral P fertiliser (superphosphate) in soils representing the three different management zones with varying levels of soil P fertility (classified as very low (VL), low (L), and medium (M)). After the 105-day experiment, soil P levels were significantly higher in the pig slurry treatment specifically for the L soil. However, in the VL and M soils, the pig slurry treatments did not show significant differences when compared to the superphosphate treatments.

**Carbon**: In the three-year orchard experiment, partial replacement of chemical fertilizers with animal manures led to an increase in soil organic carbon (SOC). These increases varied, ranging from 38% (for cattle slurry) to a substantial 80% (for cattle solid manure), when comparing with the SOC content before the trial began. Conversely, when pig slurry was applied in the experiment with vineyard soil under aerobic incubation conditions (105 days), there was no discernible impact on SOC.

## Effect of solution on the environment:

**Direct GHG emissions**: Regarding the orchard trial, the cumulative $N_2O$ emissions were significantly higher in the poultry manure and acidified cattle slurry treatments compared to the control. Specifically, emissions in the poultry manure treatment were nine times higher, while in the acidified cattle slurry treatment, they were five times higher than the control. In terms of cumulative $CH_4$ emissions, the cattle slurry treatment exhibited a significant increase (four times higher than the control), whereas the cattle manure treatment showed a significant decrease (3.5 times lower than the control).

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 773682.

Notably, the control, poultry manure, and cattle manure treatments demonstrated $CH_4$ uptake, with the highest uptake observed in the cattle manure treatment.

Cumulative $CO_2$ emissions did not exhibit significant differences among the treatments. However, the global warming potential, as indicated by $CO_2$-equivalents, was significantly higher in the poultry manure treatment compared to the other treatments.

In the incubation experiment with vineyard soil, it was observed that pig slurry treatments resulted in significantly higher $CO_2$ emissions (205 mg $CO_2$-C $kg^{-1}$ soil) compared to the superphosphate treatment (171 mg $CO_2$-C $kg^{-1}$ soil) and the control (zero-P application, 176 mg $CO_2$-C $kg^{-1}$ soil). However, no significant differences were found between the pig slurry (0.63 mg $N_2O$-N $kg^{-1}$ soil) and superphosphate (0.60 mg $N_2O$-N $kg^{-1}$ soil) treatments in terms of $N_2O$ emissions. $CH_4$ emissions were minimal and did not exhibit significant differences between the treatments.

**Energy:** the only difference from the use of chemical fertilisers is the increased use of fuel for manure/slurry distribution.

**Leaching to water:** not determined.

**Ammonia emissions:** not determined.

**Final remarks:** the results of the orchard trial revealed that partial replacement of mineral fertilizers, up to 57%, had no negative impact on crop productivity, except when cattle manure was utilised. Furthermore, fruit quality remained unaffected while soil fertility significantly improved and displayed increased levels of soil nitrogen, phosphorus, and organic matter content.

The observation of higher crop productivity in the cattle slurry treatment, although not significantly different from the control, suggested that cattle slurry exhibited the greatest potential as a replacement for chemical fertilizers. Despite the higher CH4 emissions associated with the use of cattle slurry, this treatment displayed the lowest global warming potential per kilogram of fruit produced among the organic treatments.

In relation to the vineyard results, substantial variations were observed among the three management zones, indicating the potential for implementing variable-rate application of fertilizers. Preliminary findings suggested that pig slurry exhibited comparable or even superior efficiency, depending on the indigenous phosphorus content of the soil, when compared to mineral fertilizers.

## Application of digestate in large scale orchards (SRL3-LL66). (TRL 8)

*Konzalting Doo Zaposlovne Usluge: IPS, Croatia*

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 773682.

**Aim of the solution:** Aim of the solution is to determine the effect of digestate application in orchards (raspberry). Numerous research findings indicate that digestate from agro-based biogas plants serves as an excellent fertilizer and provides an effective means to close the carbon cycle in the soil.

**Key elements of innovation with respect to the state of the art:** Use of digestate in place of chemical fertilisers as basal fertilisation. The digestate applied was produced in a biogas plant using different agro-residues from agricultural production (cattle and pig manure/slurry, corn silage, soy molasses).

In the phase of soil preparation, Vinka – a fruit and vegetable processing company from Croatia, applied the combination of Ca(OH)2, thick fraction of digestate and cattle manure.

The vast majority of Croatian farmers do not apply digestate in agricultural production and opposite dispose it, in this frame digestate application can be considered as an innovative solution/technique and needs to be showcased.

More importantly, the company also used a digestate that was produced in the near proximity of the orchard meaning that closing of nutrient cycles on a local level is supported as well as dependence on nutrients (due to geopolitical situation across the globe) is being reduced.

Currently, the plant is not using agro-streams generated at the processing line of Vinka (peas stems, sweet corn husks/piston/stems, pepper seeds loge, carrots and potatoes epidermis, onion peels, cauliflower flowers, cherries juice and pulp) but the company intends to prepare an analysis of the biogas potential of these streams and, if financially sustainable, commence using these residues in the biogas plant (digestate).

**Working principle:** The underlying working principle in the specific case refers to the application of digestate as basal fertilisation for orchard. In the phase of soil preparation, the company decided to implement the combination of $Ca(OH)_2$ in concentration of 1,00 t/ha, thick fraction of digestate in concentration of 50,00 t/ha and cattle manure in concentration of 33,00 t/ha. Next to organic fertilizers, 30 grams/plant of mineral fertilizer (NPK 7-20-30) was also applied. The digestate was applied using Strautmann fertilizer spreader. For top dressing fertilisation was used a fertigation system and a combination of mineral fertilizers Novalon (NPK 20-20-20) and Vital Power Phos (NPK 7-21-0).

**Results of the solutions on nutrient closure**

**Nitrogen:** partial replacement of chemical nitrogen with recovered nitrogen.

**Phosphorus:** partial replacement of mineral P with recovered ones.

**Carbon:** addition of carbon and increase in soil quality.

**Effect of solution on the environment:**

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 773682.

**GHG**: Not determined.

**Energy:** Not determined.

**Leaching to water:** Not determined.

**Final remarks:** This solution is not funded from Nutri2Cycle, and not listed as a priority.

## Ammonium stripping / scrubbing and $NH_4NO_3$ as substitute for synthetic N fertilizers (SRL4-LL1). (TRL 7)

*Sander Vandendriessche, Tomas Van de Sande, Inès Verleden, Ivona Sigurnjak, Gregory Reuland, Amrita Saju (INAGRO/UGENT, Belgium)*

**Aim of the solution:** The aim of this field trial is to prove the agronomic value and the environmental benefits of ammonium nitrate as a mineral N fertilizer replacement product.

**Key elements of innovation with respect to the state of the art:** In Flanders, livestock production generates large surpluses of on-farm nitrogen (N) and phosphorus (P). High P content and uncertainty on N release from animal manure have led to imposed legal limitation on N and P application rates from animal manure. Since Flemish soils are P-rich, the P has become the limiting factor in manure application thereby also limiting maximum N application from animal manure. This creates a paradoxical situation where vast quantities of manure are processed or exported out of Flanders while tons of synthetic mineral N-fertilizer are used for crop production. **Use of manure-BBFs with predictable N release and low P content can counter this situation**. One example of such a BBF is ammonium nitrate. At the moment, however, ammonium nitrate is categorized as animal manure and as such needs to comply with the same legal application constraints. It fulfils the RENURE criteria, hence having potential to replace mineral fertilizers in the future.

**Working principle:** Ammonium ($NH_4^+$), present in manure and digestate, is in balance with ammonia ($NH_3$), which is volatile. Under the influence of pH and temperature, the ratio of ammonia to ammonium can be increased so that the ammonia nitrogen can volatilize more readily. By blowing in air, the volatile ammonia is removed from the liquid fraction and the nitrogen (N) can be recovered. The air from the stripper, enriched with ammonia, is chemically bound to nitric acid in the scrubber into ammonium nitrate. The concentration of ammonium nitrate is determined by the initial amount of water in the scrubber and the amount of nitric acid added during the production process. The resulting product (ammonium nitrate) can be used as a N fertilizer.

**Results of the solutions on nutrient closure**

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 773682.

**Nitrogen:** Ammonium nitrate has a total N content of 132 – 198 g/kg and can be used as a N fertilizer as outlined in Systemic Project[1].

**Phosphorus:** There is no impact on phosphorus, the separation of N for the total digestate leave a material depleted in N, where carbon and P are still available

**Carbon:** separation of N from the main flow allows a better management and closure of the carbon cycle

**Effect of solution on the environment:**

**Direct GHG emissions**: Emissions on the field were not calculated within this field trial.

**Energy:** electricity use is involved in the processing.

**Ammonia emissions:** Not determined

**Leaching to water:** Field trials indicated no significant differences in nitrate leaching compared to mineral fertilizers.

**Final remarks:** Ammonium nitrate has a high potential to replace mineral N fertilizers, hence creating a more circular economy. Therefore, it is considered as a RENURE product. For the moment, however, it is still considered as animal manure. The field trials between 2019-2021 already proved the agronomic and environmental performance of this product, with N fertilizer replacement values ranging from 0.36 to 1.5 and comparable crop yields to that of synthetic fertilizer. In 2022 and 2023, it has also been applied on full scale in the Operational Group RENURE, in cooperation with several farmers.

**Transferability:** This technology consistently ranked between 4th and 7th throughout the averaged transferability ranking across Europe. Using recycling-derived fertilisers could be particularly relevant for Southern Europe with short-term expert rank of 1.7, short-term survey rank of 2.4, medium-term expert rank of 4 and medium-term survey rank of 3.

### Ammonium stripping / scrubbing and $NH_4SO_4$ as substitute for synthetic N fertilizers (SRL4-LL2). (TRL 9)

*Sander Vandendriessche, Tomas Van de Sande, Inès Verleden, Ivona Sigurnjak, Gregory Reuland, Amrita Saju (INAGRO/UGENT, Belgium)*

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[1] https://systemicproject.eu/wp-content/uploads/2018/06/Factsheet-product-Ammonium-Nitrate-FINAL-22052018.pdf

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 773682.

**Aim of the solution:** The aim of this field trial is to prove the agronomic value and the environmental benefits of ammonium sulphate as a mineral N (and S) fertilizer replacement.

**Key elements of innovation with respect to the state of the art:** In Flanders, livestock production generates large surpluses of on-farm nitrogen (N) and phosphorus (P). High P content and uncertainty on N release from animal manure have led to imposed legal limitation on N and P application rates from animal manure. Since Flemish soils are P-rich, the P has become the limiting factor in manure application thereby also limiting maximum N application from animal manure. This creates a paradoxical situation where vast quantities of manure are processed or exported out of Flanders while tons of synthetic mineral N-fertilizer are used for crop production. Use of manure-BBFs with predictable N release and low P content can counter this situation. One example of such a BBF is ammonium sulphate. At the moment, however, ammonium sulphate from a stripping scrubbing process is categorized as animal manure and as such need to comply with the same legal application constraints. It fulfils the RENURE criteria, hence having potential to replace mineral fertilizers in the future.

**Working principle:** Ammonium ($NH_4^+$), present in manure and digestate, is in balance with ammonia ($NH_3$), which is volatile. Under the influence of pH and temperature, the ratio of ammonia to ammonium can be increased so that the ammonia nitrogen can volatilize more quickly. By blowing in air, the volatile ammonia is removed from the liquid fraction and the nitrogen (N) can be recovered. The air from the stripper, enriched with ammonia, is chemically bound to sulphuric acid in the scrubber into ammonium sulphate. The concentration of ammonium sulphate is determined by the initial amount of water in the scrubber and the amount of sulphuric acid added during the production process. The resulting product (ammonium sulphate) can be used as a N fertilizer.

**Results of the solutions on nutrient closure**

**Nitrogen:** Ammonium sulphate has a total N content of 30 – 86 g/kg and can be used as a N and S fertilizer.

**Phosphorus:** There is no impact on phosphorus, except that N and P flows are separated and this allows a better management as mentioned in the previous section (key elements)

**Effect of solution on the environment:**

**GHG**: The direct emissions from the field were not determined within this field trial

**Energy:** Electricity use is involved in the processing.

**Ammonia emissions:** Not determined.

**Leaching to water**: Field trials indicated no significant differences in nitrate leaching compared to mineral fertilizers.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 773682.

**Final remarks:** Ammonium sulphate has a high potential to replace mineral N fertilizers, hence creating a more circular economy. Therefore, it is considered as a RENURE product. For the moment, however, it is still considered as animal manure. Several field trials already proved the agronomic and environmental performance of this product.

Ammonium sulphate derived from an acid air scrubber can already be applied on top of the 170 kg N/ha from animal manure as defined in the Nitrates Directive.

**Transferability:** This technology consistently ranked between 4th and 7th throughout the averaged transferability ranking across Europe. Using recycling-derived fertilisers could be particularly relevant for Southern Europe with short-term expert rank of 1.7, short-term survey rank of 2.4, medium-term expert rank of 4 and medium-term survey rank of 3.

## CBA findings on biobased fertilisers

The aim is to give an overview of what the farmers could pay for the recovered fertilizers without impact on the economic balance of their production. This means that if they can buy the biobased fertilizers for a price below this indicated maximum values, they will have a financial benefit for their production compared to the reference scenario.
It can also be concluded that the “most expensive” biobased N-fertilizer would be the ammonia water (0.169 €/kg for Croatia; 0.123 €/kg for Flanders), followed by ammonium nitrate (0.135 €/kg in Croatia; 0.098 €/kg for Flanders). The “least expensive” biobased N-fertilizer would be the liquid fraction of digestate for both regions (0.0056 €/kg for Croatia; 0.0004 €/kg for Flanders).
When comparing the maximum market price between regions it shows that for Croatia (i.e. the region with the shortage in nutrients) the market price can be significantly higher than in Flanders (i.e. the region with the nutrient surplus). For ammonium nitrate, ammonium sulphate and ammonium water the price in Croatia can be 38%, 34% and 37% higher respectively. For ammonium lactate the price could be up to 91% higher.

## Synoptic table of findings across WPs

| Area | WP2: experimental data collection | WP3: LCA | WP4: EU Level |
|---|---|---|---|
| **Carbon cycle** | separation of N from the main flow allows a better management and closure of the cycle | - | - |
| **Nitrogen cycle** | Ammonium nitrate has a total N content of 132 – 198 g/kg, Ammonium sulphate has a total N content of 30 – 86 | | The reduction in N mineral fertilizer use for the manure treatment options is relatively low, with a reduction of 0.28% (N-stripping) or |

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| | | | |
|---|---|---|---|
| | g/kg. Both can be used as a N fertilizer | | 0.45% (mineral concentrates), as only the Netherlands, Belgium and one region in Germany have a pig manure surplus. |
| **Phosphorus cycle** | There is no impact on phosphorus, except that N and P flows are separated and this allows a better management | - | - |
| **GHG direct emissions** | Not measured | Increased respect to baseline, also due to upstream processes<br>Fugitive $N_2O$ emissions and energy demand during nitrification-denitrification of liquid fraction of manure are major environmental hotspots that can be reduced in part by introducing stripping and scrubbing as a pre-treatment step, but post-treatment of nitrification-denitrification effluent was the study's point of contention. | N stripping of pig manure has a potential GHG reduction of 0.15 Mt (0.03%) and pig manure processing to mineral concentrates has a potential of 0.23 Mt (0.05%). |
| **Ammonia emissions** | Not measured | Increased respect to baseline, also due to upstream processes | |
| **Leaching to groundwater** | Field trials indicated no significant differences in nitrate leaching compared to mineral fertilizers. | reduced P leaching, increased N release | - |

### Liquid fraction of digestate as a substitute for mineral N & K fertilizer (SRL4-LL9). (TRL 8)

*Sander Vandendriessche, Tomas Van de Sande, Inès Verleden, Ivona Sigurnjak, Gregory Reuland, Amrita Saju (INAGRO/UGENT, Belgium)*

**Aim of the solution:** The aim of this field trial is to prove the agronomic value and the environmental benefits of the liquid fraction of digestate as a mineral N fertilizer replacement.

**Key elements of innovation with respect to the state of the art:** In Flanders, livestock production generates large surpluses of on-farm nitrogen (N) and phosphorus (P). High P content and uncertainty on N release from animal manure have led to imposed legal limitation on N and P application rates from animal manure. Since Flemish soils are P-rich, the P has become the limiting factor in manure application thereby also limiting maximum N application from animal manure. This creates a paradoxical situation where vast quantities of manure are processed or exported out of Flanders while tons of synthetic mineral N-fertilizer are used for crop production. Use of manure-BBFs with predictable N release and low P content can counter this situation. One example of such a BBF is the liquid fraction of digestate, low in P. At the moment, however, it is categorized as animal manure and as such need to comply with the same legal application constraints. Nevertheless, it is a valuable product containing more mineralized nitrogen and can be further valorised via e.g. stripping scrubbing (cfr. LL1 and LL2) or membrane filtration.

**Working principle:** The digestate is produced via anaerobic digestion, which takes place in a large reactor in the absence of oxygen. During fermentation, organic matter is converted into biogas. The biogas (mainly consisting out of methane) is subsequently burned in a combined heat and power unit (CHP) and results in a renewable energy source in the form of heat and electricity. The remaining, digested biomass is called digestate and still contains all nutrients. The liquid fraction of digestate can be obtained via a separation technique (e.g. screw press, centrifuge).

**Results of the solution on nutrient closure**

**Nitrogen:** The N content of the liquid fraction of digestate is strongly dependent on the feed used for the AD process and the separation technique. On average, the TKN is 131 g/kg DM. The separation of N and P flows make easier the closure of the cycles.

**Phosphorus:** The LF of digestate is depleted in P, (anyhow P content of the liquid fraction of digestate is strongly dependent on the feed used for the AD process and the separation technique. On average, total $P_2O_5$ is 4.42 g/kg DM). This allows a better management and closure of the N/P cycles

**Carbon:** the flows of carbon is separated from the one of nitrogen, allowing a better management of the two.

**Effect of solution on the environment:**

**GHG**: direct emissions from the field were not determined within this field trial.

**Energy:** energy is produced via anaerobic digestion during the production of digestate.

**Ammonia emissions:** Not determined.

**Water leaching:** Field trials indicated no significant differences in nitrate leaching compared to mineral fertilizers.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 773682.

**Final remarks:** The main by-product of anaerobic digestion is digestate. This product contains almost all nutrients as they were present in the in-going feed, but more mineralized and readily available. Therefore, it is suitable as a good fertilizer. After an extra separation step, the liquid fraction of the digestate could be an alternative for mineral N fertilizers. When the separation step is being done thoroughly, this even has the potential to be classified as RENURE. For the moment, however, it is still considered as animal manure as long as there is at least one droplet of manure feeding the digester.

### Manure processing and replacing mineral fertilizers in the Achterhoek region (SRL7-LL55). (TRL 7)

*Jan Peter Lesschen, Inge Regelink, Kevin Duan, Chantal Hendriks (Wageningen Research: WR, The Netherlands)*

**Aim of the solution:** This solution aims to evaluate the environmental effects of digestate treatment and use of end products as compared to a reference situation in which digestate is transported over long distances (250 km) to regions with a demand for animal manure.

**Key elements of innovation with respect to the state of the art:** This solution uses innovative manure processing techniques that help closing the N, P and C loops locally. The reverse osmosis concentrate meets the RENURE criteria and can therefore replace mineral N fertilizer.

**Working principle:** The investigated manure treatment plant is processing digestate into a solid fraction, a reverse osmosis (RO) concentrate, purified water, and a residual slurry. The RO concentrate complies with RENURE criteria and is used on local fields replacing synthetic N fertiliser. Detailed descriptions of the treatment process and mass balances are published by Van Puffelen et al. (2022) and Brienza et al. (2022). The solid fraction is rich in P and is either exported to Germany or further processed into a soil improver or a peat replacer for use in potting soil. The production of a peat replacer includes an additional treatment step in which the solid fraction is diluted with water and thereafter separated by means of a screw press to recover the coarse organic material. This leads to a significant reduction in salt level, which is a prerequisite for use as potting soil, but also creates an additional side stream.

**Results of the solutions on nutrient closure**

**Nitrogen:** The RO concentrate can replace the use of chemical N fertilizer and therefore contributes to the closure of the N-loop.

**Phosphorus:** an additional treatment step for the solid faction of digestate is required to produce P-fertiliser. The P-fertiliser can replace the chemical P fertiliser.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 773682.

**Carbon:** an additional treatment step for the solid faction of digestate is required to produce low-P soil improver. Because P is often limits the amount of organic fertiliser that can be applied, this product can enrich the soil organic C content.

**Effect of solution on the environment:**

The environmental impact of three scenarios were assessed by the ANIMO model (Groenendijk et al., 2014**;** Groenendijk et al., 2005; 1) digestate is transported to Germany (a distance of 250km) and used on arable land; 2) digestate is processed by means of a decanter centrifuge, micro-filtration unit and reverse osmosis installation producing 0.33 ton of RO concentrate.

**GHG**: direct $N_2O$ emissions ranged from 3.08 to 13.11 kg N/ha/yr in arable systems with CAN fertiliser and in grassland systems where manure and RO concentrate was applied respectively.

**Energy:** 57 kWh / ton thick fraction (or 347 kWh/day). Scaling up this technique will decrease the energy consumption to +- 20 kWh / ton thick fraction. When the installation is stand-by, it still consumes 156 kWh/day.

**Ammonia emissions:** $NH_3$ volatilization ranged from 7.7 in arable systems with CAN fertiliser to 64.4 kg N/ha/yr in grassland systems where manure and RO concentrate was applied.

**Leaching to water bodies**: Purified water after RO containing 0.2 mg N/L and 0.01 mg P/L was discharged onto surface water but it's contribution to overall emissions of $NO_3^-$ and $PO_4^{-2}$ was negligibly low and hence not shown in the results.

The application of the products resulted in a discharge of $NO_3$ to surface water of 12.3 kg/ha/yr in grassland farming systems where CAN was applied, 13 kg/ha/yr in manure was applied and 9.9 kg/ha/yr where manure and RO concentrate were applied. The discharge to groundwater was higher in arable farming systems (44.5 – 54.9 kg/ha/yr) compared to grassland farming systems (22.3 – 28.1 kg/ha/yr).

**Final remarks:** Separation of digestate producing a RENURE fertiliser, to be used locally as an alternative for synthetic N fertiliser, has little or no environmental benefits over transport (250 km) and use of raw digestate. In case of a larger transport distance for raw manure, $CO_2$-eq emissions would be lower in the scenario with manure treatment. However, in terms of $CO_2$-eq emissions, use of raw digestate is preferred in case this could be used at a distance of less than 250 km from the plant. The results suggest that digestate treatment producing a RENURE fertiliser has no benefits in terms of $CO_2$-eq emissions (climate change potential) and gives only a 10% reduction in emissions of $SO_2$-eq (terrestrial acidification potential) which is mostly emitted as $NH_3$.

**Synoptic table of findings across WPs**

| Area | WP2: experimental data collection | WP3: LCA |
|---|---|---|

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 773682.

| | | |
|---|---|---|
| **Carbon cycle** | an additional treatment step for the solid faction of digestate is required to produce low-P soil improver. Because P is often limits the amount of organic fertiliser that can be applied, this product can enrich the soil organic C content. | - |
| **Nitrogen cycle** | The RO concentrate can replace the use of chemical N fertilizer and therefore contributes to the closure of the N-loop. | - |
| **Phosphorus cycle** | an additional treatment step for the solid faction of digestate is required to produce P-fertiliser. The P-fertiliser can replace the chemical P fertiliser. | - |
| **GHG direct emissions** | The environmental impact of three scenarios were assessed by the ANIMO model (Groenendijk et al., 2014**;** Groenendijk et al., 2005; 1) digestate is transported to Germany (a distance of 250km) and used on arable land; 2) digestate is processed by means of a decanter centrifuge, micro-filtration unit and reverse osmosis installation producing 0.33 ton of RO concentrate<br>**GHG**: direct $N_2O$ emissions ranged from 3.08 to 13.11 kg N/ha/yr in arable systems with CAN fertiliser and in grassland systems where manure and RO concentrate was applied respectively. | $N_2O$ emissions are slightly higher due to more $N_2O$ emissions from the solid fraction. Difference is small but >10%. $N_2O$ emission values are compared to fertilisation with only CAN<br>LCA compared scenarios for treatment of digestate against no treatment in an area with a surplus of animal manure in The Netherlands.<br>The results suggest that digestate treatment producing a RENURE fertiliser has no benefits in terms of $CO_2$-eq emissions (*climate change potential*) and gives only a 10% reduction in emissions of $SO_2$-eq (*terrestrial acidification potential*) which is mostly emitted as $NH_3$.<br>Other considered impact categories, *terrestrial eutrophication* and *marine eutrophication*, remain unaffected.<br>The more advanced digestate treatment scenario in which the solid fraction is further upgraded towards a peat replacer shows more pronounced environmental benefits. In this scenario, the impact on climate change is being reduced mostly due the avoided oxidation of fossil peat. |
| **Ammonia emissions** | $NH_3$ volatilization ranged from 7.7 kg N/ha/yr in arable systems with CAN fertiliser to 64.4 kg N/ha/yr in grassland systems where manure and RO concentrate was applied. | Ammonia emissions are slightly lower due to digestate treatment. $NH_3$ emission values are compared to fertilisation with only CAN. |
| **Leaching to groundwater** | Purified water after RO containing 0.2 mg N/L and 0.01 mg P/L was discharged onto surface water but it's contribution to overall emissions of $NO_3^-$ and $PO_4^{-2}$ was negligibly low and hence not shown in the results | Nitrate leaching is slightly higher. $NO_3$ emission values are compared to fertilisation with only CAN |

## BIO-PHOSPHATE: high temperature reductive thermal process recovery of concentrated Phosphorus from animal bones (SRL8-LL22). (TRL 8)

*Edward Someus, Magdolna Halasz, Alexander Somfai (3R-Biophosphate Ltd. 3R (TH), Hungary)*

**Aim of the solution**: Production of P-rich animal bone char via pyrolysis technology.

**Key elements of innovation with respect to the state of the art:**

**Innovative Pyrolysis System**: The use of an innovative pyrolysis system, operating at a unique high temperature of 850°C, is a key technological advancement. This system enables efficient processing of the animal bone meal.

**Stringent Environmental Standards**: The innovation achieves a remarkably low level of PAH19 (nineteen) at 1 mg/kg, surpassing modern MS regulations and EU 2019/1009 regulations, which demonstrates a commitment to environmental responsibility and regulatory compliance.

**High Nutrient Density Biochar**: The resulting biochar contains a high nutrient density of 35% P2O5 and is combined with microbiological formulations to create BIO-NPK-C compound biofertilizer products. This combination enhances the value of the end product for agricultural use.

**Working principle:** The feed material is unexploited animal bone meal (and other low value and unexploited agri/food by-products) that are processed through an innovative pyrolysis process under EU 2019/1009 CMC14 schedule at unique high 850ºC material core temperature to receive PFC1-A-I solid organic fertilizer product and specific integrated soil biotech formulated for PFC7 BIO-NPK-C compound fertilizing product blend as of user demands.

**Results of the solutions on nutrient closure and progress beyond the state of the art:**

**Phosphorus:** 35% $P_2O_5$ content from the high pyrolysis temperature upcycled animal bone meal.

**Carbon:** As CMC14 product the BioPhosphate BIO-NPK-C formulations have significant carbon sequestration potential in agricultural land. The additional beneficial effects of the BioPhosphate are improving soil drought tolerance and providing biocontrol by-effects.

**Effect of solution on the environment:** The BioPhosphate zero emission pyrolysis processing means that all material streams in all forms and energy flows are processed and converted into useful products, including no release of greenhouse gases to the atmosphere. up take by the plants. As CMC14 product the BioPhosphate BIO-NPK-C formulations have significant carbon sequestration potential in agricultural land. The additional beneficial effects of the BioPhosphate are improving soil drought tolerance and providing biocontrol by-effects.

**Energy:** The BioPhosphate pyrolysis processing is energy independent and produces all its own energy, and under large scale conditions provides additional surplus green electricity (2 MWeh).

**Ammonia emissions**: not applicable

**Leaching to ground water**: P leaching was not detected.

**Transferability**: The BioPhosphate is a regional strategy that is centered on developing production capacity of 20,800 tonnes/year for regional value chain supply to the regional farmer and end-user community. **The scale of capacity per operational unit and the final product nutrient density are critically important factors**, as these are the ultimate defining factors for market competitive production per unit/tonnes. In this context transferability is considered best suited to regionally operating farmer groups and cooperatives.

- **Expert ranking:** The evaluations from the experts are more positive, ranking this technology as the 7th most promising technology in the short-term (transferability rank 2.3) and the 11th most transferable innovation in the medium- term (transferability rank 3.3).
- **Survey ranking**: At the EU level the usage of animal bone char for phosphorus recovery is ranked as the 12th most transferable technology in the short and medium-term within the survey feedback.
- **Geographical scope**: Animal bone char for phosphorus recovery could be particularly relevant for Eastern Europe

**Imported mineral phosphate replacement potential by 2035:** Full industrial 20,800 tonnes/year capacity replication model is expected by 2024, additional ten units by 2030 and the total EU imported mineral phosphate replacement potential by 2035 is approximately 10%, that is 160,000 t/y $P_2O_5$ from the total EU27 import.

**Final remarks:** The BioPhosphate ecological upcycling means high added value transformation of unexploited biomass into new products, perceived to be of greater quality and environmental/climate value with second life and new function that finished product becomes more practical and valuable than what it previously was.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 773682.

## Research line 5. Novel animal feeds produced from agro-residues

*Task 2.3.5 leader INAGRO*

Research line 5 is defined as new alternatives for animal feedstock to replace the current, often unsustainable, feed sources. For instance, the import of soybeans is a major source of greenhouse gas emissions for multiple reasons. The conversion of natural vegetation into arable land is probably the most important cause, since the latter generally binds considerably less $CO_2$ than the original ecosystems. GHGs are also released during the harvesting of soybeans and processing into derived products and the subsequent transport to export (ScienceDaily, 2020).

A more sustainable approach should be feasible by looking into different types of replacement. First of all, local production is encouraged in order to decrease the greenhouse gases coming from transport. Next to this, there is also the possibility to cultivate new feed sources on agricultural waste, which can also help to close nutrient loops. For instance, manure is often seen as waste material to be discarded, but it contains a lot of valuable nutrients that can be used to grow novel protein crops (e.g., floating wetland plants like duckweed). Another alternative is the more dedicated or an alternative valorisation of crop residues, of which their potential is not widely valorized up to date.

Therefore, Nutri2Cycle tested six different solutions (Table 5) aiming a more circular approach in animal feeding. These investigations are described to have an idea of their impact on closing nutrient loops and thus their potential to create a more circular agriculture.

Table 5: The six innovations associated with research line 5 of the Nutri2Cycle project

| Solution | Partner | Founded by N2C |
|---|---|---|
| LL40 Insect breeding as an alternative protein source on solid agro-residues (manure and plant wastes) | Inagro Belgium | |
| LL25 Soybeans in Poland - innovative solutions in the cultivation, plant protection and feeding on farms | PCz, Poland | |
| LL45 INPULSE: Innovating towards the use of Spanish legumes in animal feed | CARTIF | |
| LL34 Secondary harvest: additional valorisation of crop harvest and processing residues | UE and Inagro, Belgium | |

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| | | |
|---|---|---|
| LL41Floating wetland plants grown on liquid agro-residues as a new source of proteins | Inagro, UGent, Belgium | x |
| LL41b Algae grown on liquid agro-residues as a new source of proteins | UGent, Belgium | |

## Results and progress beyond the state of the art

The solutions of this research line show the potential to replace non-sustainable protein sources in the feedstock. This will ultimately lead to a more circular approach since agro-residues are being recycled and CNP loops are closed. As a second advantage, it also has a positive impact on GHG emission reduction. However, in order to really implement these solutions into practice, some extra steps are needed to have some extra insights on the business case and practicability. Furthermore, some legislative aspects might hinder the full implementation of (some of) these solutions.

## Lessons learnt from solutions in RL5

In general, it can be concluded that there is a lot of potential to replace unsustainable animal feed by local alternatives that could be cultivated on agro-residue streams (e.g. manure or crop waste). However, to create competitive products, scale will be an important factor to lower OPEX and be competitive with alternative protein sources.

Some of the investigated solutions are only a theoretical approach and are therefore still far away from implementation (LL34, LL45), while other solutions are more practically oriented in which lab tests or even pilots were being set up (LL25, LL40, LL41, LL41b). However, the TRL level of these investigations needs to be further increased before full implementation will be possible. Converting agricultural biomass waste streams into novel protein crops is a win-win situation: by processing waste streams there will be less impact on the environment, while at the same time protein rich feed sources are being produced.

## Solutions

### Insect breeding as an alternative protein source on solid agro-residues (manure and plant wastes) (SRL9-LL40). (TRL 7)

*Carl Coudron (Inagro, Belgium)*

**Aim of the solution**: Insects, specifically the Black Soldier Fly (BSF), represent a natural ‘food waste conversion engine’, and can cheaply and efficiently transform organic waste into complex proteins and fats in their bodies. As the insect larvae eat the food waste, they efficiently synthesize and concentrate the low-value biomass into much more chemically complex and valuable compounds such as proteins and fat – an ideal feed source for farmed salmon and poultry. Therefore, insects that can be fed on food waste, and with a resulting tiny carbon footprint, represent a massive opportunity for animal feed.

**Key element of innovation respect to the state of the art:** The solution effectively closes CNP loops since nutrients are being recovered from waste streams (e.g. agro-residues).

**Working principle**: In general, plant-based residues are unlikely to be balanced enough to use as a pure rearing substrate for the larvae and should be used in a mixture with other feedstocks. Faeces might have more potential, but proximate analysis of animal manure is lacking. The efficiency at which larvae can process residues will strongly depend on the degree to which the profile of the nutritional requirements of the larvae match with what the residue has to offer.

## Results of the solution on nutrient closure

All results below regarding C, N and P are based on the paper by Parodi et al. (2020) where black soldier fly larvae were grown on a substrate composed of a mixture of three feed ingredients, i.e. yeast concentrate from wheat, a starch-rich by-product from wheat and potato industry and a binding agent.

**Carbon**: 20% of carbon is recovered via larval gain, 24% was lost via air emissions and 57% was still present in the frass (a combination of excrements, undigested feed and exuviae).

**Nitrogen**: 38% of the nitrogen is recovered via larval gain, 0.7% was lost via air emissions and 62% was still present in the frass.

**Phosphorus**: 28% of phosphorus is recovered via larval gain and 72% was still present in the frass.

## Effect of solution on environment

**GHG**: Greenhouse gases produced during black soldier fly rearing will depend heavily on the substrate that is used (Table 6)

Table 6: Direct gaseous emissions that arise from black soldier fly larvae rearing (per kg of dry larvae biomass produced).

| | Larvae substrate | $CH_4$ (mg) | $N_2O$ (mg) | GWP – $CO_2$eq (g) |
|---|---|---|---|---|
| Parodi et al. (2020) | By-products from the agri-food chain | 28 | 53 | 17 |
| Parodi et al. (2021) | Pig manure | 10066 | 6 | 344 |

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 773682.

**Energy:** Bosch et al. (2019) found an energy use per kg black soldier fly larvae protein of 84 MJ when the larvae were fed with feed-grade substrates for conventional livestock.

**Ammonia emissions:** The amount of nitrogen that is emitted during black soldier fly rearing will vary greatly depending on numerous factors such as the protein content of the substrate and the presence of microbial ureases (which is especially the case in substrates of manure-origins). On by products from the agri-food chain Parodi et al. (2020) found that 1.2 g N/kg DM larval biomass was emitted while on pig manure 58 g N/kg was found (Parodi et al., 2021).

**Leaching to ground water**: Not relevant during black soldier fly larvae rearing. However, when the frass is applied on the field as an organic fertilizer leaching might occur.

**Final remarks :** Assessing black soldier fly larvae production is best done case per case as the type of substrate and rearing technique will have a major influence on the sustainability of this technique. Moreover, emissions observed should also always be assessed in the greater picture with all prior and posterior steps taken into account.

**Recommendations:** This technique is a viable way of transforming low-value residues into animal biomass (protein and fat). However, to create competitive insect-based products, scale will be an important factor to lower OPEX and be competitive with alternative protein sources. Rearing larvae on currently illegal substrates (such as manure) can be one way to circumvent at least one part of the operational costs.

**Transferability:** Rearing black soldier fly larvae on a small scale on residues is easily adoptable by farmers in different countries. However, to rear them with the goal of producing competitive protein alternatives, high associated CAPEX are expected. Moreover, the ammonia emissions associated with rearing black soldier fly larvae can lead local governments to demand to install air scrubbers on the BSF farm.

## Synoptic table of findings across WPs

| Area | WP2: experimental data collection | WP3: LCA |
|---|---|---|
| **Carbon cycle** | 20% of carbon is recovered via larval gain, 24% was lost via air emissions and 57% was still present in the frass (a combination of excrements, undigested feed and exuviae). | increase in the carbon closure |
| **Nitrogen cycle** | 38% of the nitrogen is recovered via larval gain, 0.7% was lost via air emissions and 62% was still present in the frass. | |
| **Phosphorus cycle** | 28% of phosphorus is recovered via larval gain and 72% was still present in the frass. | |

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 773682.

| | | |
|---|---|---|
| **GHG direct emissions** | Not measured | $N_2O$ increase : 42.39 kg $N_2O$ (>+100%)<br>$CH_4$: decrease -60.91 kg $CH_4$ (>-100%)<br>the manure-based diet is beneficial to the environmental in some categories. The beneficial impacts in diet 5 arise from the avoidance of the conventional treatment of pig manure including transportation, industrial composting and field application and to a smaller extent the avoidance of mineral fertiliser through field application of insect frass.<br>Insects as processed animal protein performed worse than conventional soy- and fishmeal feed in our models. However, it is still premature to disregard insect larvae production as a more sustainable pathway to provide protein for animal feed. Our results indicated that the balance between insect production and alternative changes drastically by varying the insect feed used and the source of energy for heating during insect production. Thus, investigations that identify the circumstances under which insect production is favourable, such as location, energy source, type of agro-residues and conditions of production are needed to make insect production more sustainable. |
| **Ammonia emissions** | not measured | decrease 32.73 kg $NH_3$ (>-100%) |
| **Leaching to groundwater** | not measured<br>when the frass is applied on the field as an organic fertilizer leaching might occur. | $NO_3$ decrease, 40.94 NO3 (>-100%)<br>$PO_4^{3-}$ 2.48 kg (-91%) |

## Soybeans in Poland - innovative solutions in the cultivation, plant protection and feeding on farms (SRL10-LL25). (TRL 4)

*Danuta Dróżdż, Krystyna Malińska (PCz)*

**Aim of the solution**: The main goal of this study is to increase the possibility of effective domestic cultivation of soybeans in Poland, hence decreasing transport and a more sustainable soybean use in Poland. Moreover, the investigation aims to increase the nutrition efficiency of livestock through proper techniques of soybeans treatment.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 773682.

**Key element of innovation respect to the state of the art:** to close the cycle of soybeans growing, processing, and livestock feeding in one farming unit, hence reducing transport costs, environmental impact and completing the C, N and P cycles within one farm.

**Working principle**: Soybean is a major protein source in animal fodder, but is mostly imported. By cultivating the soybean locally, emissions could be reduced on global level. The solution was based on the outcomes of an Operational Group "Moja Soja" (OG), which is implementing innovative solutions in soybeans cultivation, fertilization, and soya varieties testing in Poland.

## Results of the solution on nutrient closure

**Nitrogen**: This solution helps to reduce (i) nitrogen import, (ii) nitrogen losses by maximizing its use in soybean cultivation. Nitrogen, which was incorporated into the soil at a rate of about 38 kg/ha, was used by growing soybeans. Mature soybeans and soybean waste, which were not used in industrial processes, were used for animal feed.

**Phosphorus**: An average of about 43 kg/ha went into the soil before soybean growth, depending on the soybean species and soil properties. Mature soybeans contained about 22 kg/t of P. And as with nitrogen, there was no significant loss of phosphorus, due to further processing of the crop.

**Carbon**: local carbon cycling.

## Effect of solution on environment

**GHG**: direct GHG were not measured. However, according to the literature the assessment of GHG emission depends on the land use change in soybean cultivation. For example, Castanheira & Freire (2013) observed significant differences for alternative solutions i.e., 0.1 – 17.8 kg $CO_2$ eq. $kg^{-1}$ soybean whereas when the land use change is not considered GHG intensity can vary from 0.3 to 0.6 kg $CO_2$ eq. $kg^{-1}$ soybean.

**Energy:** The results do not include energy consumption.

**Ammonia emissions:** Ammonia emissions were not analyzed, and there was no problem of excessive gaseous emissions. This is probably due to the fact that the amount of nitrogen supplied was quite low. Hence, it is unlikely to have ammonia emissions.

**Leaching to ground water**: C, N, P leaching were not measured.

**Final remarks:** This activity focused on the practicalities, cultivation of various types of soybeans, and nutrient cycling. Soybean cultivation in Poland is at a low level. Annually, an average of 20,000 hectares is cultivated (for comparison, the cultivation of cereals takes up 880,000 hectares). Way more was imported from South America - Argentina. About 2 million tons worth PLN 4 billion (Polska Soja, 2020). But year by year Polish soybeans cultivation is growing.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 773682.

**Recommendations:** It is important to choose the right type of plant suited to the soil and weather conditions of the region. This avoids using excessive amounts of fertilizer to maintain a particular type of plant at any cost, which saves money for farmers and protects the environment.

It is important to pay attention to the market demand for a particular type of plant and the possibilities of managing it in many processes.

**Transferability:** The growing knowledge allows for further application. A comprehensive approach to plant growth, protection and later use for on-farm feed production is an important topic that will become more and more necessary every year. This is mainly due to transportation costs (saving), nutrients C, N and P (reducing losses) and the use of almost 100% of plants in production processes.

Difficulties may be the costs of installations for the production of fodder or fertilizer (e.g. composters, heaps, fermentation, pyrolysis), including legal aspects, obtaining various types of permits for farm production and storing large amounts of waste. The self-sufficiency of the farm, which is not always able to produce enough products, may also pose difficulties.

### INPULSE: Innovating towards the use of Spanish legumes in animal feed (SRL10-LL45). (TRL 9)

*Francisco Corona, Francisco Verdugo (CARTIF)*

**Aim of the solution**: Excessive dependence on imports of protein for animal feed, especially soy, undermines the competitiveness and sustainability of the entire value chain. The INPULSE Operating Group (GO_INPULSE) was created to strengthen the cultivation of legumes in Spain and reduce the external dependence of protein for feed through the design and evaluation of a systematized mechanism of use of legumes, adapted to the needs of the entire chain.

**Key element of innovation respect to the state of the art:** The main aim of the INPULSE Operational Group is to design and evaluate a systematic mechanism to promote the cultivation and use of legumes adapted to the needs of all stakeholders involved in the animal feed chain. The main activities of the Operational Group have focused on compiling information and the state of the art on legume cultivation to promote the production and use of legumes in Spain, with the aim of reducing external dependence on protein for animal feed. INPULSE contributed to the diversification of food systems in Spain, improving their sustainability, the incorporation of young people, favouring competitiveness and the economic development of the animal feed chain and reduction greenhouse gas emissions and improving the environmental impacts of agricultural production and feed supply chains. The work that has been carried out in the OG has been from a theoretical and informative point of view, with the aim of analyzing the potential and advantages of growing legumes for animal feed and avoiding imports from Latin America.

**Working principle**: The needs of the agents of the animal feed chain, the reconnection of that chain and the encouragement for the transfer of knowledge to and from research were investigated. A joint diagnosis document that describes the production and use of legumes in Spain was created, to reduce the external dependence of protein for feed through the design and evaluation of a systematized mechanism of use of legumes, adapted to the needs of the entire chain.

**Results of the solution on nutrient closure**

**Carbon**: Cereals and legume intercropping could increase carbon sequestration about 15% (depending on the type of cereal, type of legume and climatic conditions – Daryanto et al., 2020). Alfalfa rotation had the highest sequestration rates at 513 kg C/ha·year (Ghosh et al., 2020).

**Nitrogen**: When legumes are introduced into a cereal crop sequence, nitrogen consumption can be reduced by 26% (depending on the type of cereal, type of legume and climatic conditions). Decreased import of nitrogen by feed.

**Phosphorus**: There are no main effects.

**Effect of solution on environment**

**GHG**: Currently, most of the legumes consumed in Spain are imported from Argentina. Reduction of soybean transportation distance decreases the environmental burdens of this process with 78.8 kg $CO_2$eq/ton (transport).

**Energy:** In general, energy consumption will be the same regardless of where it is grown, and therefore the real benefit is considered to come from avoiding the transport of legumes from South America to Spain.

**Ammonia emissions:** As with energy consumption, ammonia emissions will be the same regardless of where the crop is grown, and therefore the real benefit is considered to come from avoiding the transport of legumes from South America to Spain.

**Leaching to ground water**: When legumes are introduced into a cereal crop sequence, water consumption can be reduced up to 15-19% (depending on the type of cereal, type of legume and climatic conditions) and thus nutrient leaching reduced.

**Final remarks**: The production of legumes and their introduction into the crop rotation will allow the diversification of food systems in Spain, the improvement of their sustainability, the incorporation of young people, favour the competitiveness and economic development of the animal feed chain, the reduction of greenhouse gas emissions and the improvement of the environmental impacts of agricultural production and feed supply chains.

**Recommendations**: The solution is suitable for leguminous crops and rotation with other types of crops.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 773682.

**Transferability**: The solution is interesting for crop producers or livestock farms. On the other hand, the solution is independent of scale, so it can be used in all different farms' sizes and it is ready to be implemented.

## Synoptic table of findings across WPs

| Area | WP2: experimental data collection | WP1/3: modelling at farm scale |
|---|---|---|
| **Carbon cycle** | Cereals and legume intercropping could increase carbon sequestration about 15% (depending on the type of cereal, type of legume and climatic conditions – Daryanto et al., 2020). Alfalfa rotation had the highest sequestration rates at 513 kg C/ha·year (Ghosh et al., 2020). | |
| **Nitrogen cycle** | When legumes are introduced into a cereal crop sequence, nitrogen consumption can be reduced by 26% (depending on the type of cereal, type of legume and climatic conditions). Decreased import of nitrogen by feed. | For the farm scale modelling this solution was implemented on dairy farms as clover in grassland and not as legumes in a crop rotation. Mineral N fertilizer is replaced by N fixed from the atmosphere by clover. |
| **Phosphorus cycle** | no effects | |
| **GHG direct emissions** | not measured | $N_2O$ emissions decreased by 25% due to lower mineral N fertilizer use. |
| **Ammonia emissions** | not measured | Decreased on average by 7% due to lower fertilizer N input. |
| **Leaching to groundwater** | not measured<br>still, when legumes are introduced into a cereal crop sequence, water consumption can be reduced up to 15-19% (depending on the type of cereal, type of legume and climatic conditions) and thus nutrient leaching reduced. | Soil N leaching increased in grass-clover leys compared to grassland for several farms. This effect was likely the result of increased N input to soil by N fixation and clover residues. The results suggest that in these farms, fertilization may be further lowered with grass-clover leys to reduce N losses without compromising yields |

## Secondary harvest: additional valorisation of crop harvest and processing residues (SRL11-LL34). (TRL 8)

*Filip Raymaekers (UE, Belgium), Sander Vandendriessche (Inagro, Belgium)*

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 773682.

**Aim of the solution**: The main aim of this solution is to have an increased valorisation of crops, by applying ‘a secondary harvest’ of residues (e.g. valorisation of the stem and leaves of Brussels sprouts) or by processing the crop in a different way. This solution is about a specific case in Flanders in which a farmer harvests natural grass clippings for feed purposes instead of composting.

**Key element of innovation respect to the state of the art:** The valley of the “Zwarte beek” is a natural area in the province of Limburg in Flanders of about 1500 ha. For this case study, a farmer is harvesting at this moment an area of about 180 ha. The grass clippings coming from part of this area is of high quality because of selective mowing and can therefore be harvested as animal feed, or for other purposes. Hence, nutrient loops are being closed. This grass was being compared with cultivated grass by a literature study and the recycling of organic carbon and nutrients was evaluated. In many similar cases the grass is harvested, collected and “composted” in situ. Therefore, carbon and nutrients are lost.

**Working principle**: When harvesting grass, it is important to apply “selective mowing” as much as possible: areas that are of high quality can be used as animal fodder; other areas result in grass clippings of lower quality and can not be used as fodder but can be valorised through alternative processing (proteins or insolation materials). An experienced farmer will know how to make the selection on sight while mowing.

**Results of the solution on nutrient closure**

**Carbon**: When natural grass is used for animal feed instead of composting in situ, the potential for organic C recycling is 477 t $y^{-1}$.

**Nitrogen**: When natural grass is used for animal feed instead of composting in situ, the potential for N recycling is 19 t $y^{-1}$.

**Phosphorus**: When natural grass is used for animal feed instead of composting in situ, the potential for phosphate recycling is 3.14 t $y^{-1}$.

**Effect of solution on environment**

**GHG**: not determined.

**Energy:** not determined.

**Ammonia emissions:** not determined.

**Leaching to ground water**: not determined.

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 773682.

**Final remarks**: The solution has the potential to close the CNP, still CAPEX and OPEX might be different according to the context.

**Recommendations**: Selective mowing is very important, since it will influence the quality of the resulting feed.

**Transferability**: In fact, the transferability of this specific case is high since natural grass clippings occur everywhere. However, this is only one specific example of an alternative way of processing. When looking at the extra valorisation of agro-residues (e.g. stems and leaves of Brussels sprouts that otherwise remain on the field), the transferability is very case specific.

### Floating wetland plants grown on liquid agro-residues as a new source of proteins (SRL12-LL41). (TRL 6)

*Reindert Devlamynck (Inagro, Belgium), Erik Meers (UGent, Belgium)*

**Aim of the solution**: Floating wetland plants like duckweed (*Lemnaceae*) can take up nutrients from wastewaters and convert them into protein-rich biomass, which can be fed to animals. Furthermore, it can be considered a substitute for commonly imported protein sources. Hence, nutrient loops are being closed locally at the farm, and the import of protein sources into Europe is reduced. This specific solution focuses on several aspects of duckweed cultivation. The productivity of duckweed cultivation is 7-22 tonnes/ha/year.

**Key element of innovation respect to the state of the art:**

The state of the art is fertilizing land crops which can be used as a feed source such as maize. Applying biological effluent from manure treatment on farm land can, however, result in nutrient leaching. Furthermore, heavy machinery is required for transport to adjacent fields, resulting in an economic and environmental cost. With duckweed, more nutrients can be supplied to a nearby pond using only pumps, while leaching is inhibited. Important, however, is to prevent that valuable nutrients such as K are discharged due to an imbalance between nutrient addition and removal.

**Working principle**: Biological effluent and liquid fraction of the pig manure treatment were added to a pond of duckweed in the same amount as the measured N and P removal rates in duckweed ponds. The dynamic equilibrium between addition and removal can be designed to lay below the discharge limits imposed by VLAREM. This solution can be implemented before, parallel or after a constructed wetland. The harvest is performed weekly (but can be automized and occur daily or even continuously).

**Results of the solution on nutrient closure**

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 773682.

**Carbon**: There is only a marginal uptake of C from the wastewater into the duckweed. But more carbon is sequestered than emitted in a duckweed pond, meaning it results in an influx of carbon into the carbon cycle of animal husbandry.

**Nitrogen**: 28% of the applied N is taken up by the plant and is thus potentially recycled into the animal feed. The rest is removed due to (de)-nitrification.

**Phosphorus**: 39% of the applied P is taken up by the plant and is thus potentially recycled into the animal feed. The rest is removed due to sedimentation.

**Effect of solution on environment**

**GHG**: Plant growth captures $CO_2$, but anoxic, and bacterial presence within the duckweed pond will result in organic decomposition and potentially even methane production. Nevertheless, research has indicated that fixation exceeds the release of GHG (Mohedano et al., 2019).

**Energy:** An energy requirement of 4556 kWh/ha/yr is estimated for the use of pumps and transporting duckweed on the farm. Optimalisation and automatization might still have a very large effect.

**Ammonia emissions:** Good pH control (neutral or preferably acid pH) prevents ammonia emissions. An ideal growing medium also contains an $NO_3\_N/NH_4\_N$ ratio of 3/1, which means that 75% of the total nitrogen is unlikely to volatilize.

**Leaching to ground water**: The foil at the bottom of the duckweed system prevents all leaching to ground water.

**Recommendations**: The results on safety of heavy metal uptake in the plant are promising, but microbial and pathological safety still needs to be investigated more thoroughly. Furthermore, the LCA performed in Nutri2Cycle showed that release of K in the discharge water from duckweed cultivation, is a potential threat for the environment. This directly to the water body but foremost by the indirect potential increased need for synthetic K fertilizers in other crops.

**Transferability**: Low potential operational costs allow small, medium and large-scale implementation and can thus be evaluated as a flexible and highly transferable technology. However, the high investment cost, the high return-to-original-state-cost, and a required adjustment to the automatic feeding system, indicate medium to large scale implementation.

- **Expert ranking:** At EU level floating wetland plants grown on liquid agro-residues as a new source of protein garnered one of the joint lowest transferability ranking both in the short-term and medium-term from the expert panels. In the short- and medium term for both the survey and the expert evaluations this technology is ranked as the 13th most transferable and received a rank of 1 from the expert evaluation and a rank of 1.4 from the survey evaluation for short-term transferability.
- **Survey ranking:** The technology received a rank of 2 from the survey evaluation for medium-term transferability.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 773682.

### CBA findings

The installation of a wetland can significantly lower the operational costs, mainly due to the diminishment of the cost for disposal of the liquid fraction.
For the floating wetlands the investment cost is almost double of the investment for the reference (= storage + disposal on land).
The benefit of lower operational costs is almost erased resulting in a similar yearly balance with only 0.04 €/$m_{3\ \text{treated}}$ difference.
The additional investment that would be required for implementing a floating wetland would be recovered only after a period of around 10 years (= payback period).

### Producer perception of the innovation

Barriers: "economic considerations" such as the high cost of investment, a lower-than-expected economic return, and difficulties in the regulatory framework that complicates obtaining construction licenses, or that simply does not recognize the product obtained as a fertilizer, which limits the scope of commercialization.

**Enables:** environmental benefits (nutrient loss reduction) related to better nutrient management (greater efficiency of nutrient use) followed by the ability to use environmental benefits to improve the business image.

### Synoptic table of findings across WPs

| Area | WP2: experimental data collection | WP3: LCA | WP4: EU modelling |
|---|---|---|---|
| **Carbon cycle** | marginal uptake of C from the wastewater into the duckweed. | | |
| **Nitrogen cycle** | 28% of the applied N is taken up by the plant and is thus potentially recycled into the animal feed. The rest is removed due to (de)-nitrification. | N fertiliser use : -5.74E-04 kg (>-100%) | The introduction of floating wetlands as an alternative protein source for animal feed in livestock agriculture may reduce external nutrient import in protein-feeds and partially closes the Nitrogen-Phosphorus cycle.<br>Potential area of almost 300 kha for application, but more likely 147 kha. The duckweed grown on this area could potentially replace about 900 kton of soybean, which is about 5% of the current import of soybeans into the EU. |
| **Phosphorus cycle** | 39% of the applied P is taken up by the plant and is thus potentially recycled into the animal feed. The | P fertiliser use: +0.02 kg (+7%) | |

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 773682.

| | | |
|---|---|---|
| | rest is removed due to sedimentation. | |
| **GHG direct emissions** | Not measured<br>Plant growth captures $CO_2$, but anoxic, and bacterial presence within the duckweed pond will result in organic decomposition and potentially even methane production. | $N_2O$ negligible decrease<br>$CH_4$ decrease -0.03 kg (-11%) |
| **Ammonia emissions** | Good pH control (neutral or preferably acid pH) prevents ammonia emissions.<br>An ideal growing medium also contains an $NO_3\_N/NH_4\_N$ ratio of 3/1, which means that 75% of the total nitrogen is unlikely to volatilize. | increase, +0.03 kg $NH_3$ (>+100%) |
| **Leaching to groundwater** | The foil at the bottom of the duckweed system prevents all leaching to ground water. | $NO_3^-$ reduced: -0.03 kg $NO_3$ (>-100%)<br>$PO_4^{3-}$ increased: +9.39E-04 kg (+16%) |

## Algae grown on liquid agro-residues as a new source of proteins (SRL24-LL41b). (TRL 4)

*Jai Sankar Saleem, Marcella Fernandes De Souza (UGent, Belgium)*

**Aim of the solution**: Microalgae are photosynthetic microorganisms that can be grown on nutrients (nitrogen, phosphorus, and trace metal elements) derived from liquid agro-effluents to obtain protein-rich biomass without the need for agricultural land. Hence, like floating wetland plants, nutrient loops can be closed locally at the farm, and the import of protein sources into Europe can be reduced.

**Key element of innovation respect to the state of the art:** The state of the art is treatment followed by discharge of liquid agro-residues, resulting in nutrient losses and costs for the farmer. Meanwhile, protein (soy meal) is imported to Europe for making balanced animal feed. The solution effectively closes CNP loops since nutrients are being recovered from waste streams and local protein that can substitute soy meal is being produced to reduce the import of protein into Europe.

**Working principle:** In this specific solution, the lab and pilot-scale valorisation of digestate to produce protein-rich microalgae biomass was investigated. In the presence of (sun)light, the algae production process actively utilizes digestate-derived soluble macronutrients (N & P) and micronutrients (trace metal elements), energy (bioelectricity) and gaseous emissions ($CO_2$) generated by a biogas facility. Therefore, the biogas facility can provide all the necessary inputs and external inputs are not needed.

A biomass productivity of 2 g/L/week was achieved with a possibility of further increasing it by inoculum optimization. Agricultural land is not needed and the reactor can be installed in any available closed space for temperature maintenance of 20-25 °C (greenhouse if using sunlight is aimed or hangar if artificial light is installed).

### Results of the solution on nutrient closure

**Carbon**: approximately 1 g/L/week of C incorporated into algal biomass.

**Nitrogen**: 0.12 g/L/week of $NH_4^+$-N incorporated into algal biomass.

**Phosphorus**: 0.01 g/L/week of P incorporated into algal biomass.

### Effect of solution on environment

**GHG**: $CO_2$ capture (all C provided to algae comes from $CO_2$).

**Energy:** high due to small scale.

**Ammonia emissions:** not quantified, but 15-30% of the N at the pH of operation is present as volatile $NH_3$, so some emissions are expected.

**Leaching to ground water**: no leaching as a closed reactor is used.

**Final remarks**:

**Recommendations**: The process can still be optimized and a better understanding of the minimal scale of operation required to have an economic attractive process is needed. The current process requires a significant volume of water for digestate dilution that should be decreased with a better understanding of the system.

**Transferability**: Due to the low amount of digestate treated per L of algae medium, it seems that this solution is currently best-suited for on-farm implementation. However, costs associated with a small scale need to be taken into consideration, especially regarding energy expenditure. If there is surplus energy and heat being produced from the local AD plant, the process will be more economically attractive for implementation.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 773682.

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# ANNEX 1 – List of publications

## Research line 1. Innovative management systems, tools & practices for optimized nutrient and GHG management in animal husbandry

1. Dróżdż, D., Wystalska, K., Malińska, K., Grosser, A., Grobelak, A., Kacprzak, M., 2020. Management of poultry manure in Poland – Current state and future perspectives. Journal of Environmental Management, 264, 110327. https://doi.org/10.1016/j.jenvman.2020.110327
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## Research line 2. Innovative soil, fertilisation & crop management systems & practices for enhanced N,P efficiency and increased soil OC content

11. Riau, V., Burgos, L., Camps, F., Domingo. F., Torrellas, M., Anton, A., Bonmati, A., 2021 Closing nutrient loops in a maize rotation. Catch crops to reduce nutrient leaching and increase biogas production by anaerobic co-digestion with dairy manure. Waste Management 126, 719–727. https://doi.org/10.1016/j.wasman.2021.04.006
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## Research line3. Tools, techniques & systems for higher-precision fertilization

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## Research line 4. Biobased fertilisers (N,P) and soil enhancers (OC) from agro-residues

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## Research line 5. Novel animal feeds produced from agro-residues

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## Broader systemic assessment of nutrient recovery and recycling

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## ANNEX 2 – List of PhD theses

| | |
|---|---|
| Name, surname | Ambrogio Pigoli |
| Institution name | Università degli Studi di Milano |
| Joint PhD (if yes, the name of second institution) | No |
| Thesis title | From Sewage Sludge to Renewable Fertilizer: Efficacy and Environmental Risks in Open Field Experiment |
| Dissertation year | 2022 |
| Supervisor(s) | Fulvia Tambone, Fabrizio Adani |
| Associated research line in Nutri2Cycle | Research line 2 |
| Associated solution(s) in Nutri2Cycle (Long List, Sub-research line (shortlist)) | SL1. Practices for increasing soil organic matter (OM) content<br>LL16. Farm using digestate, precision agriculture and no-tillage focusing on OM stocking in an area characterized by the lack of OM |
| Link to the thesis (if available) | https://air.unimi.it/handle/2434/894685 |

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|---|---|
| Name, surname | Amrita Saju |
| Institution name | Ghent university |
| Joint PhD (if yes, the name of second institution) | No |
| PhD title | Novel agro-industrial pathways for nitrogen recovery : Product assessment and market uptake |
| Dissertation year | 2024 (expected) |
| Supervisor(s) | Erik Meers, Geert Haesaert |
| Associated research line in Nutri2Cycle | Research line 4 |

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| Associated solution(s) in Nutri2Cycle (Long List, Sub-research line (shortlist)) | SL 4. Substituting external mineral nutrient input from synthetic fertilisers by recycled organic based fertilisers in arable farming - LL1 and 2. Ammonium stripping/scrubbing, and ammonium nitrate and ammonium sulphate as substitutes for synthetic N fertilisers<br>SL15. Organic matter recovery from manure and associated valorization strategies - LL24. Adapted stable construction for separated collection of solid manure and urine in pig housing (followed by separate post-processing) |
| Link to the thesis (if available) | Not yet available |

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|---|---|
| Name, surname | Anna Jasińska |
| Institution name | Częstochowa University of Technology |
| Joint PhD (if yes, the name of second institution) | Ghent University |
| PhD title | Energy recovery from poultry manure and organic waste in anaerobic digestion process |
| Dissertation year | 2024 (expected) |
| Supervisor(s) | Anna Grosser, Erik Meers |
| Associated research line in Nutri2Cycle | Research line 1 |
| Associated solution(s) in Nutri2Cycle (Long List, Sub-research line (shortlist)) | SL13. Anaerobic digestion strategies for optimized nutrient and recovery from animal manure<br>LL41. Recovery of energy from poultry manure and organic waste through anaerobic digestion |
| Link to the thesis (if available) | Not yet available |

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|---|---|
| Name, surname | Arejacy Antonio Sobral Silva |

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|---|---|
| Institution name | Instituto Superior de Agronomia, , Universidade de Lisboa |
| Joint PhD (if yes, the name of second institution) | No |
| PhD title | Closing Knowledge Gaps on Slurry Application in Conservation Agriculture with Special Emphasis on Stubble-covered Soil |
| Dissertation year | 2022 |
| Supervisor(s) | David Fangueiro |
| Associated research line in Nutri2Cycle | Research line 3 and 4 |
| Associated solution(s) in Nutri2Cycle (Long List, Sub-research line (shortlist)) | LL63. Precision fertilization of Maize using organic materials<br>LL20. Field assessment of precision fertilization of maize & cereals using bio-based fertilizers |
| Link to the thesis (if available) | https://www.repository.utl.pt/handle/10400.5/27512 |

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|---|---|
| Name, surname | Axel Mauricio Herrera Moreno |
| Institution name | Università degli Studi di Milano |
| Joint PhD (if yes, the name of second institution) | No |
| PhD title | Environmental assessment of undercurrent agricultural technologies towards circular nutrient management |
| Dissertation year | 2021 |
| Supervisor(s) | Fabrizio Adani |
| Associated research line in Nutri2Cycle | Research Line 2 and 4 |
| Associated solution(s) in Nutri2Cycle (Long List, Sub-research line (shortlist)) | SL1. Practices for increasing soil organic matter content - LL16. Using digestate, precision agriculture and no- |

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| | tillage focusing on OM stocking in an area characterized by the lack of it.<br>SL7. Pig manure processing and replacing mineral fertilizers - LL23. Pig manure refinery into mineral fertilisers using a combination of techniques applicable at industrial pig farms |
| Link to the thesis (if available) | https://air.unimi.it/handle/2434/885232 |

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|---|---|
| Name, surname | Bruno Rizzi |
| Institution name | Università degli Studi di Milano |
| Joint PhD (if yes, the name of second institution) | No |
| Thesis title | Environmental Impacts in the Use of Digestate as Substitute of Chemical Fertilizers |
| Dissertation year | 2022 |
| Supervisor(s) | Fabrizio Adani, Fulvia Tambone |
| Associated research line in Nutri2Cycle | Research line 2 |
| Associated solution(s) in Nutri2Cycle (Long List, Sub-research line (shortlist)) | SL1. Practices for increasing soil organic matter (OM) content<br>LL16. Farm using digestate, precision agriculture and<br>no-tillage focusing on OM stocking in an area<br>characterized by the lack of OM |
| Link to the thesis (if available) | https://air.unimi.it/handle/2434/896042 |

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|---|---|
| Name, surname | Catarina Esteves |
| Institution name | Instituto Superior de Agronomia, Universidade de Lisboa |
| Joint PhD (if yes, the name of second institution) | Ghent University |

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| PhD title | Valorisation of animal manures for precision fertilization of orchards and vineyards |
| Dissertation year | 2024 (expected) |
| Supervisor(s) | David Fangueiro, Henrique Ribeiro, Ricardo Braga, Erik Meers |
| Associated research line in Nutri2Cycle | Research line 2 and 3 |
| Associated solution(s) in Nutri2Cycle (Long List, Sub-research line (shortlist)) | LL57. Recovered organic materials and composts for precision fertilization of apple orchards and vineyards |
| Link to the thesis (if available) | Not yet available |

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|---|---|
| Name, surname | Danuta Dróżdż |
| Institution name | Czestochowa University of Technology |
| Joint PhD (if yes, the name of second institution) | Ghent University |
| PhD title | Production and use of organic soil enhancers and growing media from agro-residues |
| Dissertation year | 2022 |
| Supervisor(s) | Erik Meers, Krystyna Malińska, Ana Alejandra Robles-Aguilar |
| Associated research line in Nutri2Cycle | Research line 4 and 5 |
| Associated solution(s) in Nutri2Cycle (Long List, Sub-research line (shortlist) | LL47. Production of growing substrates for horticulture application from poultry manure, solid state digestate and biochar through composting<br>LL25. Soybeans in Poland – innovative solutions in the cultivation, plant protection and feeding on farms |
| Link to the thesis (if available) | Thesis at CUT website: https://bip.pcz.pl/plik,1682,rozprawa-doktorska.pdf<br>Thesis at UGent website: https://biblio.ugent.be/publication/01GK231F215ADTWG123GJ3FCKR |

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|---|---|
| Name, surname | Edilene Pereira Andrade |
| Institution name | Universitat Rovira I Virgili |
| Joint PhD (if yes, the name of second institution) | IRTA |
| Thesis title | Assessment of Environmental and Social Impacts Due to the Inclusion of Novel Solutions for Nutrient Recovery: Towards Sustainability in Agriculture |
| Dissertation year | 2022 |
| Supervisor(s) | Assumpció Antón, August Bonmatí, Laureano Jiménez |
| Associated research line in Nutri2Cycle | Broader systemic assessment |
| Associated solution(s) in Nutri2Cycle (Long List, Sub-research line (shortlist)) | LL20. Low temperature ammonium-stripping<br>using vacuum |
| Link to the thesis (if available) | https://www.tdx.cat/handle/10803/674820#page=1 |

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|---|---|
| Name, surname | Erica Yvonne Montemayor |
| Institution name | Universitat Politècnica De Catalunya |
| Joint PhD (if yes, the name of second institution) | IRTA |
| Thesis title | Environmental Impact Accounting of Organic Agricultural Production Systems: Advancing Inventory and Biodiversity Modelling Approaches in Life Cycle Assessment |
| Dissertation year | 2022 |
| Supervisor(s) | Assumpció Antón, August Bonmatí, Santiago Gassó |
| Associated research line in Nutri2Cycle | Broader systemic assessment |

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| Associated solution(s) in Nutri2Cycle (Long List, Sub-research line (shortlist)) | |
| Link to the thesis (if available) | http://hdl.handle.net/10803/689049 |

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|---|---|
| Name, surname | Gregory Reuland |
| Institution name | Ghent University |
| Joint PhD (if yes, the name of second institution) | European Biogas Association |
| PhD title | Carbon and nitrogen cycles from digestate-mediated solutions |
| Dissertation year | 2024 (expected) |
| Supervisor(s) | Erik Meers |
| Associated research line in Nutri2Cycle | Research line 4 |
| Associated solution(s) in Nutri2Cycle (Long List, Sub-research line (shortlist)) | SL1. Practices for increasing soil organic matter content<br>SL4. Substituting external mineral nutrient input from synthetic fertilisers by recycled organic based fertilisers in arable farming => LL9. Liquid fraction of digestate as a substitute for mineral N & K fertilizer |
| Link to the thesis (if available) | Not yet available |

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|---|---|
| Name, surname | Hongzhen Luo |
| Institution name | Ghent University |
| Joint PhD (if yes, the name of second institution) | No |
| PhD title | Interrelations between the nitrogen availability of biobased fertilizers and dynamics of the plant-soil system |
| Dissertation year | 2023 |
| Supervisor(s) | Erik Meers, Stefaan De Neve |

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| Associated research line in Nutri2Cycle | Research Line 4 |
| Associated solution(s) in Nutri2Cycle (Long List, Sub-research line (shortlist)) | SL4. Substituting external mineral nutrient input from synthetic fertilizers by recycled organic based fertilizers in arable farming<br>LL 6. Concentrate from vacuum evaporation/ stripping<br>as nutrient-rich organic fertilizer |
| Link to the thesis (if available) | http://hdl.handle.net/1854/LU-01GYVPBC26W4SGCQYPZGF0PV2A |

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|---|---|
| Name, surname | Joana Prado |
| Institution name | Instituto Superior de Agronomia, , Universidade de Lisboa |
| Joint PhD (if yes, the name of second institution) | No |
| PhD title | Blending of raw and treated animal mamure to produce manure-base fertilizer |
| Dissertation year | 2023 |
| Supervisor(s) | David Fangueiro, Paula Alvarenga, Henrique Ribeiro |
| Associated research line in Nutri2Cycle | Research line 4 |
| Associated solution(s) in Nutri2Cycle (Long List, Sub-research line (shortlist)) | LL62. Blending of raw and treated organic materials to<br>produce organic fertilisers (NPC) |
| Link to the thesis (if available) | Not yet available |

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|---|---|
| Name, surname | Jai Sankar Seelam |
| Institution name | Ghent University |
| Joint PhD (if yes, the name of second institution) | No |

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|---|---|
| PhD title | Creating value from waste nutrients by integrating algal and anaerobic digestion technology |
| Dissertation year | 2024 (expected) |
| Supervisor(s) | Erik Meers |
| Associated research line in Nutri2Cycle | Research line 5 |
| Associated solution(s) in Nutri2Cycle (Long List, Sub-research line (shortlist)) | LL53. ALG-AD: Integrating algal and anaerobic digestion technology for sustainable animal feed production |
| Link to the thesis (if available) | Not yet available |

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|---|---|
| Name, surname | Lluís Morey Gual |
| Institution name | IRTA – Universitat Politècnica de Catalunya |
| Joint PhD (if yes, the name of second institution) | Ghent University |
| PhD title | Closing Loops in Intensive Livestock Systems: Innovative Strategies for Nutrient Recycling and Emissions Reduction |
| Dissertation year | 2023 |
| Supervisor(s) | Víctor Riau Arenas, Marta Terré Trullà, Erik Meers |
| Associated research line in Nutri2Cycle | Research Line 1 |
| Associated solution(s) in Nutri2Cycle (Long List, Sub-research line (shortlist)) | |
| Link to the thesis (if available) | Not yet available |

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|---|---|
| Name, surname | Marie Lambert |
| Institution name | Ghent University |
| Joint PhD (if yes, the name of second institution) | Inagro vzw |

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| PhD title | Introduction of *Lemna minor* as a new protein crop in Flanders |
| Dissertation year | 2025 (expected) |
| Supervisor(s) | Erik Meers, Katleen Raes, Mia Eeckhout |
| Associated research line in Nutri2Cycle | Research line 5 |
| Associated solution(s) in Nutri2Cycle (Long List, Sub-research line (shortlist)) | LL41. Floating wetland plants grown on liquid agro-residues as a new source of proteins |
| Link to the thesis (if available) | Not yet available |

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|---|---|
| Name, surname | Merve Konucu |
| Institution name | Ghent University |
| Joint PhD (if yes, the name of second institution) | No |
| PhD title | Coagulation-Flocculation as a Sustainable Harvesting Process for Microalgae Grown in Wastewater |
| Dissertation year | 2024 (expected) |
| Supervisor(s) | Erik Meers |
| Associated research line in Nutri2Cycle | Research line 5 |
| Associated solution(s) in Nutri2Cycle (Long List, Sub-research line (shortlist)) | LL41b. Algae grown on liquid agro-residues as a new source of proteins |
| Link to the thesis (if available) | Not yet available |

|   |   |
|---|---|
| Name, surname | Miriam Beyers |
| Institution name | University of Copenhagen (UCPH) |
| Joint PhD (if yes, the name of second institution) | Ghent University (UGent) |
| PhD title | Life Cycle Assessment as a tool to design future agricultural systems – Evaluation of technologies aimed |

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| | at closing nutrient loops & decreasing farm-related environmental impacts |
| Dissertation year | 2023 |
| Supervisor(s) | Sander Bruun, Erik Meers, Lars Jensen |
| Associated research line in Nutri2Cycle | Broader systemic assessment |
| Associated solution(s) in Nutri2Cycle (Long List, Sub-research line (shortlist)) | LL18. Slurry acidification with industrial acids to reduce $NH_3$ volatilisation from animal husbandry<br>LL40. Insect breeding as an alternative protein source on solid agro-residues (manure and plant wastes)<br>LL41. Floating wetland plants grown on liquid agro-residues as a new source of proteins |
| Link to the thesis (if available) | Not yet available |

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|---|---|
| Name, surname | Rahul Ravi |
| Institution name | Ghent University |
| Joint PhD (if yes, the name of second institution) | University of Copenhagen |
| PhD title | The role of waste biorefineries towards climate neutrality: Insights from a life cycle perspective |
| Dissertation year | 2023 |
| Supervisor(s) | Erik Meers, Sander Bruun |
| Associated research line in Nutri2Cycle | Broader systemic assessment |
| Associated solution(s) in Nutri2Cycle (Long List, Sub-research line (shortlist)) | LL 1+2 Ammonium stripping/scrubbing and $NH_4NO_3$ + $(NH_4)2_SO_4$ as substitute for synthetic fertilizers<br>LL6. Concentrate from vacuum evaporation/ stripping<br>as nutrient-rich organic fertilizer<br>LL65. Struvite as a substitute of synthetic P fertilizer |
| Link to the thesis (if available) | Not yet available |

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|---|---|
| Name, surname | Reindert Devlamynck |
| Institution name | Inagro vzw |
| Joint PhD (if yes, the name of second institution) | Ghent University |
| PhD title | Sustainable protein production on agricultural effluents using duckweed |
| Dissertation year | 2021 |
| Supervisor(s) | Erik Meers, Mia Eeckhout, Jan Leenknegt |
| Associated research line in Nutri2Cycle | Research line 5 |
| Associated solution(s) in Nutri2Cycle (Long List, Sub-research line (shortlist)) | LL41. Floating wetland plants grown on liquid agro-residues as a new source of proteins |
| Link to the thesis (if available) | https://biblio.ugent.be/publication/8720917 |

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