PROJECT FINAL PUBLISHABLE SUMMARY REPORT

FP7 Grant agreement no.:	308637
Project acronym:	**BioEcoSIM**

An innovative bio-economy solution to valorise livestock manure into a range of stabilised soil improving materials for environmental sustainability and economic benefit for European agriculture

Project co-ordinator name:	Dr. Jennifer Bilbao
Project co-ordinator organisation:	Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung e.V.
Phone:	+49 711 970 3646
Email:	jennifer.bilbao@igb.fraunhofer.de
Project website address:	www.bioecosim.eu

The research leading to results in this project receives funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under GA n° [308637].

BioEcoSIM

Executive summary

The EU-funded project BioEcoSIM, a project consortium with 14 partners from 5 countries, aimed to valorise pig manure as valuable products. This circular economy approach integrates a series of modules that can be used independently or as a whole system according to regional legal aspects and context. In BioEcoSIM, the solid manure fraction was converted into biochar as soil improver and syngas for heat and power production, and the liquid fraction was processed to recover mineral fertilisers and irrigation water.

BioEcoSIM is an innovative concept that offers a real manure valorisation. The state-of-the-art on manure management is to dispose or treat manure as waste rather than treat it as a resource. In regions with intensive livestock production, surplus manure is normally transported to other regions (often > 100 of km) with nutrient demand or treated it in centralized plants using expensive energy-intensive technologies (biological nitrogen removal, reverse osmosis), where the intrinsic value within manure is not recovered. BioEcoSIM

1) is more cost-efficient than current approaches for manure disposal or treatment,

2) is automatized and easy to use to avoid expensive labour costs,

3) has a robust operation with low maintenance costs,

4) is modular, so it can fit with the different manure fertilising and disposal restrictions across Europe

5) works on the principle of circular economy recovering products (mineral fertilisers and soil improvers) from manure.

Extensive investigations in greenhouse and field studies in two different locations (temperate – Germany and Mediterranean – Spain) have shown that the recovered mineral fertilizers can be used directly in agriculture as readily available fertilizers and the biomass yield achieved with BioEcoSIM fertilizing products is comparable to commercial available mineral fertilizers such as triple-superphosphate and ammonium sulphate.

The integrated sustainability of BioEcoSIM and of three State-of-Art (SoA) systems (long distance transport, manure separation and manure drying) were assessed using economic cost-benefit analyses, Life Cycle Assessment (ISO 14040 and 14044) and social statistical polls. BioEcoSIM performed better on all aspects of sustainability: economic, environmental and social than the three state-of the-art manure management approaches. If 30 BioEcoSIM plants are sold after five years, we will be able to valorised 2.3 millions of surplus manure, produced 27 000 tonnes of phosphorus salts, 28 000 tonnes of ammonium sulphate and 61 000 tonnes of soil improvers. This will mean savings of 345 000 tonnes of CO_2eq.

BioEcoSIM is a business-driven approach with excellent potential for quick deployment and market take-up. BioEcoSIM is at a mature development stage since it has been successfully validated and demonstrated at a pilot scale of 50 kg/h for over 15 months in a farm located in Kupferzell, Germany. Currently, a full-scale prototype with 1 tonne/h is being built to demonstrate the conditioning, solid-liquid separation and P-recovery modules. The techno-economic effectiveness of the prototype will be validated in 2017 and technology will be introduce into the market by 2018.

The research leading to results in this project receives funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under GA n° [308637].

BioEcoSIM

Summary description of the project context and the main objectives

To ensure the sustainability and security of Europe's supplies of food and bio-based raw materials, there is a need to transform agriculture and reduce the adverse environmental impacts of current practices and fertiliser production methods. There have been a number of initiatives to improve the sustainability of intensified agricultural activities. However, suitable technological solutions have not yet been provided to make use of nitrogen (N) and phosphorous (P) in livestock manure to supply European fertiliser requirements.

Land application of animal manure supplies agricultural soil with valuable organic matter and essential nutrients, which help meet crop nutrient requirements and maintain soil fertility. Nevertheless, livestock intensification and regional conglomeration generates significant amounts of surplus manure in regions where it cannot be efficiently used as a resource. Manure is nowadays perceived in many regions as a waste to be treated and disposed of, losing the benefit of its fertiliser and soil conditioner value and consuming additional energy e.g. for transport and disposal.

Annually in EU27, over 10 million tonnes of N and 1.8 million tonnes of P are excreted by livestock. This quantity has the potential to fully meet the EU demands of mineral fertilisers. However, it is currently used wastefully to enrich crop growth in regions with high animal densities. Only 65% of livestock excretion is collected; over 50% of N is lost in storage and following application, resulting in harmful environmental effects:

- Eutrophication of surface and groundwater pollution caused by leaking earthen manure stores, direct run-off at outdoor storage and by N and P leaching resulted from excessive nutrient application in the fields.
- Air pollution through gaseous emissions (e.g. H_2S, CH_4, NH_3, and N_2O) during storage and land application.
- Soil pollution by land application of manure, creating imbalances of nutrients impairing plant growth
- Accumulation of heavy metals (e.g. cadmium, copper and zinc) and antibiotics in the soil after repeatedly manure applications.

Besides, due to the dramatically increasing interest in the production of bio-based products and bioenergy, soil degradation becomes a serious problem in Europe. The decline of soil fertility is masked by the overuse of synthetic fertilisers without the replacement of organic matter. This results in loss of soil fertility, carbon and biodiversity, lower water-retention capacity, and disruption of nutrient cycles.

BioEcoSIM addresses an important need for economically viable and environmentally benign practices to ensure sustainable European agriculture and supports the EU Bio-Economy Strategy and Action Plan to increase the use of bio-based raw materials. Livestock manure as an important example of valuable bio-waste will be converted into stable materials that can be easily handled, transported, and applied for agricultural and/or horticultural purposes. It targeted to develop and demonstrate a resource and energy efficient pilot plant for the continuous conversion of wasted livestock manure to:

(i) valorise manure into pathogen-and antibiotic-free biochar and mineral fertilisers (ammonium sulphate, calcium phosphate and struvite) supporting the production of food and other bio-based raw materials;
(ii) reduce negative environmental impacts in intensive livestock regions;
(iii) help to decrease ammonia (NH_3) produced by the energy-intensive Haber-Bosch process for manufacturing N-fertilisers;

The research leading to results in this project receives funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under GA n° [308637].

(iv) mitigate EU's dependency on depleting mineral sources for P-fertilisers;
(v) increase water efficiency in agricultural use; and
(vi) generate economic benefits for farmers through the sales of electricity generated from syngas and fertiliser products.

The main objectives of the project were:

- To develop, design, construct and validate an integrated thermal process designed to treat solid manure fraction. The process consisted on a superheated steam dryer (120°C to 200°C) and a pyrolysis reactor (300°C to 600°C). This integrated process was designed to convert solid manure fraction into biochar and syngas.
- To develop, design, construct and validate a process to recover phosphorus, calcium, and magnesium from the liquid manure fraction in form of a mineral phosphate fertilisers.
- To develop, design, construct and validate a process unit to recover ammonia (NH_3) from outputs from the superheated steam dryer and from the phosphorus precipitation reactor in form of ammonium sulphate (AS).
- To scale up the laboratory-scale process to a semi-mobile, robust and fully automated pilot scale with an input feed rate of 40 kg/h of pig manure, integrating the three main modules (thermal process, phosphorus recovery unit and ammonia recovery unit).
- To demonstrate the performance of the pilot-scale unit
- To validate the capability of process outputs in supporting plant growth in greenhouse experiments and agronomic field trials.
- To assess the social, environmental and economic sustainability of BioEcoSIM and three state-of-art manure management approaches.
- To ensure maximum impact of the project results.

BioEcoSIM Project video

The research leading to results in this project receives funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under GA n° [308637].

BioEcoSIM

Description of the main Science & Technological results or foregrounds

Development of a pilot plant to valorize manure

Optimal process conditions for superheating steam drying (SHSD) and correlations between processes variables and product characteristics were experimentally determined, facilitating the targeted dried manure solid output with at least 90% TS to be realised. Dried manure solid was further treated in an atmosphere of superheated steam to convert the inherent carbon into biochar and pyrolysis gas.

Pyrolysis experiments were carried out at different temperatures and retention times to determine the effects of process variables on the properties of biochar and pyrolysis gas. Accordingly, optimal parameters of superheated steam pyrolysis were identified, ensuring over 60% conversion of biochar with satisfactory specific surface area and average pore size diameter as well as pyrolysis gas of adequate calorific value for valorisation in a combined heat and power (CHP) plant. Based on the findings through experimental and analytical assessments, an integrated thermal processing unit consisting of a superheated steam dryer (SHSD) and a superheated steam pyrolysis reactor was designed and configured for handling the separated solid fraction from 100 kg/h raw pig manure.

The liquid manure fraction after the solid/liquid separation was characterised. The characterisation was then employed as a basis to determine the potential to precipitate the mineral phosphate fertiliser mixture through a comprehensive thermodynamic analysis. This assessment showed that more than 80% of P was found in the solid manure fraction after solid/liquid separation. For this reason, a pre-treatment step (before solid/liquid separation) was introduced to the process. During the pre-treatment, the P found in the solid manure fraction dissolve into the liquid manure fraction. This process was also useful to avoid ammonia losses during storage. This conditioning was carried out through an acid leaching of manure. With this, more than 95% of the phosphorus could be dissolved into the liquid fraction.

The manure separation process was also investigated in detailed. A process was developed to separate the manure using a two-step system. In the first step, a solid manure fraction was separated without any additives as soil improver with low P concentration. In the subsequently separation step, the liquid fraction was further separated through a fine filtration to obtain a particle-free liquid for further P and N recovery.

Several simulations and experimental work using Design of Experiments were then performed to assess the optimal parameter of the phosphorus precipitation. Based on these findings a laboratory scale unit reactor was designed and constructed to handle 5 kg/h raw pig manure.

Moreover, the fabrication and characterisation of the tubular gas-permeable membranes enabling selective separation of ammonia from the liquid output stream from the thermal and phosphorus precipitation units were conducted. Once the membranes of desired geometry and suitable material had been fabricated, parameterisation of the ammonia recovery process was carried out by means of numerical modelling. Based on the operating parameters determined through simulation, ancillary units were specified and consequently, a laboratory-scale ammonia recovery unit was designed and constructed.

With the quantified and qualified outputs, the dependencies between operating variables and characteristics of the generated products could be determined. Control algorithms were developed and sensors suitable for the defined working conditions were selected as well as

The research leading to results in this project receives funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under GA n° [308637].

interface boundaries to ancillary systems to be controlled, monitored and powered had been executed.

During the second year, laboratory-scale units of phosphorus precipitation and ammonia recovery have been integrated together with the pilot-scale thermal processing unit (drying and pyrolysis with superheated steam) at the facility of Agroenergie (Kupferzell, Germany). Performance of the integrated laboratory-scale unit was then verified in accordance with the targeted operation ranges and quantities of outputs (biochar, pyrolysis gas, phosphate salts and ammonium sulphate).

With the results of integrated lab-units the scale up of laboratory plant took place. Thus, pilot-scale units for thermal processing of solid manure fraction and for recovery of phosphorus and ammonia from liquid manure fraction were constructed, installed and commissioned at the facility of Agroenergie (Kupferzell, Germany). In the four year of the project, the integrated pilot-scale unit was successfully operated in continuous form. The quality and quantity of the outputs at a feed of 40 kg/h raw manure was monitored. Every hour the BioEcoSim pilot plant processes 40 kilograms of pig manure to about 500 grams of mineral phosphate fertilizer (a mixture of calcium phosphate, magnesium ammonium phosphate and magnesium phosphate), 500 grams of mineral nitrogen fertilizer (pure ammonium sulfate), as well as 900 grams of organic biochar.

Quality of the products

The quality of the outputs has been assessed in pot and greenhouse experiments, demonstrating that BioEcoSIM mineral salts and biochar have excellent fertilizing and soil improving properties. This included the development and validation of a multi-step approach for testing the suitability of novel products as fertilizers: 1) chemical characterization; 2) bioassays; 3) greenhouse experiments; 4) field experiments.

1. The chemical characterization covered total and water-soluble plant nutrients, heavy metals, antibiotics, and endocrine disruptors. For determining steroid hormones in manure, a method was developed using a two-step extraction followed by LC-MS/MS analysis.
2. The bioassays had the objective of determining any potential ecotoxicologial effects of the products at an early stage of the project. Seed germination, crop growth and earthworm mortality tests were carried out.

Based on the results of the chemical characterization and the bioassays, it was proved that the products are non-hazardous and non-eco-toxic. They are not expected to expose any major risks to soil, crops or environment regarding their chemical composition and the resulting characteristics.

3. Greenhouse experiments with all BioEcoSIM products were carried out on test crops including barley, wheat, maize, rapeseed and faba bean in different soils. Manure-based phosphate salt increased dry matter yield by up to 60% in comparison to conventional phosphate fertilizer. Biochar delivered promising results in combination with ammonium sulphate.
   Another experiment with horticultural crops assigned the phosphate salt the same effect as commercial phosphate fertilizer.

4. Field experiments were carried out with winter wheat and maize at two locations in Southwest Germany in order to validate the fertilizers' performance under practical conditions. The products have proven very good fertilizing effects when applied to the test crops at field-scale conditions at all experimental sites. They showed the same efficiency as comparable commercial fertilizers.

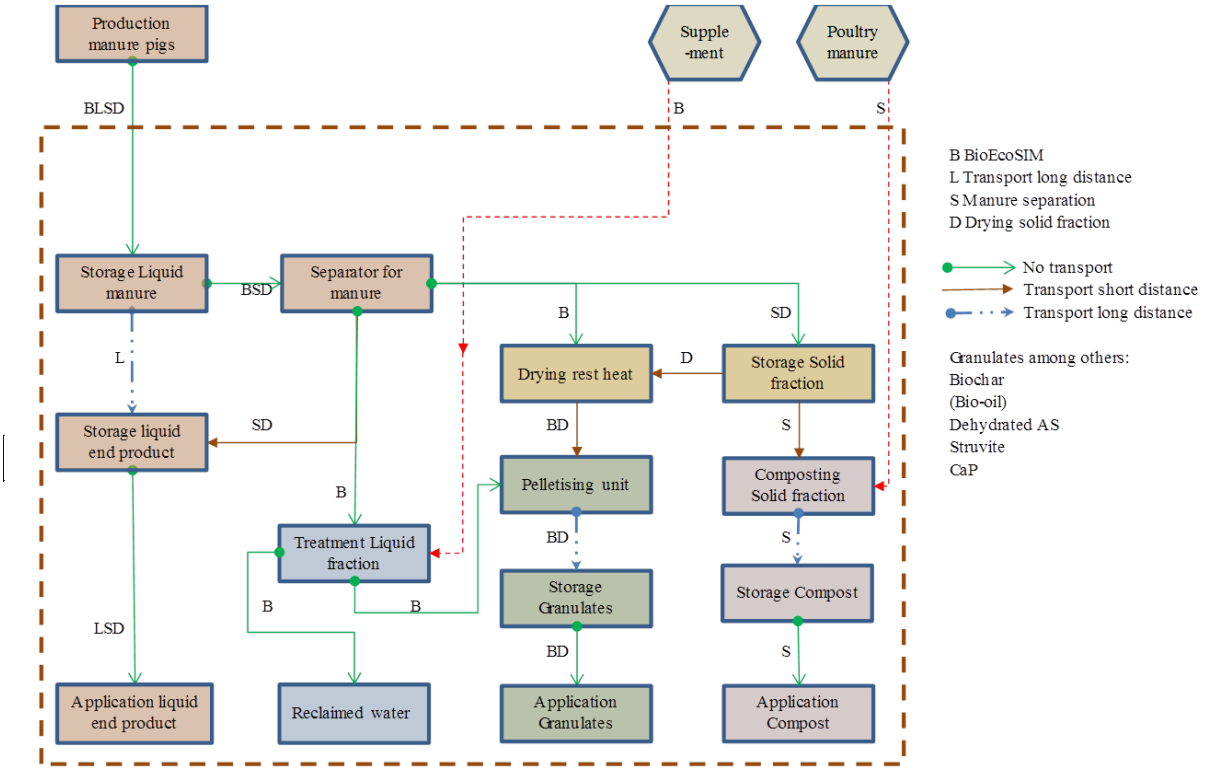
The research leading to results in this project receives funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under GA n° [308637].

GHG emissions (N_2O) following fertilizer application were determined in an accompanying soil incubation experiment. Biochar addition reduced the cumulative nitrogen losses by 50% when applied in combination with ammonium sulphate. The total N loss was below 1% in all treatments, the emission factor of the IPCC commonly used for modelling and LCA studies.

To summarize the findings from greenhouse and field experiments, the BioEcoSIM products phosphate salt, ammonium sulfate and biochar result in improved soil quality and higher crop productivity. It was clearly visible that their fertilizing properties are just as effective as those of comparable commercial products.

Integrated Sustainability Assessment

Impacts of an innovative manure management technology BioEcoSIM have been compared in the integrated sustainability assessment with three existing state-of-the-art manure processing systems: long distance transport; manure drying; and manure separation.



The comparative sustainability impact assessment also considered the alternative setup of BioEcoSIM without pyrolysis and with soil improver rather than biochar as product from the solid fraction processing.

The environmental impact assessment showed that BioEcoSIM with biochar production has the lowest net environmental effect. The environmental impacts of BioEcoSIM with biochar, and also of BioEcoSIM with soil improver, are substantially lower than of other state-of-the-art manure processing systems. Long distance transport of manure has the highest environmental impact, whereas manure drying and manure separation have comparable intermediate environmental effects. The environmental impacts per ton processed manure of the other manure processing systems, and of the BioEcoSIM process with production of soil improver, deteriorate with a higher dry matter content.

The research leading to results in this project receives funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under GA n° [308637].

Therefore, from an environmental perspective the BioEcoSIM process with biochar production is especially attractive when manure with a relatively high dry matter content is available. It should however be noted that both BioEcoSIM processes have a lower environmental impact compared to other state-of-the-art systems at both a 3%, 6% and 9% dry matter content. BioEcoSIM contributes especially to reducing climate change, eutrophication, acidification and particulate matter formation.

However, fossil energy use of the BioEcoSIM process is higher compared to the three state-of-the-art systems due to the higher use of electricity and natural gas. Also human toxicity effects of BioEcoSIM are less positive compared to other manure processing systems, due to the use of chemicals.

The economic impact assessment showed that both BioEcoSIM systems give the lowest costs per ton raw manure. When soil improver instead of biochar is produced, the results are slightly better. No treatment of the manure, only long distance transport, gives the highest costs per ton raw manure. The BioEcoSIM systems achieve net sales of the end products and are competitive on net costs (costs minus revenues) at disposal prices of raw manure of €15/ton or more. The costs per ton raw manure of the compared processing technologies are not that dependent on dry matter contents. The BioEcoSIM processes are slightly more expensive per ton raw manure, but not per kg phosphate, at higher dry matter contents due to costs for energy and supplements. The costs for manure drying and separation are by contrast a little lower at higher dry matter contents. The total investments for the BioEcoSIM processes are the highest, although the difference with the other systems is limited without pyrolysis and biochar production. The BioEcoSIM process needs much more energy for drying of the solid fraction into soil improver. If biochar is produced from the soil improver, the energy use will be somewhat lower because bio-oil and syngas produced during pyrolysis can be used elsewhere in the process and thus save external energy. Bigger sized BioEcoSIM plants might bring economic advantages, because of economies of scale and upscaling can thus be an interesting perspective.

The social impact assessment showed that citizens' knowledge about manure processing is fairly limited. Even within high density livestock areas in Europe few citizens are familiar with manure processing. The majority of the population in the studied regions that at least heard about manure processing has a positive predisposition towards manure processing, and this picture is rather similar across Europe. At the same time small minorities exist in all regions with a negative predisposition towards manure processing. These minorities would actively oppose manure plants, if they were built close to their houses. This even holds true for small plants and at the farm to better fit the countryside. The overall perception of the BioEcoSIM pilot plant is that it is environment-friendly and better aligned to people's associations with manure processing. Net energy recovery is regarded as positive, whereas clean process water (free from antibiotics) would add to its environment-friendly appearance. Thus, the BioEcoSIM system has good opportunities for social appreciation with farm-scale plants, limited regional transports and substantiated environment-friendliness claims but the threat of minorities mobilising protest always exists without sufficiently working on good relations with local communities.

The integrated sustainability impact assessment of BioEcoSIM in comparison to three other state-of-the-art manure processing systems resulted in a somewhat mixed message. The BioEcoSIM systems perform better in both environmental and economic terms than long distance transport, manure drying and manure separation. However, the BioEcoSIM system with pyrolysis performs modestly better in environmental terms, whereas the system without pyrolysis performs modestly better in economic terms. Other things being equal, societal

The research leading to results in this project receives funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under GA n° [308637].

appreciation tends to follow the environmental impacts in a preference for the BioEcoSIM system with pyrolysis.

Potential impact, including the socio-economic impact and the wider societal implications of the project so far;
Main dissemination activities and the exploitation of results

The BioEcoSIM project has delivered an innovative manure processing technology pilot plant to valorise manure into soil improvers and syngas from the solid manure fraction, and mineral fertilizers from the liquid manure fraction. The BioEcoSIM approach brings a biorefinery perspective to manure processing that aims to valorise the single components in raw manure on agricultural and non-agricultural markets and thus contributes to a sustainable circular bioeconomy in Europe.

Liquid fraction processed in BioEcoSIM pilot plant delivers products (ammonium sulphate and P-salts) with obvious agronomic value, whereas these products could also be mixed with the product from solid fraction processing without pyrolysis into a soil improver with a nutrient composition tailored to the agronomic needs of customers. Biochar as product from solid fraction processing with pyrolysis initially also promised to have agronomic value but state-of-the-art knowledge suggests that the soil-improving qualities of biochar are less convincing for (rich) soils in Europe. Since biochar production is very relevant for climate change mitigation policies, customers might be found on non-agricultural markets to valorise the (water-)binding properties of biochar for, e.g., use in the building sector, decontamination, waste and drinking water treatment. Livestock farmers could build on existing relationships with other actors in the agricultural sector for the valorisation of (mixtures of) ammonium sulphate, P-salts and soil improver as products of the BioEcoSIM systems of manure processing. The innovative nutrient recovery technology addresses the unfavourable nutrient ratio of manure, which often leads to an oversupply of P, as the amount of manure used in fertilization is usually calculated based solely on its N content. As the nutrients P and N are recovered separately, they can be used to create customized fertilizers as transportable and marketable products. This allows the fertilization of crops according to their respective requirements and the balancing of disrupted nutrient cycles. Adverse environmental consequences, such as P accumulation in soil, surface runoff and eutrophication of waterbodies, are avoided.

The fertiliser industry as incumbent player needs to be faced as a competitor on that agricultural market. Valorisation of biochar would require building novel relationships with customers on non-agricultural markets to identify their specific needs. The BioEcoSIM pilot plant could be best applied in small-scale plants for either an individual farm or as a cooperative of several neighbouring farms within a rural region to reduce short distance transport of the raw manure. Shrinking the volume of the solid fraction is pivotal to reduce long distance transport of the products of the BioEcoSIM systems.

Another option is to include an additional processing step needed to customize the BioEcoSIM products to createtailor-made products for customers by blending, mixing, enriching, packaging, etc. A uniform particle size distribution, hardness and density are important factors to tune the nutrient composition to the needs of the crop. The market requirements are decisive for the valorisation of the final products from the BioEcoSIm installation. In this way, the valorized fertilizers would compete best on the market with the alternative fertilizers and soil improvers in the marketplace.

The research leading to results in this project receives funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under GA n° [308637].

BioEcoSIM

A detailed robust post-project exploitation plan including a Plan for Use and Dissemination (PUD), detailed business plan and a monitoring tool were successfully prepared for BioEcoSIM. Following a typical diffusion of innovation trajectory, we expect to convert about 1.5% of the market as “innovators” within the first 5 years, equating to a total of 30 plants. With this we will be able to valorised 2.3 millions of surplus manure and produced 27 000 tonnes of phosphorus salts, 28 000 tonnes of ammonium sulphate and 61 000 tonnes of soil improvers. This will mean a reduction of 345 000 tonnes of CO_2eq. Plus, we will mitigate EU’s dependency on mineral P-fertilisers; and reduce nitrate in groundwater.

A widespread dissemination of the project was ensured. The project was presented in more than twelve public presentations, a peer-reviewed article has been published, three more peer-reviewed articles have been prepared and will be submitted for publication in the following months. Over one hundred participants visited the demonstration site and gave us very useful feedback from the technology.

Moreover, the project BioEcoSIM has been awarded with the Ivan Tolpe price from the Flemish coordination centre for manure processing (VCM) for the best innovation in manure treatment. This award is handed out every two years to the participant submitting an innovative, market-feasible technique contributing to a sustainable, cost-efficient manure processing in the future.

The Ivan Tolpe Award aims at supporting and develop innovative, promising techniques, in order to give the manure processing in Flanders a lasting leading role. We are proud and very thankful for receiving this important award.

BioEcoSIM is a business-driven approach with excellent potential for quick deployment and market take-up. BioEcoSIM is at a mature development stage since it has been successfully validated and demonstrated at a pilot scale of 50 kg/h for over 15 months in a farm located in Kupferzell, Germany. Currently, a full-scale prototype with 1 tonne/h is being built to demonstrate the conditioning, solid-liquid separation and P-recovery modules. The techno-economic effectiveness of the modules will be validated in 2017 and the core members of BioEcoSIM consortium aims to introduce it to the market by 2018

For further information, please visit our website: http://www.bioecosim.eu/
or feel free to contact:

Dr. Jennifer Bilbao

Fraunhofer Institute for Interfacial Engineering and Biotechnology IGB
Nobelstrasse 12
70569 Stuttgart
Germany

E-Mail: Jennifer.bilbao@igb.fraunhofer.de
Phone: +49 711 970-3646

The research leading to results in this project receives funding from the European Union’s Seventh Framework Programme for research, technological development and demonstration under GA n° [308637].