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Nutrient recycling from bio-digestion waste as chemical fertilizer substitutes

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ABSTRACT

In the transition from a fossil to a bio-based economy, it has become an important challenge to maximally recycle valuable nutrients that currently end up in waste streams. Nutrient resources are rapidly depleting. Significant amounts of fossil energy are used for the production of chemical fertilizers, whereas costs for energy and fertilizers are increasing. In the meantime, biogas production through anaerobic digestion produces nutrient-rich digestates as a waste stream. In high-nutrient regions this product cannot or only sparingly be returned to agricultural land in its crude unprocessed form. The consequential processing of digestate requires a variety of technologies producing several different derivatives, which could potentially be re-used as green fertilizers in agriculture. As such, a sustainable alternative for fossil-based mineral fertilizers could be provided. The aim of this study was to evaluate the impact of using bio-digestion waste instead of chemical fertilizers and/or animal manure on soil and crop production. In a field trial, nutrient balances were assessed and the physico-chemical soil quality, including the nitrate residue, leaching, salt content, pH, sodium adsorption ratio, as well as phosphorus and heavy metal accumulation were evaluated. The biogas yield of the harvested energy crops was determined and an economic and ecological evaluation was conducted. In the current field-trial, application of waste water from acidic air scrubbers for ammonia removal, digestates and their liquid fraction caused small, yet insignificant, improvement in crop yield, physico-chemical soil fertility and soil quality compared to current common practices involving the use of animal manure and chemical fertilizers. Moreover, it is observed that the use of bio-digestion waste can stimulate phosphate and potassium mobilization from the soil, thereby increasing the use efficiency of soil nutrients. For all re-use scenarios the energetic potential per hectare of harvested energy maize, as well as the calculated economic and ecological benefits were higher than the reference scenario. It is clear that the re-use of bio-based products as nutrient supply in agriculture should be stimulated in European legislation. Further field research is on-going in order to validate the results and evaluate the impact on soil quality in the longer term.

1. INTRODUCTION

In 2011, 10.2 million tons of nitrogen (N), 2.2 million tons of phosphate (P_2O_5) and 2.4 million tons of potash (K_2O) have been applied to 134.4 million hectares of farmland in the EU27 each season (EFMA 2011). By 2020/21, Fertilizers Europe forecasters expect that these fertilizer consumption figures will reach 10.8, 2.6 and 3.2 million tons respectively, applied to 133.7 million hectares (EFMA 2011). However, several minerals such as phosphorus (P) and potassium (K) that are nowadays being extracted through mining, are also becoming scarce at rapid pace (Fixen & Johnston 2012). If agriculture would continue to be dependent on high rates of P-application, a depletion of more than 50 % of the total resource base by 2100 and a complete depletion during the 22nd century in the worst case is predicted (Van Vuuren et al. 2010). This must be regarded as a very serious threat to the security of the P-supply, as currently there are no substitutes for P supporting high agricultural yields (Van Vuuren et al. 2010). Meanwhile, the demand for nutrients is still increasing (EFMA 2011). This imbalance between availability and demand will consequently raise the prices for nutrient resources considerably in the near future. In addition, the increasing cost for fossil energy is another important price influencing factor, as there is a strong positive correlation between energy prices and fertilizer costs (Oskam et al. 2011).

Next to these economic consequences, the use of chemical fertilizers also results in a serious environmental impact. The production and transport of mineral fertilizers requires significant amounts of fossil energy (Gellings & Parmenter 2004). For example, the production of ammonium (NH_4) through the extraction of atmospheric nitrogen gas (N_2) via the Haber Bosch process amounts to a fossil energy consumption of 29 GJ t^{-1} under the most optimal conditions (EFMA 2003). At the same time, upon processing, a large proportion of minerals are again released in the environment in different waste streams, however often in hard-extractable form such as sewage sludge, industrial sludge, animal manure, domestic waste, incinerator ashes, etc. In turn these waste streams can have detrimental ecological effects (Deyi et al. 2012). In the transition from a fossil-based to a bio-based economy, it is therefore an important challenge to maximally close the nutrient cycles and migrate to a more sustainable resource management, both from an economical as an ecological perspective.

In Europe and many other parts of the world, an important nutrient source exists in digestates, which are produced as a waste stream during anaerobic digestion of animal manure, energy maize and organic biological wastes. In high-nutrient regions this product cannot or only sparingly be returned to agricultural land in its crude unprocessed form (Lemmens et al. 2007). The consequential processing of digestate requires a variety of technologies producing several different derivatives, which could potentially be re-used as green fertilizers in agriculture. As such, a sustainable alternative for fossil-based mineral fertilizers could be provided (Vaneeckhaute et al. 2012).

The aim of this study is to demonstrate the fertilizer potential of digestates and its derivatives by means of a field trial in which eight different cultivation scenarios will be compared. In these scenarios liquid fractions (LF) of digestate, waste water from an acidic air scrubber for ammonia removal, and a mixture of raw digestate and LF-digestate will be applied to soil, either as substitute for chemical fertilizers or animal manure for the cultivation of energy maize. It is hypothesized that the use of these products will not cause significant differences in crop yield and nutrient uptake compared to the common practice (animal manure + chemical fertilizers). In order to evaluate the potential environmental impact using these bio-based products in agriculture, nutrient balances will be assessed and the physico-chemical soil quality, including the nitrate residue, leaching, salt content, pH, organic carbon content, sodium adsorption ratio (SAR), as well as phosphorus and heavy metal accumulation will be evaluated. Finally, the biogas yield of the harvested energy maize will be determined. As such, the nutrients coming from the digestate are again recycled to the anaerobic digestion plant and nutrient cycles are maximally closed.

The results obtained in this research should help to better classify these bio-based products in European legislation and serve as a support to stimulate their use. Moreover, re-use of bio-digestion waste can improve the economic viability of anaerobic digestion plants, especially in high-nutrient regions, which in turn can serve as a catalyst to meet the 2020 directives.

2. FIELD EXPERIMENT

2.1 Site description and experimental set-up

The test site is located in Wingene, Belgium. It concerns a 0.8 ha large sandy-loam field. The field was divided into 32 subplots of 9 by 0.75 m. Based on the soil characteristics, the fertilizing advice was formulated at 150 kg workable N ha^{-1}, 270 kg K_2O ha^{-1} and 30 kg MgO ha^{-1}. For phosphate, the maximum allowable dosage of 80 kg P_2O_5 ha^{-1} for the cultivation of maize on non-sandy soils was respected as described in the Flemish Manure Decree (2011). Eight different fertilization scenarios (Sc 1-8) (Table 1) were tested in four replicate subplots (n=4) spread in the field in order to minimize the potential influence of variable soil conditions on the results.

Table 1 Eight different fertilization scenarios (Sc) for the cultivation of energy maize expressed as workable nitrogen (kg ha^{-1})

Group[a]	Sc	Workable N (kg ha^{-1})					
		Chemical start[b]	Chemical[b]	Air scrubber water	Animal manure	Mixture[c]	LF[d] digestate
0.	1	25	29	0	96	0	0
I.	2	25	0	29	96	0	0
	3	0	0	54	96	0	0
II.	4	25	18	0	0	107	0
III.	5	25	0	18	0	107	0
	6	0	0	43	0	107	0
IV.	7	25	0	0	84	0	35
	8	0	0	0	78	0	59

[a] Group: 0 = Reference- conventional fertilization, I = Substitution by air scrubber water, II = Substitution by a mixture of digestate/LF-digestate (V/V=0.5), III = Substitution by air scrubber water and a mixture (V/V=0.5) of digestate/LF-digestate, IV = Substitution by LF-digestate; [b] ammonium-nitrate (27% N); [c] Mixture (V/V=0.5) of digestate and liquid fraction of digestate; [d] LF = Liquid Fraction

On April 12 2011, digestate and LF-digestate were sampled at the site of Sap Eneco Energy, Belgium. This concerns an anaerobic co-digestion plant, with an influent feed of 30 % animal manure, 30 % energy maize and 40 % organic biological waste from the food industry. Furthermore, pig manure was collected at the pig farm of Huisman, Aalter, Belgium and acidic air scrubber water was collected at the piggery of Ladevo BVBA, Ruiselede, Belgium. The samples were collected in polyethylene sampling bottles (5 L), stored cool (4 °C) and transported to the laboratory for physico-chemical analysis. The data were used to calculate the maximum allowable dosage (Table 1) for the different cultivation scenarios with respect to the Manure Decree (2011). Because the pH of the air scrubber water was very low, it was neutralized by adding NaOH (1 L NaOH per 200 L acidic waste water) before application to the field.

Next, by the end of April 2011, the fertilizers were applied to the soil and again samples were taken for analysis in the same way as described before. LF-digestate was applied manually on April 28 to ensure high precision for the targeted application on the test subplots. The fertilization of the digestate/LF-digestate mixture (V/V=0.5) and pig manure was conducted by use of pc controlled injection (Bocotrans BVBA, Tielt, Belgium) on April 29. Thereafter the field was ploughed and on April 30 the pH-corrected air scrubber water and the chemical fertilizers, ammonium-nitrate (27 % N) and patent-kali (30 % K_2O and 10 % MgO), were applied to the plots by hand-application, again to ensure high precision of the applied dosage. On May 5, energy maize of the species Atletico KWS (FAO Ripeness Index: 280) was sown at a density of 102.000 seeds ha^{-1}, while chemical start fertilizers were applied. Preceding crops consisted of fodder maize. The weather conditions during the field trial were recorded.

2.2 Sampling and laboratory analysis

During the growing season, samples of soil and plant were taken on July 5-6, September 5-6 and at the harvest, October 7 (plant samples) and 13 (soil samples) 2011. On October 22, Italian rye-grass was sown as an intercrop and on November 25 again soil samples were taken in order to evaluate the NO_3-residue in the soil. At each sampling moment, one soil sample was taken in the middle of each subplot using a soil core sampler and six plants were harvested manually by use of trimming scissors in a rectangular around the bore hole. The samples were collected in polyethylene sampling bags and transported within 1 h from the test site to the laboratory, carried in cooler boxes filled with ice. In the laboratory, the replicate samples were stored cool (1–5 °C) for analysis. Also a length measurement was performed on August 17 (n=320). The harvest was conducted by use of a maize chopper and the crop fresh weight yield was determined at the field.

Physico-chemical analyses on products, soils and plants were performed in the laboratory for Analytical and Applied Ecochemistry (Ghent University) using methods of Van Ranst et al. (1999). The biogas potential of the energy maize was determined in the biogas lab of the university college of West Flanders (Innolab), Kortrijk, Belgium via a mesophyll batch test at 37 °C. Statistical analysis was performed with SAS 9.2. Nutrient balances for P_2O_5, K_2O, Ca, Mg, Na and S were set up based on the product, plant and soil analyses. The nutrient surplus on the soil balance was calculated by the difference between supply (chemical fertilizers, animal manure, digestate derivatives, deposition) and crop demand. The obtained nutrient surplus on the soil balance is a measure of potential pollution to soil, air and water by agricultural practices. The lower the surplus, the better for the environment. Modeling of N was conducted with the computer model NDICEA *(Nitrogen Dynamics In Crop rotations in Ecological Agriculture)* nitrogen planner 6.0.16 (Van Der Burgt et al. 2006). The methodology used for the economic and ecological evaluation of the application of bio-based mineral fertilizers in agriculture can be found in Vaneeckhaute et al. (submitted).

3. RESULTS AND DISCUSSION

3.1 Fertilizer impact on crop production and biogas potential

The DW-content of the biomass and DW-yield at the harvest are key parameters for determination of the biogas yield (Amon et al. 2007, Matjaz et al. 2010, Inagro 2011). Before energy maize is digested, the maize first has to be ensilaged in order to reach a maximum yield (Amon et al. 2007). Therefore a minimum DW-content in the total plant of 28 % is required in order to prevent sap losses in the silage. The DW-content may also not exceed 35 %, because then the fermentation potential diminishes due to the higher lignin content of more ripened maize (Inagro 2011). The energy maize species under study was Atletico (KWS), which is a late cultivar with a FAO ripeness index of 280. These species bloom later in the season, so that they have a longer vegetative period in which they can grow more biomass (Amon et al. 2007, Matjaz et al. 2010). The DW biomass yield in this study was at the harvest approximately the same in all scenarios, 23±1 t ha^{-1}, which is regular for the cultivation of this species in Flanders and higher than that of silo maize, 15 t ha^{-1} (Inagro 2011). The average DW-content at the harvest was 28±1 %, so the energy maize was suitable for biogas production (desired 28-36 %).

Nevertheless, in this study the average biogas potential of the energy maize expressed as m^3 CH_4 per ton DW (307±13 m^3 t^{-1} DW) was slightly lower than in the study of Inagro (2008), where 345 m^3 t^{-1} DW in average was reported. Otherwise, when taking in account the biomass yield, the energetic potential of the energy maize (7,135±364 m^3 CH_4 ha^{-1}) was higher for each treatment in this study compared to the range of 4,856-6,621 m^3 CH_4 ha^{-1} obtained in Inagro (2008) and to the average of 220 GJ ha^{-1} obtained in Veldeman et al. (2007). Interestingly, it was found that although there was not much effect of the fertilizers used on the biogas potential, the energetic potential per hectare was higher for Sc 4-7 compared to Sc 1-3, due to the higher fresh weight biomass yield in these scenarios.

3.2 Fertilizer impact on soil fertility and soil quality

The crop demand was in each scenario covered by the availability of N from manure and soil supply, so it is likely that the amount of NH_3-evaporation was not specifically higher in the scenarios where the pH-corrected waste water was used. Also, there were no significant differences in N-uptake by the plant, indicating that the air scrubber water can be a valuable substitute for chemical fertilizer N. Furthermore, nitrogen balances are roughly similar for each scenario and in equilibrium, indicating that the amount of NO_3-leaching was not much influenced by the fertilizer type. However, modeling of N-dynamics with NDICEA indicated that average NO_3-leaching was slightly lower for all scenarios, except Sc 7, compared to the reference. In addition, all scenarios, except Sc 5, exhibited lower NO_3-residues than the conventional fertilization (Sc 1). The NO_3-residue was significantly higher for Sc 5 compared to Sc 2, 4, 6 and 8, which on their turn showed significantly lower NO_3-residues compared to the reference (Sc 1). All the other treatments showed no significant difference with the reference at the 5 % level. Although Italian rye-grass was sown on the field as an intercrop in October, the NO_3-residue was only in treatment 4, 6 and 8 lower than the maximum allowed level of 90 kg NO_3-N ha^{-1} (Flemish Manure Decree 2011). As there is no connection between the NO_3-residue and the fertilizer type applied, other factors must have caused this undesired effect.

At first, the exceptional dry spring and wet summer, as well as the autumn characterized by exceptional high temperatures, can explain the higher NO_3-residue values for maize. The Flemish Land Agency (2012) has reported that in 2011 approximately 40 % of the NO_3-residue measurements in West Flanders exceeded the allowable level. Further, it might also be possible that the dose of 150 kg ha^{-1} workable N, which is the advice for the cultivation of maize on non-sandy soils (Flemish Manure Decree 2011), was too high for the field under study, since during the experiment it was observed that the 0-90 cm soil layer was rather sandy than sandy-loam. In all respects, these high NO_3-residues may increase the risk for NO_3-leaching to ground and surface waters. Therefore, next year guided measures will be implemented on the field (Flemish Land Agency 2012).

Concerning the intercrop, it is likely that the density of the Italian rye-grass was too low and that the grass was sown too late, so that it could not yet take up its maximum amount of N at the sampling moment. The N-uptake is dependent of the date of sowing and is normally for this species between 40 and 60 kg ha^{-1}, and up to 80 kg ha^{-1} under good conditions. In order to reach a maximum N-uptake, it is advised to sow the rye-grass as soon as possible after the harvest and not later than October 15 (Flemish Land Agency 2012). Therefore, in the next experimental year the intercrop will be sown immediately after the harvest to optimally enjoy the maximal benefits.

Next, an important remark is that the amount of P_2O_5 applied to the soil in Sc 1-3 and 7-8 exceeded the maximum level of 80 kg ha^{-1} as described by the Flemish

Manure regulation (Flemish Manure Decree 2011). This is caused by the variability in animal manure composition between the first and second sampling moment. The P_2O_5-content in digestates and derivatives seems to be more stable in time, which is an interesting observation in terms of fertilizer application. Although significantly less P_2O_5 was applied to the soil in Sc 4-6, a higher crop P_2O_5-uptake was observed in these scenarios. This could be attributed to the higher relative amount of mineral P_2O_5 to total P_2O_5 in the digestate/LF-mixture than in animal manure. However, because the P_2O_5-supply could not cover the crop demand in all scenarios, the plants must also have extracted P_2O_5 from the soil pools, especially in Sc 4-6. Up to now no differences in soil P-content were observed ($p>0.05$), but in frame of P becoming rapidly depleted (Fixen & Johnston 2012, Van Vuuren et al. 2010), this opportunity to mobilize P_2O_5 in the soil can be an interesting way to recuperate and recycle P_2O_5 in the longer term. An evaluation of the bio-availability of P in the soil and the partitioning among the different P-pools by application of these new fertilizers is required and will be aspect of further research.

A similar effect as for P_2O_5 was found for K_2O. The crop K_2O-uptake was significantly higher for Sc 4-6 compared to the reference. Interestingly, in these scenarios approximately three times less chemical K_2O was used. This could turn out in serious economic and ecological benefits, especially in Sc 5-6, where chemical N was simultaneously replaced by air scrubber water. As for P_2O_5, also the relative amount of mineral K_2O to total K_2O was higher in the digestate/LF-mixture than in animal manure, and since the crop demand was higher than the K_2O-supply, the crops must also have extracted K_2O from the soil, especially in Sc 4-6. As chemical K_2O is currently extracted through mining, this reduction in chemical K_2O-use simultaneously with the extra liberalization of K_2O from the soil, might be an interesting path to recycle this valuable macronutrient in a sustainable way.

Next to N, P_2O_5 and K_2O, also S is an essential macronutrient for plants. However, too high doses of sulfate could also lead to salt accumulation in soils (Hillel 2008). In the scenarios where air scrubber waste water was used (Sc 2, 3, 5 and 6) the S-supply was higher than the crop demand, resulting in a potential S-surplus on the soil balance. Reversely, in the scenarios where no air scrubber water was used the crop demand was higher than the S-supply by manure application, resulting in a net S-extraction from the soil. Up to now no significant differences in soil S-content and soil pH were observed during the growing season and at the harvest ($p>0.05$), but these are parameters that require follow-up in the longer term. An interesting observation is that, while there was no effect of the use of air scrubber waste water on the crop S-uptake, in the scenarios where digestate and/or LF was used as base fertilizer (Sc 4-8) the crop S-uptake was slightly higher than in the scenarios where only animal manure was used (Sc 1-3). This is likely due to the higher relative amount of mineral S compared to total S in the digestate derivatives.

Calcium and magnesium both play an essential role in the development of plants and the flocculation of colloidal clay, hence influencing soil structure. Although in all scenarios the crop demand for Ca and Mg was higher than the supply by manure application, no adverse effects (chlorosis) were observed and the content of Ca and Mg in the plants were in the range of Hillel (2008), 0.4-2.5 % Ca and 0.1-0.4 % Mg on DW-content. The plants have thus extracted Ca and Mg from the soil, especially in Sc 4-6, where the Ca- and Mg-supply by fertilizer application was the smallest, while the plant uptake was slightly higher compared to the other scenarios. Nevertheless, up to now no significant differences in soil Ca- and Mg-concentration were observed throughout the field. However, in the long term this Ca- and Mg-deficit could have a negative influence on the soil structure, if no additional liming is provided. On the other hand significantly more organic carbon was applied to the soil in the scenarios where digestate derivatives were used as base fertilizers (Sc 4-8) compared to the scenarios where only animal manure was used (Sc 1-3). This additional carbon supply could significantly improve soil structure, thereby counterbalancing the above mentioned deficit.

Sodium has a minor role as trace element in plant nutrition. Too high doses can cause increased soil salt contents and SAR's, leading to soil degradation in the long term. More Na was applied to the soil in Sc 4-8 compared to Sc 1-3, while the crop Na-uptake was not significantly different among the treatments. This results in a higher Na-surplus on the soil balance for Sc 4-8, where digestate derivatives were used as base fertilizer. Up to now, no significant impact on the soil salt content and the SAR could be observed. These are however important parameters that will be followed up in the long term.

Because digestate is the waste product of the co-digestion of animal manure, energy crops and organic biological waste from the food industry, it could also contain an important amount of micronutrients and heavy metals. Moreover, raw animal manure can contain significant amounts of Cu and Zn (Dourmad et al. 2007). On the one hand Fe, Mn, B, Zn, Cu, Mo, Co and Ni are all essential trace elements for plants, but on the other hand there also exist soil environmental quality standards for Cu, Zn and Ni, as well as for As, Cd, Cr, Hg and Pb (Flemish Soil Decree 2006). Results have shown that the standards were only exceeded for Cu in all scenarios, including the reference. It should however be remarked that the Cu-enrichment in this region is likely the legacy of the millions of shells that were fired in the First World War (Van Meirvenne et al. 2008).

3.3 Technical and legislative implications

It is clear that waste water from an acidic air scrubber for ammonia removal can be a valuable N-S-rich mineral fertilizer. No differences in crop yield, soil fertility and soil quality were observed by use of the air scrubber water compared to the reference. However, there still remain some technical and legislative implications, hindering its use. First, the pH of the acidic air scrubber water in this study amounted to 2, which is practically very low for use as fertilizer. The low pH could cause corrosion to application instruments, leaf burning, and soil acidification after long-term application. Moreover it causes a potential hazard for the farmer. It is therefore advised to neutralize the acidic pH. In this study this was conducted by addition of NaOH. However, environmental technical solutions are required to neutralize the pH of this waste stream in a practical, economic and ecological way. Possibilities could be to correct the pH with waste water of an alkaline air scrubber, or to develop air scrubbers that directly produce air scrubber water with a higher pH.

Another technical implication is the way of spreading the air scrubber water to the field. As the N-content of this product is only 2-3 %, approximately 1,000 L ha^{-1} has to be applied, implying that the farmer must drive much slower than when applying animal manure, which usually only amounts to 300 L ha^{-1}. One potential way to overcome this problem is to evaporate (part of) the water and crystallize the ammonium-sulfate, but then significant amounts of energy have to be used. Modified or new application techniques should be investigated for this new type of fertilizer and/or methods to concentrate the N-content in an economic and ecological way should be discovered. Although waste water from an acidic air scrubber has high potential as mineral fertilizer, it is not often applied up to know due to legislative constraints and farmers' distrust. Therefore it is highly important that the results obtained in this study are widely spread and that the European Commission stimulates the use of air scrubber water.

Next, from the results it is clear that the substitution of animal manure by digestate and LF-digestate does not reduce the crop yield, physico-chemical soil fertility and soil quality. It is even observed that the substitution can result in a higher P_2O_5- and K_2O-uptake from the soil, which is an interesting aspect in frame of nutrient recycling and nutrient resources becoming rapidly depleted. Furthermore, the nutrient availability in these products is mostly higher than in animal manure, indicating that it has better mineral fertilizer properties, next to the organic properties. Therefore, the use of these bio-based products should be stimulated in European legislation. It is reasonable that they should no longer be classified as animal manure and that the introduction of a new legislative framework, in which these products are classified based on their own specific fertilizer properties, is indispensable.

3.4 Economic and ecological evaluation

The application of bio-based fertilizers in agriculture can result in significant economic benefits for the agriculturist, as well as ecological benefits through energy use and GHG-emission reduction. The complete substitution of chemical fertilizer N by air scrubber water (Sc 3) could almost double the economic benefits, while the energy use and GHG-emissions were 2.5 times reduced. When meanwhile substituting animal manure by the digestate/LF-mixture (Sc 4-6), the observed benefits were even higher, because here less chemical N was required due to the higher N:P-ratio of the mixture, while also the need for chemical K_2O was less. The economic and ecological benefits were the highest for Sc 8, respectively 3.5 and 4.4 times higher than the reference, as both chemical N and K_2O were completely eliminated in this treatment.

4. CONCLUSION

The use of waste water from an acidic air scrubber for ammonia removal, digestates and liquid fraction of digestates as substitute for animal manure and/or chemical fertilizers in agriculture causes small, albeit insignificant, improvement in energy maize yield, physico-chemical soil fertility and soil quality by one year application. Moreover, application of these bio-based products could stimulate the mobilization of P_2O_5 and K_2O from the soil, thereby providing a potential path to recycle these valuable, but depleting, nutrients in a sustainable way. In addition, the energetic potential per hectare of harvested energy maize is slightly higher, and the economic and ecological benefits significantly higher, when digestate derivatives are used, compared to animal manure additionally supplied with chemical fertilizers. It is therefore clear that the use of these products should be stimulated in European legislation and that the results obtained in this study should be widely spread. This one-year field trial is continued in 2012 in order to validate the results and evaluate the impact on soil quality in the longer term.

5. REFERENCES

Amon, T., Amon, B., Kryvoruchko, V., Zollitsch, W., Mayer, K., Gruber, L. (2007), “Biogas production from maize and dairy cattle manure - Influence of biomass composition on the methane yield.” *Agric. Ecosys. Environ.*, Vol. **118**, 173–182.

Deyi, H., Abir, A.T., Peter, G. (2012), “Sustainable waste and materials management: national policy and global perspective.” *Environ. Sci. Technol.*, Vol. **46**(5), 2494-2495.

Dourmad, J.Y. and Jonderville, C. (2007). “Impact of nutrition on nitrogen, phosphorus, Cu and Zn in pig manure, and on emissions of ammonia and odours.” *Livest. Sci.*, Vol. **112**, 192-198.

EFMA (2003), *Understanding nitrogen and its use in agriculture,* Brussels, Belgium.

EFMA (2011), *Forecast of food, farming and fertilizer use in the European Union 2011-2021*, Brussels, Belgium.

Flemish Soil Decree (2006). Order of the Flemish Government of 14 December 2007 establishing the Flemish soil remediation and protection regulations.

Fixen, P.E. and Johnston, A.M. (2012), “World fertilizer nutrient reserves: a view to the future.” *J. Sci. Food Agr.*, Vol. **92**(5), 1001-1005.

Flemish Land Agency (2012), *Guide of measures against nitrate residue violations*, Brussels, Belgium.

Flemish Manure Decree (2011), Decree concerning the protection of water against nitrate pollution from agricultural sources, Decree No. BS13.05.2011-MAP4.

Gellings, C.W. and Parmenter, K.E. (2004), *Energy efficiency in fertilizer production and use*, in *Efficient Use and Conversation of Energy*, in *Encyclopedia of Life Support Systems (EOLSS)*, Eolss Publishers, Oxford, U.K.

Inagro (2008), *Anaerobic digestion on farm scale: Techniques, resources and end products,* Beitem, Belgium.
Inagro (2011), *How to get the highest rendement from energy maize?,* Provincial Research and Advise Centre for Agriculture and Horticulture, Beitem, Belgium.
Lemmens, E., Ceulemans, J., Elslander, H., Vanassche, S., Brauns, E., Vrancken, K. (2007), *Best available techniques (BAT) for animal manure processing*, 3rd ed., Academia Press, Ghent, Belgium.
Matjaz, O., Bogomir, M., Peter, V. (2010), Biogas production from maize hybrids. *Biomass Bioenerg.*, Vol. **15**, 38-45.
Oskam, A., Meester, G., Silvis, H. (2011), *EU policy for agriculture, food and rural areas*, Wageningen Academic Publishers, Wageningen, NL.
Van der Burgt, G.J.H.M., Oomen, G.J.M., Habets, A.S.J. (2006), "The NDICEA model, a tool to improve nitrogen use efficiency in cropping systems." *Nutr. Cycl. Agroecosys.*, Vol. **74**(3), 275-294.
Vaneeckhaute, C., Meers, E., Michels, E., Christiaens, P., Tack, F.M.G. (2012), "Fate of macronutrients in water treatment of digestate using vibrating reversed osmosis." *Water Air Soil Poll.*, Vol. **223**(4), 1593-1603.
Vaneeckhaute, C., Meers, E., Michels, E., Buysse, J., Tack, F.M.G. (Submitted), "Economic and ecological benefits of the application of bio-based mineral fertilizers in modern agriculture.", *Biomass Bioenerg*.
Van Meirvenne, M., Meklit, T., Verstraete, S., De Boever, M., Tack, F.M.G. (2008), "Could shelling in the First War have increased copper concentrations in the soil around Ypres?" *Eur. J. Soil Sci.*, Vol. **59**(2), 372-379.
Van Ranst, E., Verloo, M., Demeyer, A., Pauwels, J. M. (1999), *Manual for the soil chemistry and fertility laboratory: analytical methods for soil and plants equipment, and management of consumables,* International Training Centre for Post-Graduate Soil Scientists, Ghent, Belgium.
Van Vuuren, D.P., Bouwman, A.F., Beusen, A.H.W. (2010), "Phosphorus demand for the 1970-2100 period: A scenario analysis of resource depletion." *Global Environ. Chang.*, Vol. **20**, 428-439.
Veldeman, Van Aacken, S., De Keyser, N. (2007), *Production of bio-energy from energy maize*, KU Leuven, Leuven, Belgium.