Ecological and economic benefits of the application of bio-based mineral fertilizers in modern agriculture

C. Vaneeckhaute, E. Meers, E. Michels, J. Buysse, F.M.G. Tack

Laboratory of Analytical and Applied Ecochemistry,
Faculty of Bioscience Engineering,
University of Ghent
Coupure Links 653, 9000 Ghent, Belgium
E-mail: Celine.Vaneeckhaute@ugent.be, Erik.Meers@ugent.be, Evi.Michels@ugent.be, Filip.Tack@ugent.be

Department of Agricultural Economics,
Faculty of Bioscience Engineering,
University of Ghent
Coupure Links 653, 9000 Ghent, Belgium
E-mail: Jeroen.Buysse@ugent.be

Corresponding author:

C. Vaneeckhaute
Laboratory of Analytical and Applied Ecochemistry,
Faculty of Bioscience Engineering,
University of Ghent
Coupure Links 653, 9000 Ghent, Belgium
E-mail: Celine.Vaneeckhaute@ugent.be
Tel.: +32/478.43.24.64
Fax: +32/9.264.62.42
Abstract

In the transition from a fossil to a bio-based economy, it has become an important challenge to maximally recuperate valuable nutrients coming from 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. In high-nutrient regions, these products cannot or only sparingly be returned to agricultural land in its crude unprocessed form. The consequent processing of this digestate requires a variety of technologies producing lots of 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. This study aims to characterize the physico-chemical properties of digestates and derivatives, in order to identify the fertilizer value and potential bottlenecks for agricultural re-use of these products, in line with European legislative constraints. In addition, the economic and ecological benefits of substituting conventional fertilizers by bio-based alternatives are quantified and evaluated. Waste water from acidic air scrubbers for ammonia removal shows potential for application as N-S fertilizer. Analogously, concentrates resulting from membrane filtrated liquid fraction of digestate show promise as N-K fertilizer. Substituting conventional fertilizers by digestate derivatives in different cultivation scenarios can result in significant economic and ecological benefits for the agriculturist. Starting from theoretical scenarios outlined in the current study, field test validation will be required to confirm the potential substitution of fossil-based mineral fertilizers by bio-based alternatives.

Abbreviations: AF = Artificial Fertilizer, AM = Animal Manure, DD = Digestate Derivatives, LF = Liquid Fraction, NUE = Nitrogen Uptake Efficiency, TF = Thick Fraction
**Introduction**

In 2010, chemical fertilizer use in Europe (EU-27) was as high as 10.4 Mt of nitrogen (N), 2.4 Mt of phosphate (P$_2$O$_5$) and 2.7 Mt of potash (K$_2$O) [1]. By 2019/2020, forecasters expect these fertilizer consumption figures to reach 10.8 Mt, 2.7 Mt and 3.2 Mt, respectively [1]. Unfortunately, fertilizer production requires significant amounts of fossil energy. Up to 29 GJ t$^{-1}$ is used for the production of NH$_4$ through the Haber-Bosch process under optimal conditions [2]. Also, prices for mineral fertilizers are increasing, whereas nutrient resources are depleting [3], [4], [5], and [6]. Particularly phosphorus is a nutrient with fast increasing scarcity. It is expected that the direct available phosphorus resources will be completely depleted by the end of this century [5], [6], and [7]. In the transition from a fossil-based to a bio-based economy, it has therefore become an important challenge to maximally recuperate and recycle valuable nutrients from waste streams in a sustainable and environmentally friendly manner.

In frame of the 2020 directives, the conversion of biomass such as energy crops, organic residues and animal wastes, into biogas through anaerobic digestion has been evaluated as one of the most energy-efficient and environmentally beneficial technologies for bio-energy production [8]. However, the anaerobic digestion of biomass produces besides renewable energy also nutrient-rich digestates as a “waste” stream. In high-nutrient regions such as Flanders (Belgium), Barcelona (Spain), Nord-Rein Westfalen (Germany), Bretagne (France), Denmark and the Netherlands, these digestates need to be processed further and cannot or only sparingly be returned to arable land as a fertilizer in its crude unprocessed form [9]. The underlying reason for this technical prerequisite is that, due to intensive industrial animal production, these regions are characterized by an overproduction of animal manure in comparison to the available arable land.

Initial steps of digestate processing generally comprise the use of separation and/or
dewatering technologies, using emulsion or powder based polymers for flocculation [10]. The resulting thick fractions are mostly dried, turning them into pasteurized and stabilized exportable organic soil conditioners, high in phosphorus and organic matter [11]. The liquid fraction (LF) produced by the separation step contains the majority of the digestate’s potassium and inorganic nitrogen. This liquid fraction can be processed further by ammonia stripping or membrane filtration, for example microfiltration (MF), ultrafiltration (UF) and/or reversed osmosis (RO) [12] and [13]. Each step in a membrane cascade again generates two downstream products, concentrate and permeate, with varying characteristics concerning macro- and micronutrient composition. Alternatively, the liquid fraction after separation can be treated biologically, for example by nitrification-denitrification. However, nitrification-denitrification ultimately converts valuable nitrogen into nitrogen gas (N₂), which is then eliminated from the local agricultural cycle. In regions where agricultural nitrogen emissions to the environment are already excessive and in conflict with the European nitrate directive for protection of water bodies, this nitrogen elimination may be economically and ecologically sensible for a given portion of the nitrogen. Furthermore, exhaust gases of the biogas cogen-engines and driers need to be washed before emission into the atmosphere. This involves the use of acidic, alkaline and/or oxidative scrubber techniques, again resulting in different types of specific streams, some of which contain large amounts of inorganic nutrients. In acidic air scrubbers, for example, sulfuric acid is dosed to capture NH₃ and amines, thereby producing (NH₄)₂SO₄ as a nutrient-rich waste stream. Alkaline air scrubbers are then used to neutralize acidic components that escaped from the system or to oxidize organic compounds such as H₂S [14].

The above described derivatives can function as either inorganic or organic fertilizers and/or soil conditioners, in the meantime providing renewable substitutes for mineral fertilizers based on fossil resources. Such a sustainable development strategy is in line with...
the cradle-to-cradle approach [15]: waste turns into secondary resources (Fig. 1).

In the past, only digestates in their crude form have been compared with animal manures in comprehensive research [16]. Insights in the composition and properties of the more important derivatives is lacking, though very relevant, as the treatment and the transport of these products is expensive and energy consuming, while valuable nutrients are often wasted. If a sustainable market for digestate and its derivatives would exist, the digestate problem could be turned into an economic and ecological opportunity. Valorization of macro- and micronutrients from digestate processing is therefore an important challenge for the future.

This study aims to characterize the physico-chemical properties of the different derivatives coming from digestate processing, with attention for general conditions such as pH and conductivity, macronutrients, essential and non-essential trace elements, organic carbon (OC) and nutritive ratios. The fertilizer value and the potential bottlenecks for re-use of these products in comparison with conventional fertilizers are identified. Finally, the economic and ecological benefits of substituting conventional fertilizers by digestate derivatives are calculated for the most relevant cultivation scenario’s. The knowledge obtained in this research should greatly enhance the understanding and useful application of digestate and its derivatives. Getting a better view on the dilemmas and opportunities posed by these products can in turn help to improve the underlying economics of biodigestion. As such, this research can serve as a catalyst to stimulate this vital, yet fragile, innovative economic activity in frame of the 2020 objectives.

2. Material and methods

2.1 Site description and experimental set-up

Samples of the various digestate derivatives were taken in three different anaerobic digestion
plants in Belgium: Goemaere Eneco Energy Diksmuide, Mandel Eneco Energy Roeselare and Sap Eneco Energy Merkem. The incoming feed to the digesters is composed of animal manure, organic-biological waste and energy maize. The following process streams were sampled: digestates, thick fractions (TF) of digestates after separation, thick fractions (TF) of digestates after separation and drying, liquid fractions (LF) of digestates after separation, concentrates produced by one vibrating membrane filtration step of the liquid fraction using reversed osmosis (RO) membranes, concentrates produced by two subsequent vibrating membrane filtration steps, waste water from an acidic air scrubber and waste water from an alkaline air scrubber. For detailed process description, see [13]. The samples in the digestion plants were taken on three different points in time during approximately one year (2010-2011). Acidic air scrubber water was additionally sampled two times at the pig farm of Ladevo BVBA, Ruiselede, Belgium and conventional pig slurry was sampled two times at the site of Huisman, Aalter, Belgium. The samples (10 L each) were collected in polyethylene sampling buckets 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) and kept separate for replicate analysis.

2.2 Liquid sample analysis

Conductivity and pH were determined potentiometrically using a WTW F537 conductivity electrode (Wissenschaftlich Technischen Werkstätten, Weilheim, Germany) and an Orion model 520A pH meter (Orion Research, Boston, VS), respectively. Suspended solids (SS) were determined by vacuum filtration (0.45 µm) of 100-300 mL sample and subsequent drying of the filter in a furnace (Memmert, Schwabach, Germany) at 105 °C. Total nitrogen content was determined using a Kjeltec system 1002 distilling unit (Gerhardt Vapodest, Köningswinter, Germany) after digestion of the sample in a sulphuric-salicylic acid mixture.
Finally, the captured ammonia in the distillate was titrated with 0.01 mol L$^{-1}$ HCl in the presence of a methyl red bromocresol green mixed indicator [17]. Total phosphorus content was determined using the colorimetric method of Scheel [17] after wet digestion of the liquid samples (2.5 g sample + 2 mL HNO$_3$ + 1 mL H$_2$O$_2$). The absorbance at 700 nm of samples and standards was determined using a Jenway 6400 spectrophotometer (Barloworld Scientific T/As Jenway, Felsted, UK). Calcium, magnesium and heavy metals were analyzed using ICP-OES (Varian Vista MPX, Palo Alto, CA, USA) after wet digestion (see above). Sodium and potassium of the digested samples (see above) were analyzed using a flame photometer (Eppendorf ELEX6361, Hamburg, Germany). Ammonium was determined using a Kjeltec system 1002 distilling unit (Gerhardt Vapodest, Königswinter, Germany) after addition of MgO to the liquid sample (50 mL). Finally, the captured ammonia in the distillate was titrated with 0.01 mol L$^{-1}$ HCl in the presence of a methyl red bromocresol green mixed indicator [17]. Nitrate, chloride and sulphate were analyzed using ionic chromatography (Metrohm 761, Herisau, Switzerland) after centrifugation and subsequent vacuum filtration (0.45 µm) of the liquid fraction. Total sulfur was analyzed as described by [18]. The extractable amount of macronutrients was determined in an NH$_4$OAc-EDTA pH 4.65 extract of the samples [17].

2.3 Thick sample analysis

Dry weight (DW) content was determined as residual weight after 48 h drying at 100 °C. Ash and organic carbon (OC) were determined by incineration of the dry samples in a furnace (Nabertherm, Lilientahl, Germany) at 550 °C during 4 h. Conductivity and pH were measured using a WTW F537 conductivity electrode (Wissenschaftlich Technischen Werkstätten, Weilheim, Germany) and an Orion model 520A pH meter (Orion Research, Boston, VS), respectively, after equilibration for 1 h in deionized water at a 5/1 liquid to dry sample ratio and subsequent filtering (white ribbon, MN 640 m, Macherey–Nagel, Düren, Germany). Total
nitrogen was determined using the Kjeldahl procedure on fresh weight (FW) content [17]. For the determination of phosphorus, dry samples were incinerated at 450 °C during 4 h in a furnace (Nabertherm, Lilientahl, Germany). The phosphorus content was then determined by the colorimetric method of Scheel [17] after digestion of the residual ash (1 g ash + 5 mL 3 mol L⁻¹ HNO₃ + 5 ml 6 mol L⁻¹ HNO₃). Calcium and magnesium of the digested samples (see above) were analyzed by means of ICP-OES (Varian Vista MPX, Palo Alto, CA, USA). Sodium and potassium of the digested samples (see above) were determined using a flame photometer (Eppendorf ELEX6361, Hamburg, Germany). Ammonium was determined using a Kjeltec system 1002 distilling unit (Gerhardt Vapodest, Köningswinter, Germany) after addition of MgO to the sample (50 mL). Finally, the captured ammonia in the distillate was titrated with 0.01 mol L⁻¹ HCl in the presence of a methyl red bromocresol green mixed indicator [17]. Chloride was determined by means of a potentiometric titration using an automatic titrator (Methrohm, Herisau, Switzerland), provided by a Hg/(Hg)₂SO₄ referential electrode [17]. The available amount of macronutrients was determined in an NH₄OAc-EDTA pH 4.65 extract of the samples [17].

2.4 Economic and ecological analysis

The economic and ecological benefits were calculated for the current most relevant re-use scenarios of green fertilizers for the cultivation of maize (Table 1).

For each scenario the total amount of available N applied to soil is 150 kg ha⁻¹, according to the Flemish manure regulation for the cultivation of maize on non-sandy soils [19]. Hereby, the amount of available N in both animal manure and digestate derivatives was considered to be 60% of the total N content, as described by policy [19]. Furthermore, the maximum application standard of 80 kg ha⁻¹ y⁻¹ for total P₂O₅ [19] and a total K₂O dose of 220 kg ha⁻¹ y⁻¹
were respected for each scenario. The different scenarios are compared with the common practice (scenario 0): maximum amount of animal manure (P$_2$O$_5$ = limiting factor), artificial start fertilizer (N) and additional optimizing fertilization with artificial manure (N, K$_2$O), with respect for the maximum allowable levels of N and P$_2$O$_5$ application on agricultural land [19].

The data used for the economic and ecological analysis of the different cultivation scenarios are presented in Table 2.

[Table 2 here]

The economic and ecological impact of artificial fertilizer production, packing, transport and application was taken in account. Hereby the energy use for transport and application was calculated for a lorry with a capacity of 20 t and a diesel consumption of 11.6 MJ km$^{-1}$ (personal communication, EnergieTransitie, 2011; [22]) that travels from the port of Antwerp, distribution point in Belgium, to Ypres in the west of Flanders (129 km), region with the highest nutrient use in Belgium. Next, the impact of transport and application of animal manure and digestate derivatives were incorporated in the calculation [22]. Here it was assumed that the transport distance from the farm to the field is less than 5 km and that a tractor of 88.3 kW is used, with a diesel consumption of 10 L h$^{-1}$. In this way, it is possible to apply 30 t ha$^{-1}$ h$^{-1}$ of animal manure or digestate derivatives, which are common figures [22]. The transport costs were then calculated based on the current average cost prize for diesel in Europe (1.37 € L$^{-1}$ [23]). Further, it was assumed that an agricultural contractor was paid 2.5 € t$^{-1}$ FW for fertilizer application [9].

Next to these costs, also the economic benefits for the agriculturist when accepting animal manure or digestate derivatives as base-fertilizer were handled. This amounts to 250 € ha$^{-1}$ [9], resulting in 11.9 € t$^{-1}$ FW or 1.47 € kg$^{-1}$ N for animal manure. When animal manure is substituted by digestate, LF digestate and a mixture of digestate ($\phi = 0.5$) and LF digestate ($\phi = 0.5$), the benefits are 9.99 € t$^{-1}$ FW, 5.29 € t$^{-1}$ FW and 6.91 € t$^{-1}$ FW respectively, based
on the N content of these streams. Nevertheless, it is expected that in the future these benefits will have to be calculated using the P content of the product, in line with the legislative P standards for soil application that become the more and more strict [19].

Based on all these data, the economic and ecological impact was calculated using the following functions:

\[
\text{Economic cost (€ ha}^{-1}\text{)} = AF_{\text{production}} + AF_{\text{packing}} + AF_{\text{application}} + AF_{\text{transport}} + DD_{\text{application}} + DD_{\text{transport}} + AM_{\text{application}} + AM_{\text{transport}} - AM/DD_{\text{benefits}}
\]

(1)

\[
\text{Energy use (GJ ha}^{-1}\text{)} = AF_{\text{production}} + AF_{\text{packing}} + AF_{\text{transport}} + AF_{\text{application}} + DD_{\text{transport}} + DD_{\text{application}} + AM_{\text{transport}} + AM_{\text{application}}
\]

(2)

where “AF” are artificial fertilizers, “DD” are digestate derivatives and “AM” is animal manure.

Finally, when fossil-based mineral fertilizers are replaced by digestate derivatives, significant savings in greenhouse gas (GHG) emissions can be expected. The GHG-emission was calculated for the different scenarios in terms of carbon dioxide (CO\(_2\)) equivalents (kg ha\(^{-1}\)). It was assumed that diesel is used for the transport and application of fertilizers and that natural gas is used for the production of artificial fertilizers.

3. Results

3.1 Physico-chemical analysis

Digestates, thick (TF) and liquid (LF) fractions of digestates after separation, thick fractions (TF) of digestates after separation and drying, as well as conventional pig slurry were sampled and physico-chemically analyzed (Table 3). Also, a mixture of digestate (φ = 0.5) and LF digestate (φ = 0.5) was made and characterized (Table 3).

[Table 3 here]
The N/P/K ratio was very variable for the different products: 2.8/1/1.6 for digestates, 0.77/1/0.36 and 13/1/11 for thick and liquid fractions after separation respectively, 5.4/1/2.5 for the mixtures and 3.4/1/1.5 for pig slurry. Micronutrient contents were in all samples lower than the Flemish legislation criteria [24] for use as fertilizer and/or soil conditioner in agriculture.

Furthermore, concentrates produced by one vibrating membrane (RO) filtration step of LF digestate, as well as concentrates following two subsequent vibrating membrane (RO) filtration steps were sampled and physico-chemically analyzed (Table 4).

Results show that concentrates produced by the first filtration not only contained more macronutrients and organic carbon on Fresh Weight (FW) content, but also more salts and trace elements. In all concentrate samples, concentrations of trace elements were however below the Flemish legislation criteria [24] for use as fertilizer and/or soil conditioner in agriculture.

Finally, waste waters produced by both acidic and alkaline air scrubbers were sampled and physico-chemically analyzed (Table 5).

3.2 Economic and ecological analysis

Twenty-one different cultivation scenarios were economically and ecologically evaluated (Table 6-7; Fig. 2).
In scenario 3 to 5 and 16 to 21 the economic cost was higher than that of the reference scenario. Hereby in scenario 3, 16 and 17 also the ecological impact was higher as compared to the reference. Interestingly, all the other scenarios under study had a significantly lower ecological and economic impact than the common practice.

4. Discussion

4.1 Fertilizer value

In nutrient-rich regions crude digestates cannot or only sparingly be returned to agricultural land. Nevertheless, analytical results show that application of this product can be beneficial. Advantages while using digestates in comparison to conventional animal manure are for example the higher C/N ratio, 3.9 vs. 1.9, and the higher nitrogen uptake efficiency (NUE), which is the relative amount of NH$_4$-N compared to the total amount of nitrogen, 81 vs. 65-69 % (Table 3; [9]). The reason for this is that through anaerobic digestion organic nitrogen is converted into NH$_4$, which is directly available for the plant [16]. Also, during the anaerobic digestion easily biodegradable organic compounds are converted into biogas, while complex molecules such as lignin stay behind [16]. Hereby, the digestate keeps its soil enhancing properties. Furthermore, it was observed that the extraction efficiency of macronutrients (P, K, Na, Ca, Mg) using NH$_4$OAc-EDTA at pH 4.65 as an extraction agent, is higher (up to 100 %) for digestate derivatives than for conventional pig manure. This translates into a higher nutrient availability for plants. A final interesting observation was that the N/P ratio is about four times higher for liquid fractions of digestates than for animal manure, 13 vs. 3.4, and approximately five times higher than for digestates as such, 13 vs. 2.8, as most of the
phosphorus ends up in the thick fraction after separation. In light of phosphorus becoming more restrictive in legislative frameworks for soil nutrient application rates [19], this nutrient has become the limiting element in allowed dosage of organic fertilizers. In this perspective the use of phosphorus reduced liquid fractions of digestate is highly interesting, because more nitrogen can be applied to the soil for the same amount of phosphorus. When mixing digestate ($\phi = 0.5$) and its liquid fraction ($\phi = 0.5$), the relative amount of N to P stays high, while also the soil structure enhancing properties (Ca, Mg, OC) increase. All of these benefits make it an interesting opportunity for agriculturists to treat their manure by anaerobic digestion and reuse the digestate and/or its derivatives on soil, either as base fertilizer and/or as substitute for mineral fertilizers that are based on fossil resources.

In addition, results indicate that concentrates produced by membrane filtration have potential as N-K fertilizer. The observed N content was $6.4\pm0.4$ kg t$^{-1}$ FW, comparable to conventional pig manure, 5-10 kg t$^{-1}$ FW [9]. The average NUE was 78 %, which is higher than conventional pig manure, 69 % in this study or 65 % in [9]. Furthermore, waste water from acidic air scrubbers shows potential as N-S fertilizer. The N content was $23\pm9$ kg t$^{-1}$ FW and the S content was approximately 34 kg t$^{-1}$ FW. Both the N and the S extraction efficiency were 100 %, which is a prerequisite for recognition as a valuable mineral fertilizer according to the EU requirements for ‘sulphate of ammonia’ (EC 2003/2003 [25]). Finally, waste water from alkaline air scrubbers was poor in nutrients and therefore exhibits no potential as green fertilizer.

From the above it can be concluded that the classification of digestate and its derivatives should be reconsidered on national and European scale, with attention for their qualitative fertilizer properties. The legal categorization of such derivatives as ‘green mineral fertilizers’ next to the existing framework of ‘fossil-based mineral fertilizers’ (EC 2003/2003 [25]) might be indispensable for their success in the European Union.
4.2 Potential bottlenecks for re-use

When using acidic air scrubber water in agriculture, one should be aware of some practical limitations. At first, the low pH (2 to 3) of this waste stream shows that this waste water does not only contain ammonium sulfate, but also significant amounts of sulfuric acid. As a consequence, this product has acidifying and corrosive properties. It is therefore advised to use corrosion-durable injectors and to avoid direct contact with skin and plants. Another, more practical solution for this problem is to mix the acidic with the alkaline waste water (pH 9), thereby neutralizing the pH, or at least maintaining a weak acidic pH to avoid unwanted ammonia emissions. Next, it is important to indicate that while mixing or storing the acidic waste stream, H$_2$S can be released which is very toxic even at low concentrations. This can be explained by the presence of sulfate reducing bacteria, which are able to use sulfates for the oxidation of organic compounds or hydrogen under low-oxygen conditions, a process in which H$_2$S is produced [26]. For all of these reasons, best practice requirements for implementation and use of waste water from acidic air scrubbers should be set up in order to minimize health risks and to prevent soil degradation. Finally, a critical point when using acidic waste water in agriculture could be the salt content. Results show that the EC of this stream is 112±42 mS cm$^{-1}$, while that of conventional pig manure amounts to 35 mS cm$^{-1}$, which is in line with literature data, 30-50 mS cm$^{-1}$ [9] and [27]. Too high salt contents can cause soil salinification and can dramatically reduce crop production [28] and [29].

As for acidic air scrubber water, results show that also membrane filtration concentrates have elevated salt contents, 60±8 mS cm$^{-1}$, resulting in high salt/N ratios (up to 6) for this product. Therefore, when using concentrates in agriculture, it is important to pay attention to the salt doses per unit nitrogen applied to the soil. Next, high sodium adsorption ratios (SAR), which are ratios of monovalent cations such as K and Na to divalent bases such as Ca and Mg,
can cause soil structure degradation, especially when soils are rich in clay [28]. Finally, results show that the K$_2$O content of the concentrates produced by the $1^{st}$ filtration was $5.2 \pm 3.2$ kg t$^{-1}$ FW, which is slightly lower than the expected range of [30], but still higher than that of conventional pig manure, 4.3 kg t$^{-1}$ FW. Although this element can be important for crop production, high ratios of potassium to nitrogen are not preferred in every agricultural application. Particularly livestock-farmers rather use potassium-poor fertilizers, because of the potential health risks for cattle, such as head illness, at high potassium fertilization, > 50 t ha$^{-1}$ y$^{-1}$ [31] and [32]. Therefore, depending on the composition of the base fertilizer and the soil characteristics, more or less concentrate can be applied as mineral fertilizer, with a maximum advised K$_2$O-dose of 70 kg ha$^{-1}$ y$^{-1}$ [31] and [32].

None of the analyzed products exceeded the legal composition and use requirements of heavy metals for re-use as fertilizer and/or soil conditioner in agriculture, as described in Flemish legislation [24]. Only for one sample of dry thick digestate the amount of Ni slightly exceeded the legal value. Furthermore, it should be remarked that because the relative amount of NH$_4$-N compared to the total amount of N is higher for digestates and its derivatives than for conventional animal manure, emission poor application techniques, for example direct injection, should be used. Also, fields must be ploughed as soon as possible after application of these fertilizers in order to minimize NH$_3$-emissions to air. Research on the microbiological quality of digestate and its derivatives was not included in this study, but will be aspect of future research. Yet, an orientating study [16] demonstrated that the amount of both aerobic and plant pathogens in digestate is less than in animal manure, while the amount of anaerobic pathogens is higher. More research in this field is, however, required.

4.3 Economic and ecological benefits

Re-use of valuable nutrients coming from digestate processing as a substitute for artificial
fertilizers could result in significant fossil energy and CO$_2$-emission savings, as well as cost savings. The energy consumption for artificial fertilizer use (N, P$_2$O$_5$, K$_2$O) in the reference scenario was 3.5 GJ ha$^{-1}$, which results in a GHG-emission of 193 kg ha$^{-1}$ yr$^{-1}$ in terms of CO$_2$-equivalents, assuming that natural gas was used for the production of artificial fertilizers and that diesel was used for the transport and application of fertilizers. The economic fertilizer cost for the agriculturist in this scenario amounts to 54 € ha$^{-1}$. It is observed that the substitution of artificial fertilizers by acidic waste water results in significantly less economic and ecological costs (scenario 1-2), because the impact of artificial fertilizer production diminishes. This is also the case when artificial fertilizers are substituted by membrane filtration concentrates (scenario 14-15). On the contrary, substitution of artificial fertilizers by digestates (Scenario 16-17) and mixtures of digestate ($\phi = 0.5$) and LF digestate ($\phi = 0.5$) (Scenario 20-21) requires more artificial N than the common practice, because of the low N/P$_2$O$_5$ ratio of these products. Therefore, these scenarios seem not interesting. It should however be remarked that in this study the relative amount of available N compared to the total amount of N in the digestate derivatives was assumed to be 60 %, according to the manure regulation. Nevertheless, results indicate that the actual amount of available N in digestate derivatives is higher. The implementation of a new categorization for these products could therefore result in a lower economic and ecological impact than predicted in the current study. Furthermore, substituting artificial fertilizers with LF digestate turns out in significantly less artificial K$_2$O requirements, while no artificial N is necessary. This results in a very low ecological impact: an energy use of 0.77 GJ ha$^{-1}$ and a GHG-emission of 55 kg ha$^{-1}$ expressed in terms of CO$_2$-equivalents. However, because the N concentration in the liquid fraction is low, the application and transportation costs for artificial fertilizers in this scenario are higher than in the common practice.

Substituting animal manure with biomethanisation digestates as base fertilizer (Scenario 3-
results in more artificial N requirements than the common practice, because the ratio of N to P is lower for digestates than for animal manure. This results in a higher economic impact than the common practice for all these scenarios and a higher ecological impact for scenario 3. Also additional artificial P₂O₅ can be required in these scenarios. On the other hand, substitution of animal manure with LF digestate (Scenario 6-7-8) results in significantly less artificial K₂O use. This results in economic and ecological benefits for the agriculturist. However, also in these scenarios additional artificial P₂O₅ can be required. Substituting animal manure by a mixture of digestate (φ = 0.5) and LF digestate (φ = 0.5) (Scenario 9-10-11) also results in less artificial K₂O use than the common practice, while maintaining a high N and P₂O₅ dose. When simultaneously substituting artificial fertilizers with membrane filtration concentrates, the highest economic benefits were reached, up to 82 € ha⁻¹ (Scenario 13), while a relative reduction of 65.4 % in the ecological impact was obtained compared to the common practice.

Finally, it is interesting to notice that significant amounts of sulfur are applied to the soil in scenario’s 1, 2, 4, 5, 7, 8, 10, and 11. This could result in an extra economic benefit of 0.75 € kg⁻¹ S (personal communication, Triferto, 2010), depending on the sulfur need of the agricultural crops.

5. Conclusion and future perspectives

Recuperation and cradle-to-cradle re-use of macronutrients from digestate derivatives can be an important aspect in the further development of sustainable agriculture, anaerobic digestion and green chemistry. Concentrates following membrane filtration through reversed osmosis show potential as green N-K fertilizer, whereas waste water from acidic air scrubbers shows potential as green N-S fertilizer. Important bottlenecks for agricultural re-use of concentrates could be the salt content, the sodium adsorption ratio and the potassium content, especially for
livestock-farmers. Bottlenecks for agricultural re-use of acidic air scrubber water could be the pH, the salt content and its corrosive properties. Substituting artificial fertilizers by acidic air scrubber water or membrane filtration concentrates theoretically always results in significant economic and ecological benefits for the agriculturist. The highest economic benefits were obtained when animal manure is substituted by a mixture of digestate ($\phi = 0.5$) and liquid fraction of digestate ($\phi = 0.5$), while artificial fertilizers are replaced with membrane filtration concentrates. Field research is now on-going in order to evaluate the impact on soil and crop production by application of these new green fertilizers.

Acknowledgements

The authors would like to thank the Agency for Innovation by Science and Technology for financing the IWT/KMO-project 90831.
References


[7] Laherrere JH. Learn strengths & weaknesses to understand Hubbert curve. Oil Gas J 2000;98(16).


