Energy Demand and Economy of Nutrient Supply through Distillers Grains with Solubles from Bioethanol Production

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ABSTRACT

Two different distillers grains with solubles (DGS) are analysed for their nitrogen and phosphorus contents in untreated and processed fractions. Processing includes decanting, heating and anaerobic digestion. Untreated DGS contains approx. 3.3 to 8 g $N \cdot l^{-1}$ and 0.2 to 0.5 g $P \cdot l^{-1}$. These concentrations can be increased by one order of magnitude through processing. Anaerobic digestion shifts the availability of nutrients from organic fixed forms to inorganic forms. Furthermore, anaerobic digestion delivers energy from produced methane rather than the consumption of energy found in other processing methods.

Keywords: anaerobic digestion, separation, nitrogen, phosphorus, DGS, DDGS

1. INTRODUCTION

During the production of bioethanol from cereals, its dry matter is divided into three almost equivalent fractions: one third is converted into ethanol, one third into carbon dioxide and one third into residues. These residues are usually assigned as distillers wet grains or as distillers grains and solubles (Rosentrater and Lehman 2008). Considering the dry matter content of the third fraction, approximately ten litres of distillers grains with solubles (DGS) remain if one litre of ethanol is produced from cereals (Kaltschmitt and Hartmann 2001). DGS is usually used as feed for ruminants (Engelhard et al. 2005; Spiekers et al. 2006). DGS cannot be stored due to fast infestation by bacteria, yeast, and moulds (Steinhöfel 2008). This implies that it has to be used rather quickly or it has to be dried to obtain a stable product. In the first case it supplies only a limited number of animals, while in the second case it consumes a large quantity of energy for drying (Garcia and Kalscheur 2007). The increasing demand for ethanol as a fuel – called bioethanol – increases the amount of DGS and hence the need arises for alternative uses of DGS.

One of the alternatives is the use of DGS as organic fertiliser with nitrogen and phosphorus as the main nutrients. This study considers the direct use of untreated DGS and three processed forms, i.e. concentrated by decanting and additional drying as well as in the form of digestate after anaerobic digestion. The investigation included the analyses of nitrogen and phosphorus availability and the paths of losing these nutrients, e.g. ammonia emissions. Energy input and output, as well as costs from processing and from field application were determined in scenarios according to the different processing pathways. In addition, heavy metal concentration in DGS were analysed in order to assess possible risk of soil contamination.

For this study two kinds of DGS were used, both derived from rye fermentation: S1 from agricultural bioethanol production and S2 from the industrial process. Both DGS were compared

in four types of processing: untreated, decanted, decanted and dried and as feedstock of anaerobic digestion.

2. METHODS OF PROCESSING DISTILLERS GRAINS WITH SOLUBLES

DGS can only be used for a two-day period, after which mould starts to grow on it. Spoilage can be delayed through drying and thus reducing moisture. A relative stable product can be obtained if the DGS is dried to 80% dry matter content (DM). The reduction of moisture also improves the transportability of the DGS.

2.1 Decanting of DGS

Bioethanol production without DGS recycling (S1) generates a DGS with a dry matter content of approx. 6% of fresh matter (FM). If DGS is recycled (S2) the final product has a dry matter content of approx. 12% FM. DM content is increased to 30 to 35% FM by decanting the DGS. A combination of belt filters and screw separators are used in industrial scale. The separated liquid (approx. 80% of the source material) still contains a fraction of the solid matter, especially the dissolved minerals.

2.2 Decanting and Drying of DGS

Drying of the already decanted DGS leads to a product (DDGS – Distillers Dried Grains with Solubles) which is relatively stable and can be used for a number of days. Drying increases dry matter content to a value of 80% FM and volume is further reduced to 10% of the original volume. As the moisture reduction is reached by vaporisation all minerals remain in the solid fraction.

2.3 DGS as Feedstock for Anaerobic Digestion

DGS is a very suitable feedstock for anaerobic digestion. It is easily pumped with a DM of 6 to 12% FM and can be discharged directly from the bioethanol production into the digester. During anaerobic digestion fast degradable organic substrates (organic acids, lipids, proteins, sugars, and starch) are converted to biogas (methane and carbon dioxide) while slow degradable carbon compounds as well as minerals remain in the digestate (Lehtomäki 2006). Organic fixed nitrogen and phosphorus are released to the same extent as organic compounds are degraded and are dissolved as ammonium and ortho-phosphate. In comparison to the above described DGS processing, anaerobic digestion increases pH-value. While the pH-value of untreated, decanted and dried DGS ranges around 3.5, the pH of digestate is approx. 8.0. This pH value as well as the increased availability of ammonium leads to losses of nitrogen due to ammonia volatilisation.

3. LAB-SCALE INVESTIGATIONS

Lab-scale investigations were conducted on two DGS samples obtained from different production origins:
- S1 - DGS of agricultural processing without recycling
- S2 - DGS of industrial processing with recycling

These samples were treated in three ways leading to four fractions for further analyses:
- untreated DGS
- decanted DGS
  - solid phase
  - liquid phase
- solid phase after drying

Liquid phases were taken from supernatant. The solid phases were obtained by filtration using 150 µm filters, resulting in dry matter contents of 30 to 35% FM, while DM of 80% FM was achieved after oven drying at 60 °C.

Concentrations of heavy metal and phosphorus were analysed in material dried at 105 °C and dissolved in aqua regia. Heavy metal concentrations were detected using a flame atomic absorption spectrophotometer. Phosphorus contents were determined gravimetrically through quinoline precipitation. Total nitrogen content was obtained with a Kjehldal apparatus. Ammonium and nitrate concentrations were analysed by ion chromatography from filtrate.

Digestability of DGS samples was determined in lab-scale batch digestion tests according to VDI guideline 4630 (VDI 2006; Herrmann et al. 2007).

4. SCENARIOS

In order to assess the provision of fertilisers from DGS four scenarios were distinguished according to the processing methods of DGS:
1. direct field application of untreated DGS
2. a) field application of decanted DGS
2. b) field application of decanted and dried DGS (DDGS)
3. field application of digestate of DGS

These scenarios regarded the following assumptions and definitions:

In general, the recycling of DGS is possible and should be conducted for energy reasons. This is normal at industrial scales but not agricultural ones. Recycling increase the stationary dry matter concentration according to the values obtained for S2.

The low ammonium concentrations (<0.05 kg·m⁻³) and the low pH values (approx. 3.5) of DGS make it rather improbable for the scenarios 1 and 2 a) and b) to have significant ammonia emissions. However, ammonia emissions do have to be considered for scenario 3.

In scenario 2 two options were distinguished: a) decanting of DGS which separates a large quantity of liquid with low dry matter content and b) drying which increases dry matter concentration as only water is evaporated.

In scenario 3 DGS is added directly to the feedstock of anaerobic digestion. The flux of the other feedstock, e.g. manure and energy crops, is not balanced, nor are associated fluxes of nitrogen and phosphorus. Anaerobic digestion increases pH, decreases dry matter content and shifts the share of organic fixed nitrogen and phosphorus towards inorganic fixed ones. The higher pH-

value and the increased ammonium concentration enhance the risk for ammonia emissions from digestate application to field. From model calculations (Plöchl 2001) one can assume a maximum emission potential of 30% of available ammonium-N. Figure 1 displays these scenarios and the associated fluxes of dry matter, nitrogen, phosphorus as well as the correlated ergy input and output fluxes.
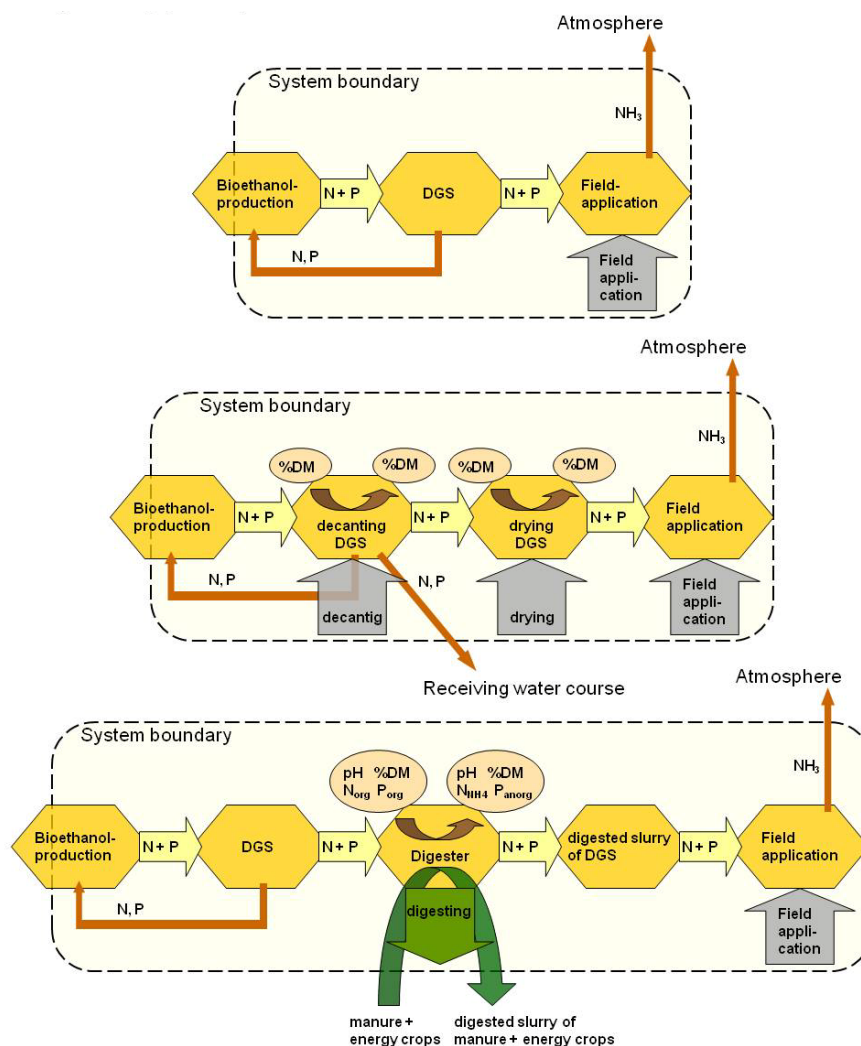
Figure 1. Fluxes of nitrogen (N), phosphorus (P) as well as energy input and output during DGS processing and application to field. In the case of dried distillers grains S1 there is no recycling of material from decanting into production.

5. RESULTS AND DISCUSSION

5.1 Lab-scale analysis

In tables 1 and 2 the analytical parameters are summarised for DGS S1 and S2 distinguishing untreated DGS, supernatant, decanted solid phase and solid phase after drying. Results illustrate

that the processing does not influence pH-values. Ammonium and nitrate remain in the liquid phase. Phosphorus and organic fixed nitrogen are found mainly in the solid phases.

Table 1. Physico-chemical properties of S1

parameter	untreated DGS	supernatant	solid phase (decanted)	solid phase (dried)
pH	3.8	3.7	3.8	3.8
DM [$g \cdot l^{-1}$]	63.1	25.8	278.2	889.5
N_{tot} [$g \cdot l^{-1}$]	3.33	0.65	18.78	60.04
N_{NH4} [$g \cdot l^{-1}$]	0.007	0.007	-	-
N_{NO3} [$g \cdot l^{-1}$]	0.003	0.001	-	-
P_{tot} [$g \cdot l^{-1}$]	0.202	0.121	0.67	2.14

Table 2. Physico-chemical properties of S2

parameter	untreated DGS	supernatant	solid phase (decanted)	solid phase (dried)
pH	3.4	3.3	3.4	3.4
DM [$g \cdot l^{-1}$]	125.8	57.7	371.2	798.2
N_{tot} [$g \cdot l^{-1}$]	7.98	3.30	24.86	53.45
N_{NH4} [$g \cdot l^{-1}$]	0.027	0.034	-	-
N_{NO3} [$g \cdot l^{-1}$]	0.005	0.006	-	-
P_{tot} [$g \cdot l^{-1}$]	0.494	0.326	1.10	2.36

These values are in typical range of DGS from grain sources. The difference in DM between S1 and S2 reflects very well the difference between agricultural, simple bioethanol production without recycling and industrial bioethanol production with recycling (Steinhöfel 2008). In addition, heavy metal concentrations were analysed in order to exclude environmental hazard from DGS application (table 3).

Table 3: Heavy metal concentrations of DGS S1 and S2

DGS	copper	zinc	nickel	cadmium	lead	chrome
S1 [$g \cdot m^{-3}$]	2.66	4.86	0.72	<0.06	<0.63	<0.63
S2 [$g \cdot m^{-3}$]	1.91	10.18	1.27	<0.13	<1.26	<1.26
S1 [$mg \cdot kg_{DM}^{-1}$]	42.1	77	11.4	<1	<10	<10
S2 [$mg \cdot kg_{DM}^{-1}$]	15.2	80.9	10.1	<1	<10	<10
Threshold value BioAbfV[*] [$mg \cdot kg_{DM}^{-1}$]	100	400	50	1.5	150	100

[*] BioAbfV is German regulations for biological wastes

Anaerobic batch digestion tests delivered mean values of 483 m³ methane, equivalent to 878 m³ biogas with a methane content of 55%, which could be formed from one ton DM independent which kind of DGS is used. 483 m³ methane are equivalent to 21.3 kmol, i.e. that the same number of moles of carbon are transformed to methane. As 1 ton DM is equivalent to approx. 490 kg carbon and hence 40.8 kmol. From this it can be concluded that approx. 52% of the dry matter will be transformed to methane.

5.2 Scenarios

5.2.1 N and P Fluxes

On the basis of the lab-scale analyses and according to the scenarios described, fluxes of nitrogen and phosphorus were calculated as well as energy input and output. These were then related to the fertiliser potential of the DGS.
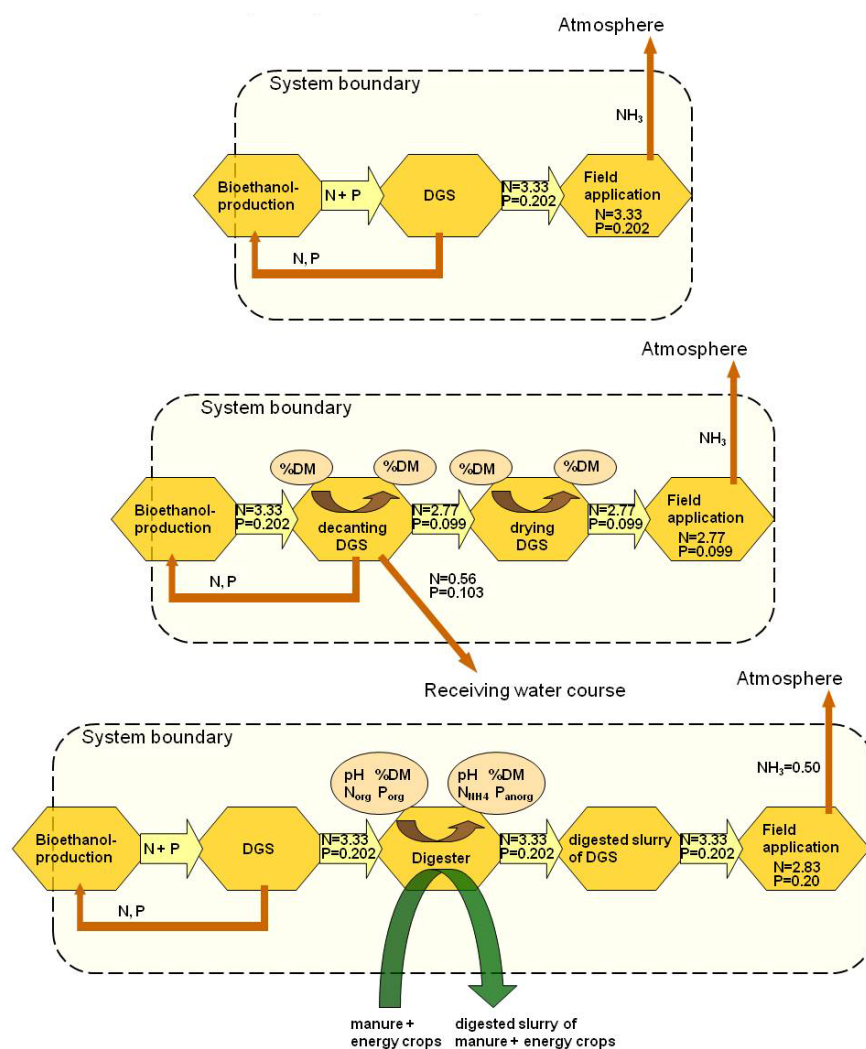

Figure 2. N and P fluxes as constituents of DGS S1 for four scenarios

All calculations are based on 1 m³ of untreated DGS, thus in scenario 1 and 3 there is still 1 m³ of DGS for application. Although there is a 52% reduction in dry matter by anaerobic digestion the overall reduction in volume of the fresh material ranges between 3 and 6% and can be neglected for further calculations. In scenario 2 a) the volumes for application amount to 0.148 m³ for S1 and 0.217 m³ for S2. Drying further reduces these volumes to 0.046 m³ (S1) and 0.101 m³ (S2) in scenario 2 b). All these fluxes are displayed in table 4 as well as in figures 2 and 3 for all scenarios.

Table 4. DM, N, and P fluxes of scenarios 1, 2, and 3 (same values for scenarios 2 a) and b)) of DGS S1 und S2, based on 1 m³ untreated DGS (all values in kg)

parameter	S1 scenario 1	scenario 2	scenario 3	S2 scenario 1	scenario 2	scenario 3
DM_{tot}	63.1	63.1	63.1	125.8	125.8	125.8
N_{tot}	3.33	3.33	3.33	7.98	7.98	7.98
P_{tot}	0.202	0.202	0.202	0.494	0.494	0.494
$DM_{dec.loss}$[1]	-	22	-	-	45.2	-
$N_{dec.loss.}$[1]	-	0.56	-	-	2.58	-
$P_{avail.}$[2]	0.202	0.099	0.202	0.494	0.239	0.494
$P_{dec.loss}$[1]	-	0.103	-	-	0.255	-
N_{NH3^-loss}	-	-	0.50	-	-	1.24
$N_{avail.}$[2]	3.33	2.77	2.83	7.98	5.4	6.74
of which						
N_{NH4}	0.007	0.001	1.22	0.034	0.001	2.89
N_{NO3}	0.003	0.002	-	0.006	0.000	-

[1] dec.loss = losses at decanting; [2] avail. = potentially available
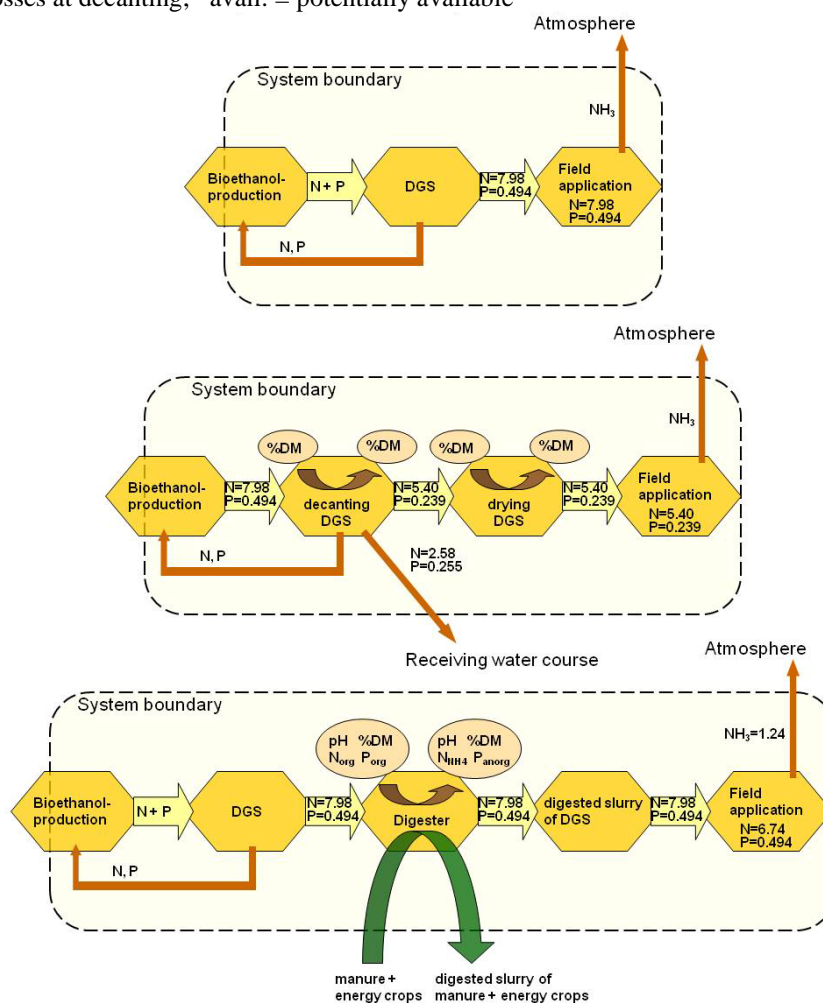
Figure 3. N and P fluxes as constituents of DGS S2 for four scenarios

If the fluxes of DM, N, and P are normalised to 1 m³ it can clearly be seen how much of the original material will be maintained as nutritional value during processing (figure 4).
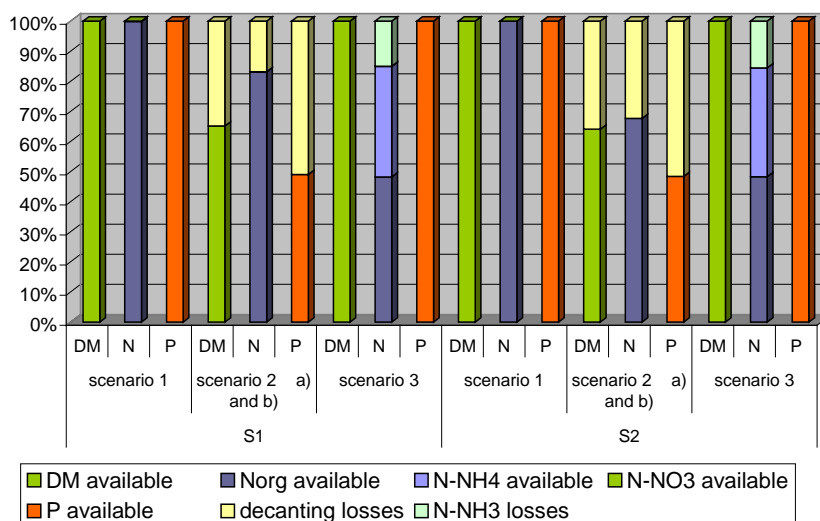

Figure 4. DM, N, and P fluxes relative to 1 m³ of untreated DGS for S1 and S2

There is no loss of any nutrients in scenarios 1 because the material is applied to field as it leaves bioethanol production. In scenarios 2 decanting removes approx. 30% of the dry matter and hence, approx. 50% of the phosphorus and 20 to 30% of the nitrogen. Further drying has no influence on these materials as only water evaporates. In scenarios 3 there are no losses of phosphorus and approx. 50% of the organically fixed nitrogen is converted to inorganic ammonium, of which a third is lost as ammonia after field application.

5.2.2 Energy Fluxes

Large-scale decanting requires 1.8 to 5.5 kW of electrical energy depending on the performance of the decanter, which ranges between 10 to 35 m³·h^{-1} (Schmitz 2005). This amounts to an average energy consumption of 0.65 MJ·m^{-3}.

Drying requires energy for heating the DGS first to 100 °C, whereas the DGS comes with a temperature of approx. 80 °C from bioethanol production or decanting, and finally the energy for volatilisation. Here, values of pure water are used as an approximation. Heating requires 4.184 kJ·kg^{-1}·K^{-1} and enthalpy for volatilisation is 2.26 MJ·kg^{-1}. It is further assumed that heat exchange can be done with an efficiency of 100%.

Field application requires diesel for the transport (an average distance of 10 km is assumed) and for the application itself, considering a trail hose applicator for liquid fertiliser and a manure sprayer for solid fertilisers (DM > 25% FM). Diesel consumption is further related to the amount of material and nutrients to be distributed. Transport uses 0.09 l diesel·km^{-1}·t^{-1}, application consumes 7 l diesel·ha^{-1} for liquid fertilisers and 14 l diesel·ha^{-1} for solid ones (ÖKL 2005). The areal performance of application depends on DM content and ranges from 24 t·ha^{-1} at DM = 6% FM to 10 t·ha^{-1} at DM = 12% FM and to 5 t·ha^{-1} at DM > 25% FM (DLG 1997; DLG 2001). The heat of combustion of diesel is 35.952 MJ per litre.

Anaerobic digestion, in contrast to the above consumptions, delivers energy in the range of 483 m^3 $CH_4 \cdot t_{DM}^{-1}$ which equals 17388 $MJ \cdot t_{DM}^{-1}$ (36 MJ per m^3 CH_4).

These particular energy fluxes summarise to a range of values from 6.98 MJ (13.14 MJ) for S1 (S2) in scenario 2 a) to 244.8 (286.4) in scenario 2 b), scenario 1 in between and scenario 3 with a negative value of -1054 MJ (2130 MJ) due to the energy delivery from anaerobic digestion (table 5).

Table 5: Energy fluxes relative to 1 m^3 untreated DGS for all scenarios of S1 and S2 (values in MJ)

energy for	decanting	drying	application	of biogas	sum
S1					
scenario 1	-	-	42.84	-	42.84
scenario 2 a)	0.648	-	6.33	-	6.98
scenario 2 b)	0.648	238	6.15	-	244.82
scenario 3	-	-	42.84	-1097	-1054
S2					
scenario 1	-	-	57.52	-	57.52
scenario 2 a)	0.648	-	12.50	-	13.14
scenario 2 b)	0.648	272	13.44	-	286.43
scenario 3	-	-	57.52	-2187	-2130

Energy demand for N and P as fertiliser can be calculated from these energy fluxes and the amount of nitrogen and phosphorus available in these different fractions in comparison to energy demand for mineral fertiliser (table 6). These values refer to the energy demand, in scenario 3 energy output, for pure nutrients and for the solely application of one nutrient, i.e. neglecting the associated application of the other nutrient.

Table 6. Energy demand for N and P from DGS for four scenarios, in comparison to energy demand of mineral fertilisers

	N energy demand [$MJ \cdot kg\ N^{-1}$]	P energy demand [$MJ \cdot kg\ P^{-1}$]
S1		
scenario 1	12.86	212.1
scenario 2 a)	2.09	34.55
scenario 2 b)	73.47	1212
scenario 3	-316.4	-5220
S2		
scenario 1	7.21	116.4
scenario 2 a)	1.65	26.61
scenario 2 b)	35.90	579.8
scenario 3	-266.9	-4312
mineral fertiliser[1]	35.18	35.69

[1]Data from REPRO (www.landw.uni-halle.de/**repro**/)

5.2.3 Cost assessment

In 2004 DDGS as animal feed was sold for 90 €per ton (Gangl 2004) which was approximately 10% above the production costs. Since then the index for energy has increased from 113% to 153% (Destatis 2008) resulting in energy costs for DDGS production of 110 €per ton. Relating these costs to the nitrogen and the phosphorus content delivers the costs for the respective nutrients (table 7). The relatively high costs for phosphorus in scenarios 2 can be compensated by saved input of mineral nitrogen due to the nitrogen content of the DGS. In contrast, scenario 3 produces revenue rather than costs. Producing electricity with the biogas from DGS digestion would result in an unit price of 0.176 €kWh^{-1} electricity produced, which reflects the basic fee plus a bonus for cogeneration guaranteed by the German law for renewable energies (BMU 2008). This price would equal a unit price for natural gas of 0.04584 €kWh^{-1}. On the basis of these prices an income could be achieved ranging from 4.57 (S1)/3.81 (S2) € per kg N and 154.11 (S1)/127.21 (S2) €per kg P. Due to the direct field application no costs are considered in scenario 1.

Table 7. Costs and revenue for N and P from DGS

	costs for nitrogen [€kg N^{-1}]	costs for phosphorus [€kg P^{-1}]	bonus by associated N application [€kg P^{-1}]
S1			
scenario 1	0.00	0.00	
scenario 2 a)	2.05	57.50	51.04
scenario 2 b)	1.83	51.38	45.45
scenario 3	-4.19	-141.29	
S2			
scenario 1	0.00	0.00	
scenario 2 a)	1.55	34.99	12.85
scenario 2 b)	2.06	46.50	18.52
scenario 3	-3.49	-116.63	
mineral fertiliser[1]	1.30	1.50	

[1]Data from (Linker 2008) – Since the beginning of 2008 these prices underwent rapid changes and may have expanded two- to three-fold in the meantime.

6. CONCLUSIONS

DGS is a reliable source of nitrogen and phosphorus in comparison to other organic fertilisers. The load of heavy metals is low and lies in every case below the threshold values of German regulations for biological wastes. The direct application of untreated DGS is less favourable due to its low pH-value which implies either a low application rate or the associated application of lime.

The anaerobic digestion of DGS is explicitly favourable for several reasons:
- more energy is produced than consumed
- pH is raised to acceptable values
- a large quantity of organic fixed nitrogen is converted to readily accessible ammonium

Although a share of the nitrogen is lost in form of ammonia emissions, the overall balance can be considered positive.

The results for anaerobic treatment of DGS are confirmed by earlier experiments (Wilkie et al. 2000) as well as recent experiments (Cassidy et al. 2008) which reported on the anaerobic treatment of various feedstocks derived from ethanol production. In general, the degree of chemical oxygen demand (COD) removal is more than 50% and the removal of biological oxygen demand (BOD) is about 90%. Methane contents were reported in the range of 55 to 60% and biogas productions were comparable with 250 l per kg COD.

Experiments using DGS as feed for hens, cattle or pigs showed that the uptake of both nitrogen and phosphorous into the animal organism is much better than from mineral sources (Swiatkievicz and Koreleski 2007; Greenquist et al. 2007). From this one can conclude that both nutrients will have good plant availability. (Lory et al. 2008).

The energy balance of nutrients from DGS is favourable in this study and confirms the results of Murphy and Power (2008), which regarded the energy balance of anaerobic digestion of DGS in relation to bioethanol production.

The economic assessment is less favourable for the scenarios 2 a) and b), especially for phosphorous, which is much more expensive than mineral fertilisers. These disadvantages are more than compensated if DGS is anaerobically digested. Another compensation can be achieved if the associated application of nitrogen would be regarded as a bonus for the costs of phosphorus. With an average proportion of N:P of 15 the application of P would receive a bonus of 15 times the costs of N ranging from 12.85 to 51.04 €kg P^{-1}.

Many regard the utilisation of DGS as animal feed as favourable due to its large protein content, approx. 40% of DM, and drying produces a relatively stable product. In feeding tests ruminants took up 3.6 kg_{DM} per day per head (Engelhard et al. 2005). Other experiments also showed that DGS or DDGS, respectively, could replace up to 15% of the usual diet of hens, cattle, beef and dairy, and pigs. Higher shares of (D)DGS in the diet led to reduced performances (Swiatkievicz and Koreleski 2007; Greenquist et al. 2007; Lumpkins et al. 2004). Hence, if DGS from large scale bioethanol production should completely be used as feed one requires large quantities of animals and the obligate drying to DDGS. This pathway may be favourable if low cost energy is available for drying. The anaerobic digestion pathway is in any case favourable. In general, a combination of both pathways can be considered as an optimum solution.

7.   ACKNOWLEDGEMENT

8.   RFERENCES

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