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D3.5 REPORT ON THE LCA OF THE SOLUTION

DIGESMART

CONTRACT ECO/12/332882

European Commission | Executive Agency for Small and Medium-sized Enterprises

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INTRODUCTION

This Report is divided in two sections. In the first one, the Life Cycle Assessment (LCA) approach is briefly described while, in Section 2, LCA is applied in order to evaluate the environmental performance of the solution proposed and realised during the project DIGESMART.

THE LIFE CYCLE ASSESSMENT APPROACH

Life Cycle Assessment (LCA) also known as life-cycle analysis, eco-balance, or cradle-to-grave analysis, is a standardised technique to assess environmental impacts associated with all the stages of a product's life cycle (i.e., from raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling) including all intervening transportation steps necessary or caused by the product's existence.

LCA is an important and comprehensive method for the analysis of the environmental impact of products and services in which the whole system involved in the production, use and waste management of a product or service is described. SETAC (Society of Environmental Toxicology and Chemistry) defines LCA as "a process to evaluate the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and materials used and wastes released to the environment; to assess the impact of those energy and materials used and released to the environment; and to identify and evaluate opportunities to affect environmental improvements. The assessment includes the entire life cycle of the product, process or activity, encompassing, extracting and processing raw materials; manufacturing, transportation and distribution, use, re-use, maintenance, recycling, and final disposal".

LCA **origins** go back to 1960s, when concerns over the limitations of raw materials and energy resources led to the development of a method that enabled the quantification of resources use. In 1969, an internal study was carried out for The Coca-Cola Company. This study aimed at comparing different containers in terms of the environmental burden associated with their production. During the 1970s other companies in both the United States and Europe performed similar comparative LCA studies. Given the great importance gained by LCA methodology over the years, standard rules were developed in 1997 by the International Standards Organization (ISO 14040 series).

The concept of a product life cycle can be understood intuitively: it means that a product is studied from the **"cradle"** that means where raw materials are extracted from natural resources, through its production and use and finally to its **"grave"** disposal. LCA also means describing the whole procedure for how such studies are done and interpreted. To do this, four main phases can be considered: firstly, the product and purpose of the study have to be specified; secondly, an inventory is completed, that means the construction of the life cycle and calculation of the emissions produced and the resources used; thirdly, emissions and resources are related to environmental problems through classification and characterisation; fourth, the different environmental impacts are weighted, putting all of them on the same scale.

LCA procedure has **four main phases** to go through; they (**Figure 1**) are stated by the ISO 14040 and 14044 standards, the main standard LCA methodologies to be followed internationally. The four phases are often interdependent so the results of one of them will inform how the other phases are completed. The phases are reported and described in detail below:

i) goal and scope definition, this step includes the definition of the aim of the study, of the Functional Unit (i.e., the defined as a quantified performance of a product system to be used as a reference unit in an LCA) (ISO 14040, 2006) and the system boundary of the studied system;

ii) inventory analysis, this phase is the most time and cost consuming and involves the collection of data about all the flows of materials and energy among the evaluated production systems and the environment;

iii) impact assessment during which the inventory data are summarised in a limited number of indicators;

iv) interpretation of the achieved results and identification of possible solutions to reduce the environmental impact.

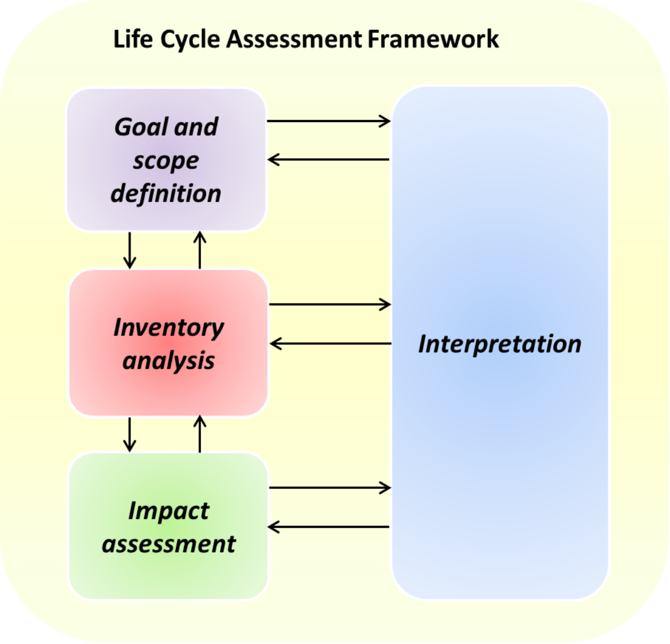

Figure 1 - Diagram of the four phases of LCA

LIFE CYCLE ASSESSMENT OF THE SOLUTION

The management of the raw digestate produced by an agricultural anaerobic digestion plant of medium-large size (electrical power of the CHP around 1 – 1.5 MW) can be performed in different ways. Each solution for digestate management involves a different consumption of production factors and different emissions released in the environment and, therefore, different environmental consequences.

GOAL AND SCOPE DEFINITION

The goal of this LCA study is twofold:

1) To assess the environmental performances of the solutions for digestate management that have been investigated during the digesmart project.
2) To compare the environmental impact of the green fertiliser (18% of N) produced by the experimental plant with the one of Ammonium Nitrate.

FUNCTIONAL UNIT

The functional unit (FU) is defined as a quantified performance of a product system to be used as a reference unit in an LCA (ISO 14040, 2006).

Concerning the comparison among different digestate management solutions the functional unit is defined as ‘the management of 20,000 tonnes of raw digestate. With regard to the compassion between Ammonium Nitrate and the green fertilised the selected functional unit is 1 kg of nitrogen in the fertiliser.

SYSTEM DESCRIPTION

Three different scenarios were compared:

- Baseline (BS), in this scenario the raw digestate (10.0% of dry matter content, 7 kg of N/t) is spread as organic fertiliser without any type of treatment;
- Alternative scenario 1 (AS1), in this scenario the raw digestate is separated into solid (SF; 30% of dry matter content, 1.05 kg of N/t) and liquid fraction (LF; 6.5% of dry matter content, 5.82 kg of N/t) that are spread as fertilisers;
- Alternative Scenario 2 (AS2), where: (i) raw digestate is separated into SF and LF, (ii) the LF is stripped by means of heat, HNO_3 and CaO (3 kg of N per t of LF are removed); (iii) a liquid fertiliser (green fertiliser - 18% of nitrogen content is produced). In this

scenario, SF and stripped LF (sLF; 6.5% of dry matter content, 2.82 kg of N/t) are spread on field.

The system boundary includes the operations carried out after the digestate storage and the fertilisers application to the soil (e.g., separation, stripping, LF stripping, transport to the field and spreading). Operations related to digestate production (e.g., biomass production, anaerobic digestion) and storage are not included in the evaluation because are supposed to be the same for all the different scenarios. Fertilisers related emissions due to ammonia volatilisation and dinitrogen oxide emissions have been considered according to Brentrup et al (2000). Fertiliser application has been supposed to take place in spring (temperature between 10 and 15°C) on cereal stubble before ploughing. Nitrate emissions have not been included, due to the absence of data about the nutrient crop removal. Capital goods have been excluded from the system boundary considering that their life span is longer than 3 years.

LIFE CYCLE INVENTORY

The main inventory data were collected during the experimental tests foreseen by the digesmart project and can be found in the deliverable “D4.2 DIGESMART VALIDATION AND REPLICATION POSSIBILITIES IN EUROPE”. In particular, primary data were collected concerning:

1. Capacity of digestate separator (t of raw digestate/year), plant for the stripping of liquid fraction (t of LF/year);
2. Electricity consumption of screw separator and stripping plant (kWh/year);
3. Consumption of HNO_3 and CaO for stripping (kg/t of liquid fraction);
4. Concentration of N in the green fertiliser (%);
5. Annual production of green fertiliser (t/year).

Main inventory data and assumptions considered in the environmental assessment:

1. For the different fertilisers, the nitrogen efficiency has been assumed equal to 100%; therfore all the N is considered availble for the crops, both the mineral (NH_3 and nitrate) and the organic one;
2. During digestate separation, electricity consumption is equal to 2.48 kWh/t of raw digestate (electrical power of scew separation = 8.2 kW; productivity = 3 t/h; load factor = 90%)
3. During stripping, for each tonne of LF are consumed: (i) 20.33 kg of HNO_3; (ii) 2.0 kg of CaO and (iii) 2.13 kWh of electricity.
4. In the three scenarios, the transport distance varies depending on the characteristics of raw digestate and digestate products (SL, LF, sLF).
    a. For the BS, considering a 170 kg of N/ha as maximum nitrogen dose, 705.88 ha are needed to spread the 20,000 tonnes. **Table 1** reports the transport distance

as well as the fractioning of the area fertilised by the raw digestate. Globally, the transport distance is 252,082 tkm;

Table 1 - Transport of raw digestate in BS

Parameter	Unit	Distance (km)					
		5	10	15	20	25	30
Area	ha	200	200	150	80	46	30
Spread mass	t	5667	5667	4250	2267	1300	850
Transport	tkm	28333	56667	63750	45333	32498	25500

b. For the AS1, considering a 170 kg of N/ha as maximum nitrogen dose, 123.5 ha are needed to spread the 3,000 tonnes of SF and 582 ha for the 17,000 t of LF (**Table 2**). Globally, the transport distance is 225,080 tkm;

Table 2 - Transport of SF and LF in AS1

Parameter	Unit	Distance (km)					
		5	10	15	20	25	30
Area for SF	ha	0	0	18	105.5	0	0
Spread mass of SF	t	0	0	437.2	2562.6	0	0
Transport of SF	tkm	0	0	6558.3	51251.9	0	0
Area for LF	ha	200	200	182	0	0	0
Spread mass of LF	t	5838.4	5838.4	5312.9	0	0	0
Transport of LF	tkm	29191.9	58383.8	79693.9	0	0	0

c. For the AS2, considering a 170 kg of N/ha as maximum nitrogen dose, 123.5 ha are needed to spread the 3,000 tonnes of SF and 282 ha for the 16,950 tons of sLF (**Table 3**), while 567 t of liquid fertiliser with a nitrogen content of 18% are also produced. Globally, the transport distance is 83.786 tkm.

Table 3 - Transport of SF, sLF in AS2

Parameter	Unit	Distance (km)					
		5	10	15	20	25	30
Area for SF	ha	0	118	5.5	0	0	0
Spread mass of SF	t	0	2865.7	133.6	0	0	0
Transport of SF	tkm	0	28657.1	2003.6	0	0	0
Area for sLF	ha	200	82	0	0	0	0
Spread mass of sLF	t	5838	2393.6	0	0	0	0
Transport of sLF	tkm	29190	23935.8	0	0	0	0

Finally, background data regarding the production of all required inputs such as diesel fuel, chemicals, lubricant oil and ammonium nitrate as well as CHP emissions were taken from ecoinvent® database (Althaus et al., 2007; Dones et al., 2007; Jungbluth et al., 2007; Nemecek and Käggi, 2007; Spiermann et al., 2007). In more details, the processes retrived from the databases (Ecoinvent, Agrifootprint, LCA Food DK) are reported in **Table 4**.

Table 4 - Processes retrieved from the databases

PROCESS and INPUT	ECOINVENT PROCESS
Raw digestate spreading	Liquid manure spreading, by vacuum tanker {CH}| processing | Alloc Def, U[1]
Liquid fraction spreading	Liquid manure spreading, by vacuum tanker {CH}| processing | Alloc Def, U[1]
Solid fraction spreading	Solid manure loading and spreading, by hydraulic loader and spreader {CH}| processing | Alloc Def, U[1]
Green fertiliser spreading	Fertilising, by broadcaster {CH}| processing | Alloc Def, U[1]
Transport	Transport, tractor and trailer, agricultural {GLO}| market for | Alloc Def, U[1]
Tractor	Tractor, 4-wheel, agricultural {GLO}| market for | Alloc Def, U
Operative machine	Liquid manure tank trailer {GLO}| market for|Alloc Def, U[2]
	Agricultural machinery, unspecified {GLO}| market for | Alloc Def, U[3]
Diesel fuel	Diesel {CH}| market for | Alloc Def, U
Lubricant oil	Lubricating oil, at plant/RER U
Electricity	Electricity, medium voltage {BE}| market for | Alloc Def, U
Nitric acid	Nitric acid, without water, in 50% solution state {RoW}| nitric acid production, product in 50% solution state | Alloc Def, U[4]
Calcium oxide	Calcium oxide {RER}| production | Alloc Def, U

[1] Field operations have been modified considering site specific parameters (recorded by the farmer or by means of surveys at the farm) as regard to: working time, fuel and lubricant oil consumptions, annual use and lifespan of tractors and operative machines; [2] for spreading of liquid fraction, stripped liquid fraction and green fertiliser; [3] for spreading of solid fraction; [4] corrected considering Nitric acid with 68%.

IMPACT ASSESSMENT

The impact assessment has been estimated according to ILCD 2011 methodology v1.05 (Hauschild et al. 2013), using SimaPro software (PRé Consultants, 2015). A full set of impacts are assessed: climate change (CC, kg CO_2 eq.), ozone depletion (OD, kg CFC-11 eq.), human toxicity, considering both cancer effects (HT-c, CTUh) and non-cancer effects (HT-nc, CTUh), particular matter (PM, kg PM2.5 eq); photochemical ozone formation (POF, kg NMVOC eq.), terrestrial acidification (TA, molc H+ eq.), terrestrial eutrophication (TE, molc N eq.), freshwater eutrophication (FE, kg P eq.), marine eutrophication (ME, kg N eq.), freshwater ecotoxicity (FET, CTUe), mineral, fossil & renewable resource depletion (MFRD, kg Sb eq.).

RESULTS

COMPARISON AMONG THE DIFFERENT SCENARIOS

Table 5 reports the absolute comparison among the three different scenarios for the considered FU (the management of 20,000 tonnes of raw digestate), while **Figure 2** shows the relative comparison (for each impact category the scenario with the highest values is set equal to 100%).

Table 5 - Environmental impact for the three scenarios (FU = management of 20,000 tonnes of raw digestate)

Impact category	Acr.	Unit	BS	AS1	AS2
Climate change	CC	kg CO_2 eq	658377	687748	1724681
Ozone depletion	OD	kg CFC-11eq	0.0146	0.0182	0.0357
Human toxicity, cancer effects	HT	CTUh	0.3096	0.2913	0.2377
Human toxicity,non-cancer effects	HTnoc	CTUh	0.0120	0.0119	0.0204
Particulate matter	PM	kg PM2.5 eq	2098.21	1819.53	1409.00
Photochemical ozone formation	POF	kg NMVOC eq	981.62	994.20	2118.76
Acidification	TA	molc H+ eq	91074	78494	54100
Terrestrial eutrophication	TE	molc N eq	405714	349469	238266

Freshwater eutrophication	FE	kg P eq	27.763	29.270	50.690
Marine eutrophication	ME	kg N eq	3103.2	2943.6	2784.3
Freshwater ecotoxicity	FEx	CTUe	1034308	1094702	3353743
Mineral, fossil & ren res. depletion	MFRD	kg Sb eq	24.643	23.619	30.823

Mainly due to stripping, and in particular to the consumption of acid nitric, the AS2 (scenario with separation and stripping) shows the highest environmental load for 8 (CC, OD, HT, HTnoc, POF FE, FEx and MFRD) of the 12 evaluated impact categories. For PM, TA, TE and ME, BS shows the worst performances mainly due to the fertiliser related emissions (above all ammonia volatilisation) and raw digestate transportation.

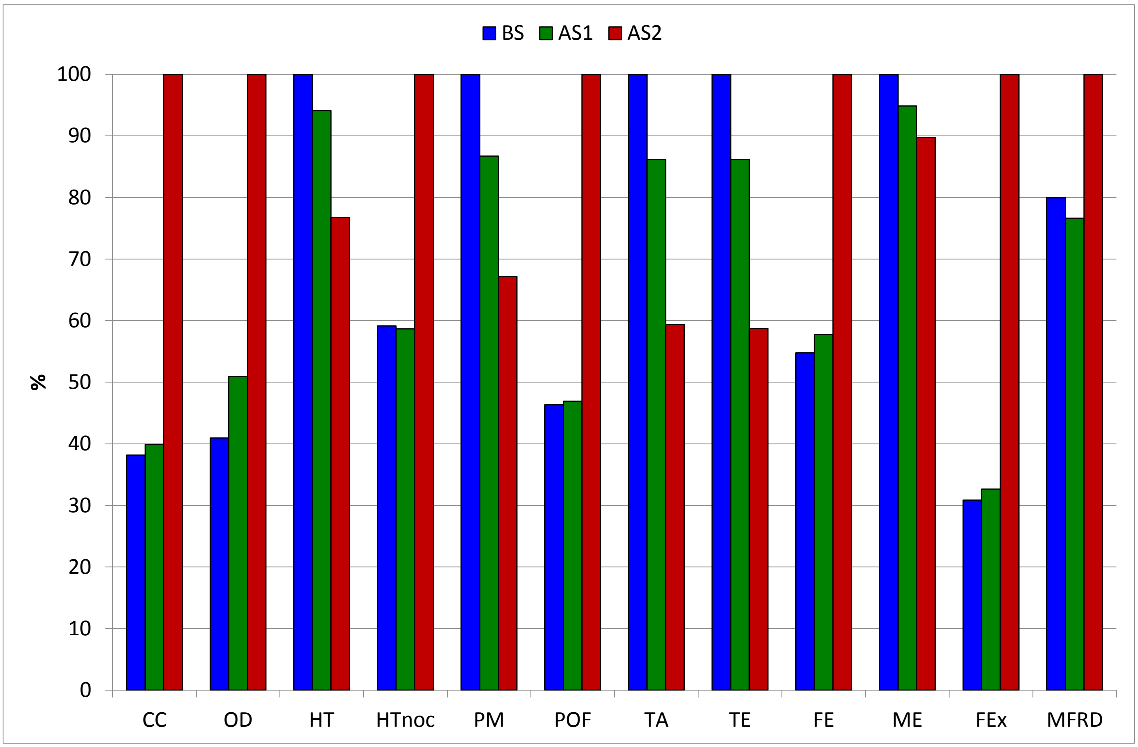

Figure 2 - Relative comparison among BS, AS1 and AS2

HOTSPOTS IDENTIFICATION

In **Figure 3-5** the environmental hotspots (processes or emissions to which is associated the highest proportion of the environmental impact) are highlighted for the 3 scenarios. The stripping is responsible for the major part of the environmental impact of AS2. As can be observed also in **Figure 6,** stripping impact is mainly related to HNO_3 consumption.

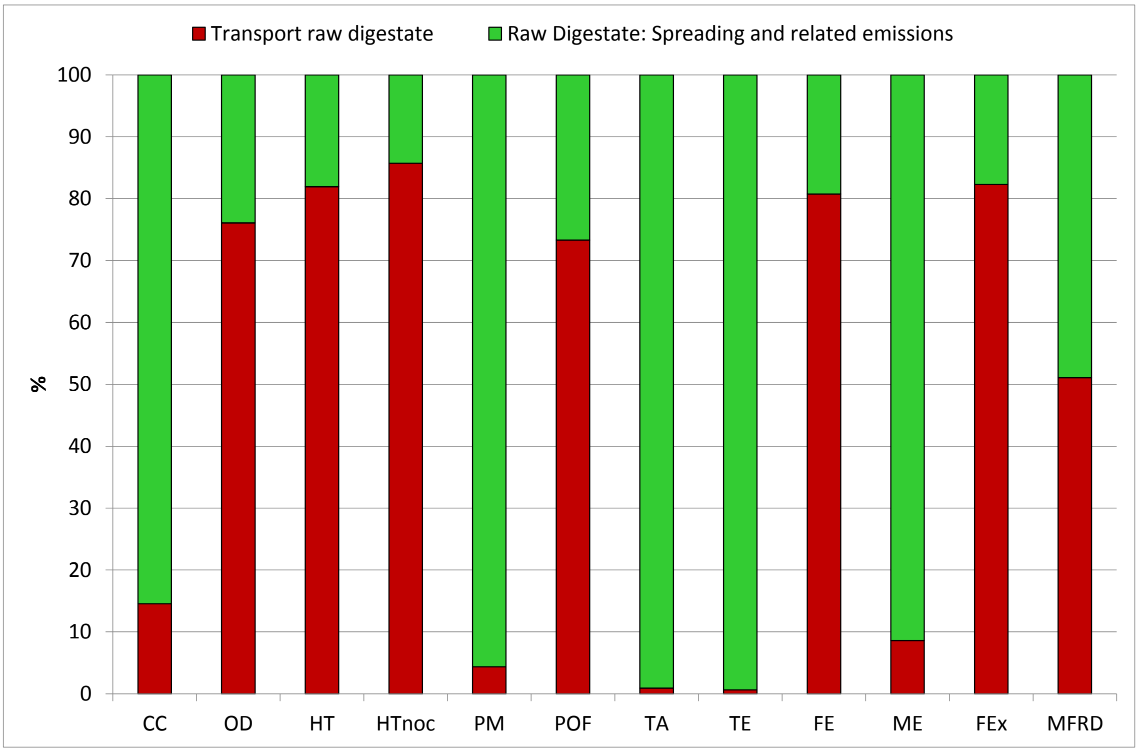

Figure 3 - Environmental hotspots identification for BS

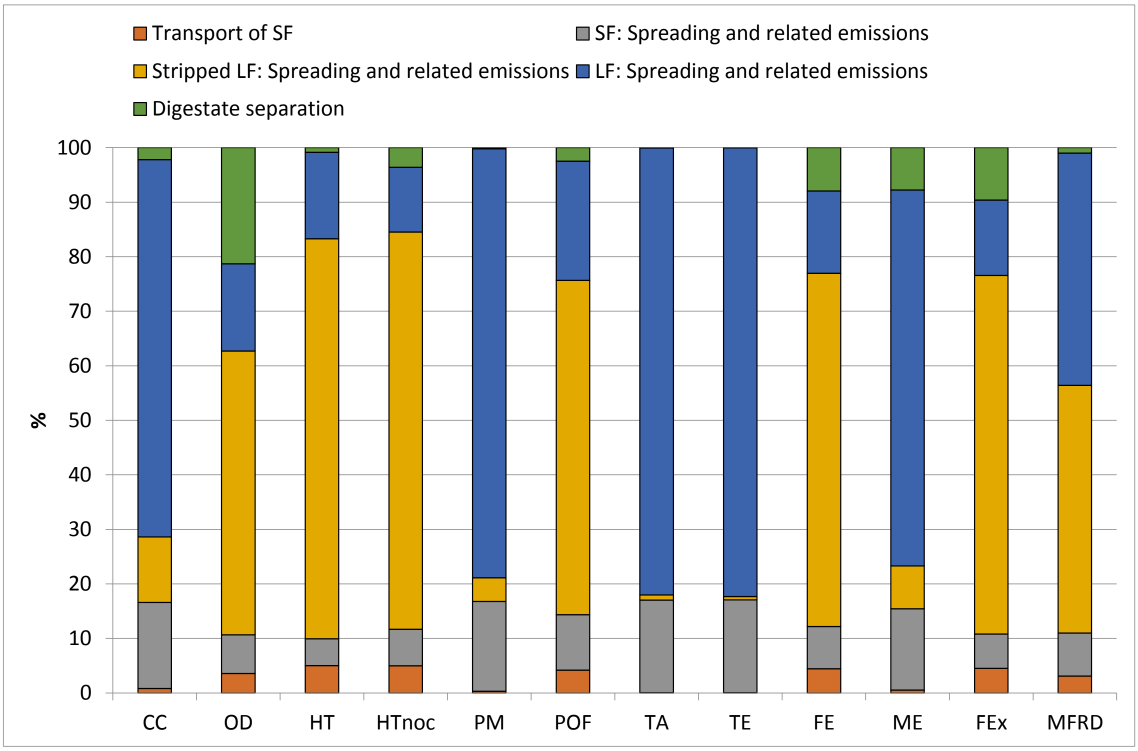

Figure 4 - Environmental hotspots identification for AS1

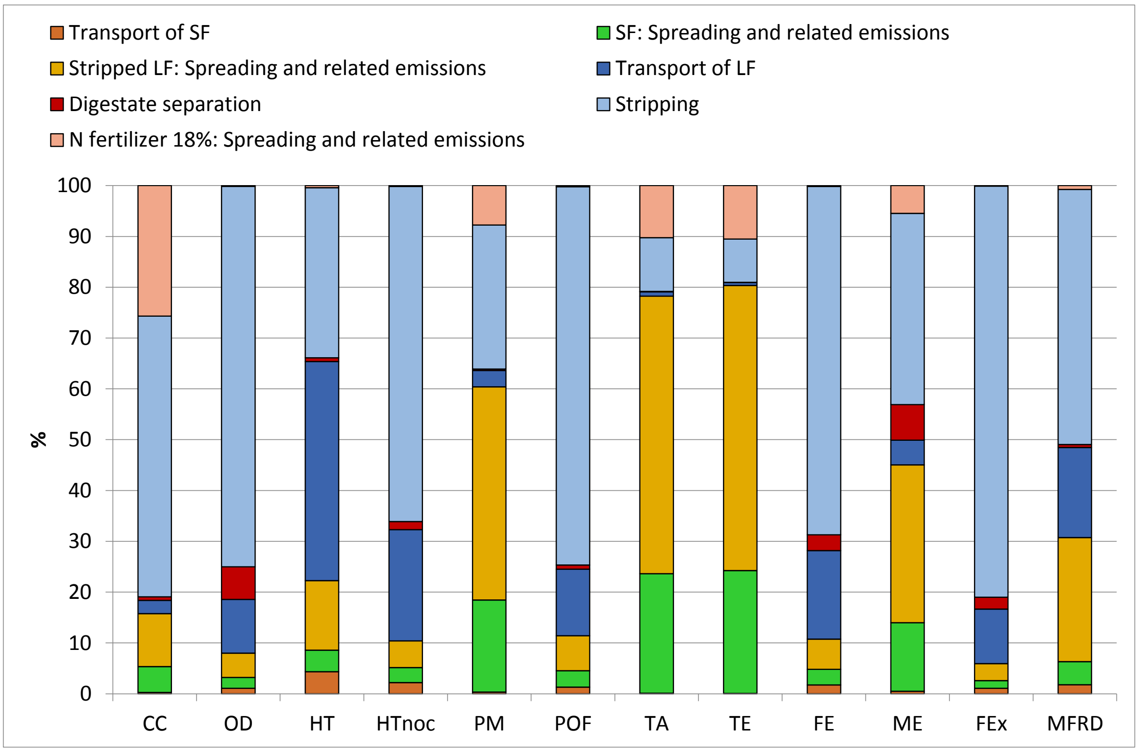

Figure 5 - Environmental hotspots identification for AS2

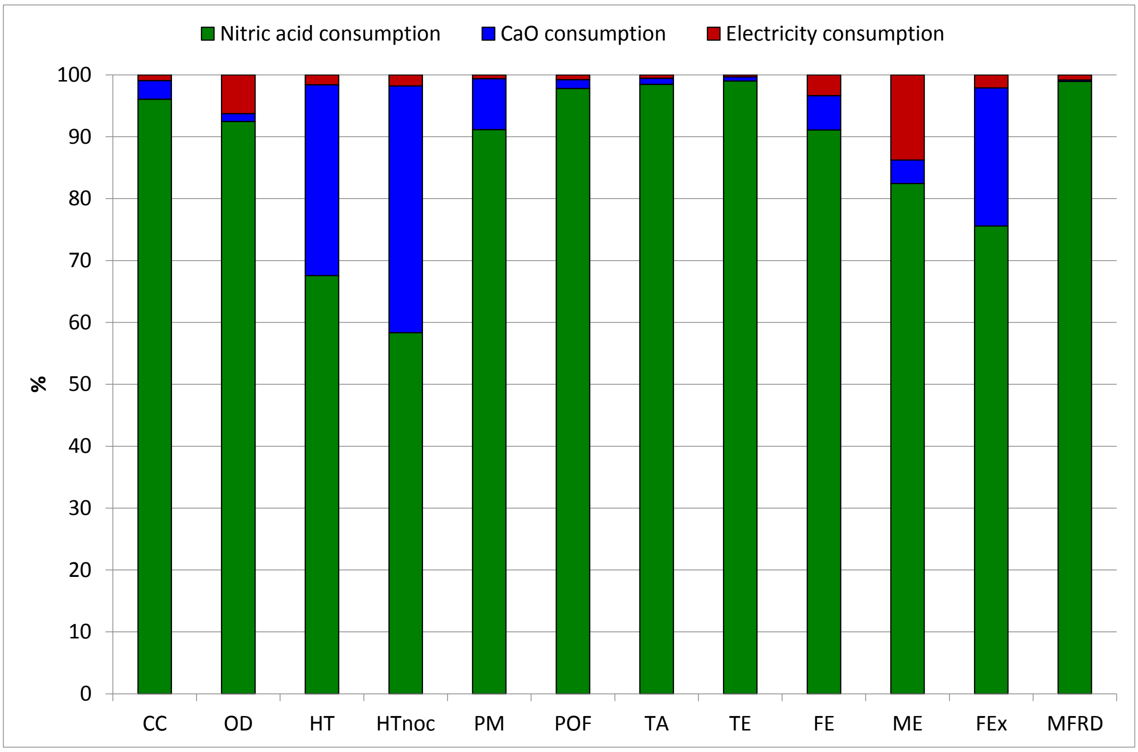

Figure 6 - Environmental hotspots identification for the stripping of LF

TRANSPORT IN THE DIFFERENT SCENARIOS

Figure 7 shows the comparison among the environmental impacts related to transport activities in the three evaluated scenarios. For this aspect, AS2 shows by far the best performances, while BS is, by far, the worst.

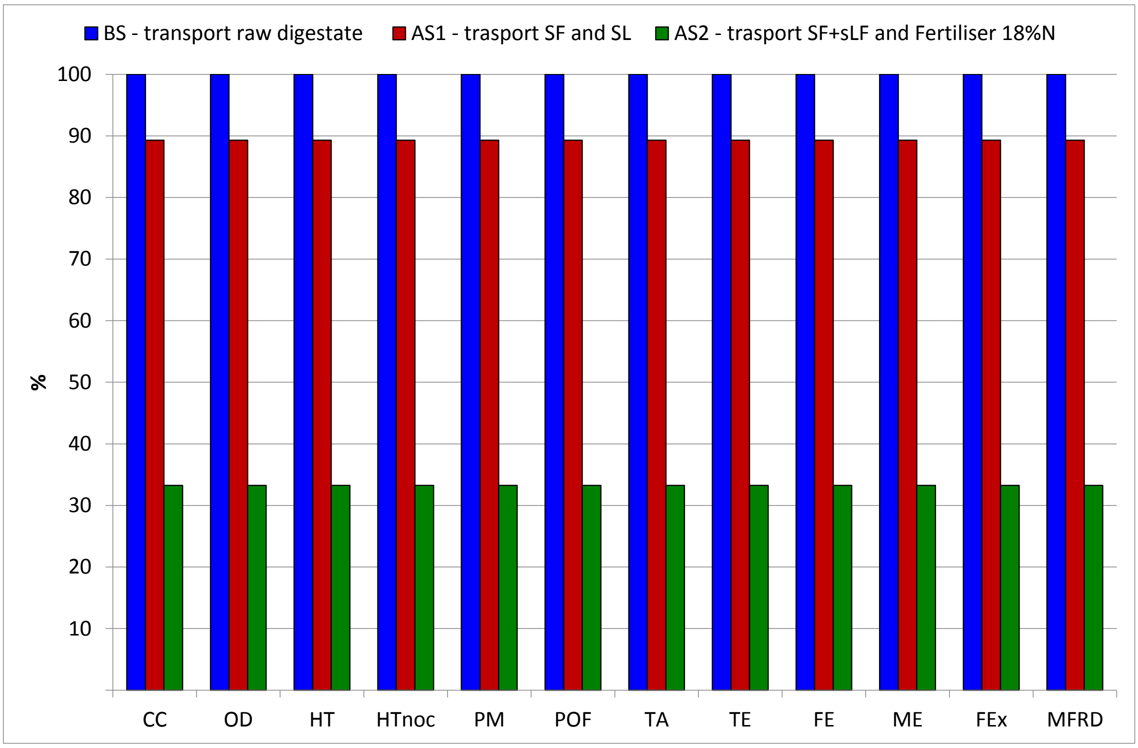

Figure 7 - Comparison among the impact related to transport in the three different scenarios

COMPARISON BETWEEN THE GREEN FERTILISER AND AMMONIUM NITRATE

Figure 8 shows the comparison, expressed per kg of Nitrogen, between the green fertiliser that is produced after the recovery of the ammonia produced during stripping and the ammonium nitrate. Except for ME, the green fertiliser shows a better environmental performance for all the evaluated impact categories. The impact reduction ranges between -2% and -53% for OD and MFRD (the impact categories mostly affected by the consumption of energy and fossil resources).

In **Table 6** are reported the absolute impacts.

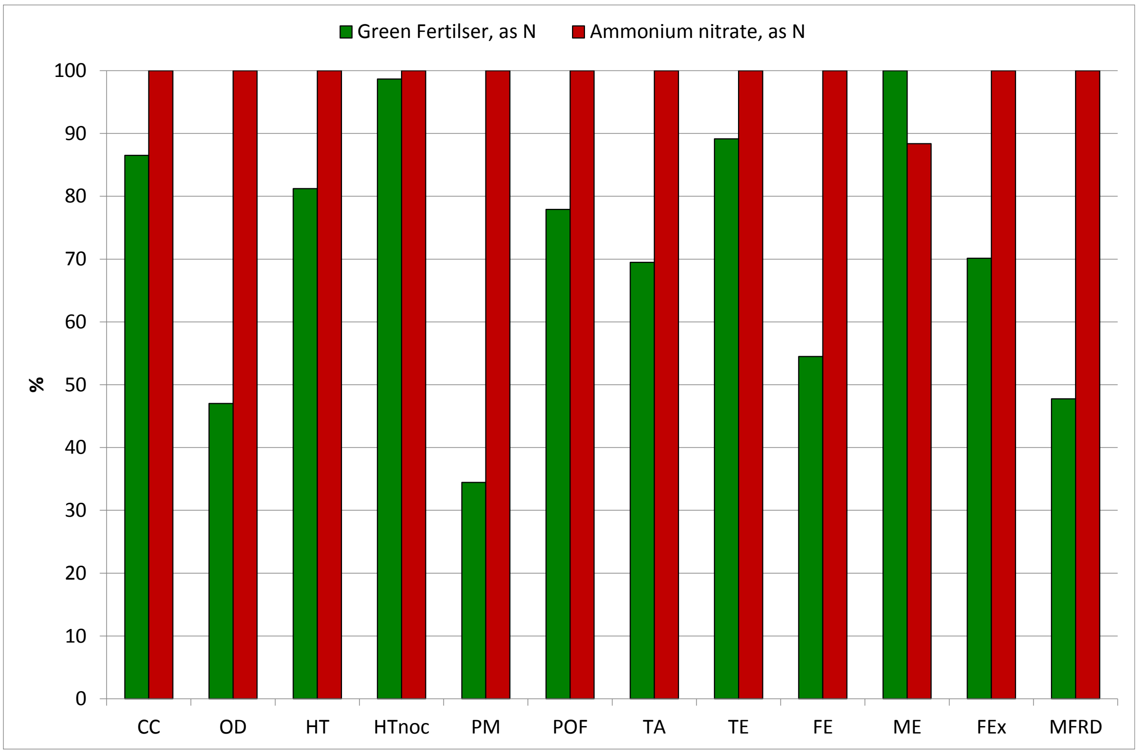

Figure 8 - Relative comparison: green fertiliser & ammonium nitrate

Table 6 - Environmental impact assessment for 1 kg of N in the green fertiliser

Impact category	Unit	Impact
CC	kg CO2 eq	7.90947
OD	kg CFC-11 eq	2.69E-07
HT	CTUh	8.78E-07
HTnoc	CTUh	1.43E-07
PM	kg PM2.5 eq	0.002499
POF	kg NMVOC eq	0.01515
TA	molc H+ eq	0.037074
TE	molc N eq	0.136667
FE	kg P eq	0.000354
ME	kg N eq	0.010251
FEx	CTUe	27.77082
MFRD	kg Sb eq	0.000139

DISCUSSION

The comparison among the different solutions for digestate management highlights how, respect to the BS where raw digestate is spread, the introduction of digestate separation and stripping involves an increase of the environmental impact for important environmental effects such as CC, OD and MFRD. For these impact categories, the reduction of the impact related to transport (see **Figure 7**) results completely offset by the consumption of electricity for digestate separation (in AS1 and AS2) and of HNO_3 and CaO for the stripping of the liquid fraction (only in AS2).

On the contrary, for the impact categories more affected by the emissions related to organic fertiliser application (e.g., TA, TE and, although with a lesser extent, ME), the scenario involving separation and stripping (AS2) achieves a considerable improvement respect to BS. This improvement is mainly due to the reduction of ammonia volatilisation during the fertiliser application:

1. In AS1, ammonia emission is reduced because liquid fraction penetrates quickly into the soil respect to raw digestate;
2. In AS2 for the quick penetration of LF but also because about 60% of the nitrogen content of LF (3 kg/t_{SL}) is removed during stripping and applied as green fertiliser.

Concerning the comparison between the produced green fertiliser and the most similar mineral nitrogen fertiliser (ammonium nitrate), the results are favourable for the first one and highlight how, despite the use of nitric acid, N recovery from the liquid fraction to produce the green fertiliser is associated with environmental benefits. This is due to the high energy consumption that is related to the production of mineral nitrogen fertilisers from atmospheric N_2.

COMPARISON CONSIDERING THE USEFUL NITROGEN FOR THE DIFFERENT SCENARIOS

Respect to BS and AS1, in which a total of 120,000 kg of “useful[1]” nitrogen are spread, in AS2, the amount of useful N is higher because half of the nitrogen content of the green fertiliser arises from the nitric acid used during ammonia stripping. To consider this extra nitrogen, a system expansion[2] approach can be adopted. In other words, the extra useful nitrogen displaces

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[1] “Useful” nitrogen = N applied x N efficiency; N efficiency = 100% in this study

[2] In the “system expansion approach”, the production of a co-product generates an environmental benefit for the production process under evaluation. This benefit is equal to the environmental impact related to the production of products that can be displaced by the co-product.

the production of nitrogen fertiliser and, consequently, the impact production of this amount of N fertiliser is subtracted to the global impact related to AS2.

With the system expansion approach the environmental performances of AS2 are dramatically improved (**Figure 9**). AS2 becomes the most environmental friendly solution for OD, HT, HTnoc, FE, ME, FEx and MFRD (for TA and TE it was already the best solution). In particular, for FE, ME and FEx, the absolute impact becomes negative and an environmental benefit is achieved.

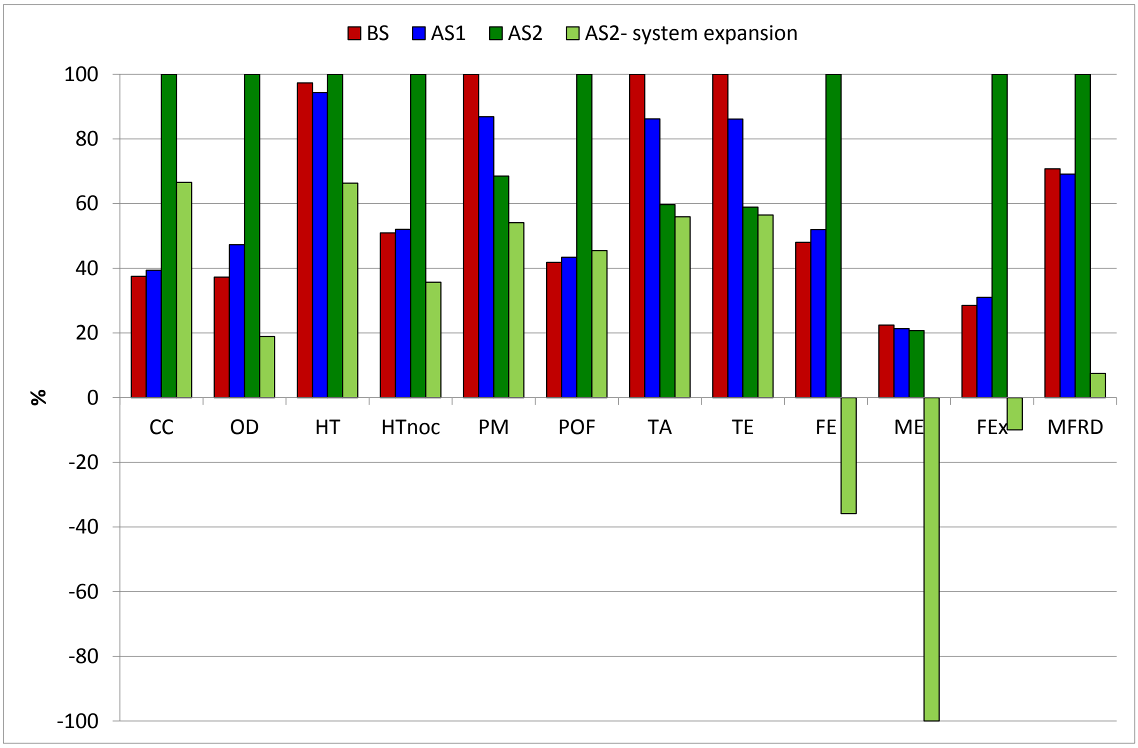

Figure 9 - Relative comparison among the different scenarios considering the system expansion in AS2 for the production of extra useful nitrogen

CONCLUSIONS

The environmental results of the different solutions for digestate management deeply depend on the assumptions and, in particular, on the considered system boundary. In fact, without the system expansion, the AS2 results the worst scenario for 8 of the 12 evaluated impact categories.

Future developments of the study should consider:

1. a different nitrogen efficiency for the fertilisers. In the evaluated scenarios, conservatively, the nitrogen efficiency was considered equal to 100%; in other words, all the nitrogen content of the fertiliser is available for the crop and the N content of raw digestate has the same effectiveness of the green feriliser. Considering (i) a lower efficiency for the N from raw digestate (e.g., 65%, according to De Vries et al., 2012a,b) and (ii) higher efficiency for the N in the liquid fraction (e.g., 75%-85% according to Bacenetti et al., 2016) and for the green fertiliser (100% being completely mineral nitrogen), the two alternative scenarios will take advantage of having a higher amount of useful nitrogen respect to BS. Respect to BS, for AS1 and AS2, this difference in terms of useful nitrogen could generate an environmental credit (equal to the impact arising from the production of mineral fertilisers that should be applied in BS to reach the same mass of available N);
2. an increase of transport distances considering shorter distances for the liquid fraction and longer ones for the solid fraction and for the green fertiliser;
3. a system boundary expansion that includes also the storage of raw digestate as well as of the different fractions before being spread as fertilisers. De Vries et al. (2012a,b) highlighted that storage emissions differ depending on how the digestate is stored. In more details, the storage of raw or liquid digestate potentially produces more methane and ammonia than the storage of the solid fraction (0.17 and 0.004 kg CH_4/t digestate, respectively). Instead, regarding nitrous oxide emissions, the storage of the raw or liquid digestate entails lower emissions compared with the solid fraction (0.001 and 0.02 kg N-N_2O/kg N digestate). To this purpose, detailed inventory data concerning the solutions (e.g., open or covered tanks), the climatic conditions during storage (e.g., temperature, wind, precipitation) and the storage duration are needed.

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