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ENERGY AND CO_2eq ANALYSIS OF THE AGRICULTURAL PHASE IN THE SUNFLOWER BIODIESEL CHAIN

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ABSTRACT The European Directive on renewable energies indicates the reference values on CO_2eq emissions for every phase of the biofuels chain. The paper reports the results of an LCA analysis focused on sunflower agricultural phase. In the studied cases, CO_2eq emissions due to the cultivation phase exceed the reference value indicated by the EU. The relevance of the allocation methods to spread out energy consumption and CO_2eq emissions among sunflower biodiesel and oilcake are highlighted. Allocation was made according to the principles of mass content, energy content and economic value of co-products. The CO_2eq reductions obtainable with the three methods are about 60%, 50% and 25%, respectively when compared to the "No allocation" case. These methods do not distinguish the different functionality of co-products in relation to their real use, although this issue is strongly recommended by the LCA methodology. For this reason the method of system expansion and allocation by substitution is also taken into account. The considered equivalent functions of oilcake are: animal feed (soybean meal), fuel (coal) and fertiliser. The results show that while the substitution with coal gives rise to an emission credit, the others allow only minor improvements. A sensitivity analysis stresses the importance of fossil fuels and fertilisers on energy depletion and CO_2eq emission. As a conclusion we can state that, within the constrains for CO_2eq emissions indicated by the EU, in Central Italy only a major revision of farm practices, aimed primarily at reducing the use of N-fertilizer, can allow the sunflower to be suitable for biodiesel.

Keywords: sunflower biodiesel, LCA, co-products allocation, oilcake, sustainability.

INTRODUCTION The decreasing stocks of petroleum, the problems related to climate changes and the continuous growth of energy needs for transport and electricity are determining an increasing interest in renewable biofuels and bioliquids from biomasses considered as a partial alternative to fossil sources (GBEP, 2007). Due to the different energy or environmental balances of bioenergy chains, several countries require minimum objectives to activate biofuel and bioliquid production chains admitted to receive public incentives (Van Dam et al., 2008). In this context, the recent EU decisions reported in Directive 2009/28/EC on Renewable Energy Sources (RES Directive) and the decision to delegate the definition of Plans for sustainable bioenergy chains to national level have opened interesting development perspectives focused on reaching the ambitious objective by 2020. The RES has, for the first time, included sustainability criteria for the evaluation of an agro-energy chain, indicating the requirements of GHG emission reduction for the entire production chain and also the specific GHG emission saving for cultivation of raw materials. The RES indicates that the analysis has to be focused on assessing the Global Warming Potential (GWP), which is a measurement of the global rise in temperature due to the increase of GHG in the atmosphere. The methodology applied was essentially that of LCA (Consoli et al, 1993) but this methodology, even if widely applied in various fields and regulated by specific rules (ISO 1997, 1998, 2000a, 2000b, 2006), is characterised by a wide margin of uncertainty (Gnansounou et al., 2009; Reap et al., 2008a; 2008b). When applied for GHG balance evaluation, the difference between the results obtained from various approaches is very high (Farrel et al., 2006), ascribing these differences in particular to the approach used for the evaluation of co-products (plant residues, oilcake, glycerine). Co-product evaluation could play a fundamental role in environmental impact calculation of the entire production chain, an aspect that has been clearly highlighted since the first experiences of LCA application (Wegener Sleeswijk et al., 1996; Heijungs et al., 1993). In addition, the RES reports detailed information on GHG emissions of the co-products that have to be carefully considered. In this regard, the RES decisions partially penalise the agricultural phase, because plant residues are suggested to be considered as cultivation waste and for this reason do not have to be considered for co-product evaluation.

The aim of this paper is to report and discuss the results of a sustainability analysis of a biodiesel chain’s agricultural phase based on High Oleic Sunflower cultivated in rotation with cereals in Central Italy (Tuscany) (Bonciarelli and Bonciarelli, 2001). Like all the oleaginous energy crops, sunflower can supply some additional benefits to the agro-ecosystems, such as biodiversity improvement, salinity mitigation and pest problem reduction, in addition to a carbon sink effect derived from soil incorporation of a part of the plant biomass (essentially crop residues and, if necessary, oilcake) that contributes to soil fertility and water permeability improvement (Lazzeri et al, 2009, Cherubini et al., 2009). In addition to the impact on climate change as required by the RES, the analysis considered the energy balance, following the approach of several other studies on biofuel chains (Wang, 2005; Elsayed et al., 2003; Shapouri et al., 2002). The oilcake obtained after mechanical oil extraction of sunflower seeds was considered as an agricultural co-product because this process can be carried out also at farm level.

MATERIALS AND METHODS

Sunflower cultivation and processing data The data regarding High Oleic Sunflower cultivation phase were obtained from the results of the S.I.En.A. - a biennial pilot project for the Integrated Development of renewable Energies from Agriculture, closed in 2008 (Mazzoncini, 2009). The first aim of this project was the activation of a local pilot biodiesel production chain and its utilization for public transport mixed in diesel oil at 25%. The data for the calculation of environmental balance came from two farms involved in the Project located in the Siena Province, Tuscany. Farm 1 and Farm 2 cultivated 53.48 ha and 31.25 ha of High Oleic Sunflower, respectively. Yields refer to a moisture content of 15%. The cultivation techniques (Table 1) were those commonly applied in Central Italy and sunflower was included in a sunflower-wheat-fallow rotation at Farm 1 and an alfalfa (four years)-wheat-tomato-sunflower-wheat-tobacco rotation at Farm 2.

Table 1. Sunflower cultivation techniques referring to 1 hectare.

Field operations	Technical means (FARM 1)	Technical means (FARM 2)
Trenching	60 kW wheel tractor + trencher	60 kW wheel tractor + trencher
Ploughing	120 kW caterpillar tractor + three-body plough	220 kW wheel tractor + ripper
Harrowing	60 kW wheel tractor + disc harrow	90 kW wheel tractor + disc harrow
Seed bed preparation	60 kW wheel tractor + tine harrow	60 kW wheel tractor + rotary harrow
Pre-plant fertilization	60 kW wheel tractor + fertilizer spreader + N-P fertilizer (11-25-0) 300 kg	60 kW wheel tractor + fertilizer spreader + diammonium phosphate (18-46-0) 200 kg
Sowing	60 kW wheel tractor + precision seed drill + seed 5 kg	60 kW wheel tractor + precision seed drill + seed 6 kg
Weed control	60 kW wheel tractor + boom sprayer + Global® 0.6 l	60 kW wheel tractor + boom sprayer + Goal® 1 l
Post-emergence fertilization	60 kW wheel tractor + steerage hoe + urea (46-0-0) 150 kg	60 kW wheel tractor + steerage hoe + ammonium nitrate (26-0-0) 150 kg
Combine harvesting	Combine harvester 140 kW	Combine harvester 140 kW

The harvested seed was characterized by an oil content of 52% on dry matter (DM). For mechanical oil extraction a loss of around 2% (Oil World, 2005) was considered, with an extraction yield of 75% (Scrosta, 2008). Trans-esterification efficiency was considered at 94% (personal communication, Fox Petroli).

Life Cycle Impact Assessment specifications

Impact categories Following the indications of the RES Directive, the analyses were focused on the Global Warming Potential (GWP) evaluation. The greenhouse gases (GHG) considered were carbon dioxide (CO_2), methane (CH_4) and nitrogen protoxide (N_2O) whose effect on GWP is reported as the amount of CO_2 equivalent (CO_2eq) through the following coefficients: 1 for CO_2, 23 for CH_4 and 296 for N_2O (IPCC, 2001). The consumption of energy resources (Energy Depletion - ED) was also evaluated, reported as MJ of fossil energy needed by the agricultural process.

Functional unit "The functional unit is a measurement of output performance of the production chain" (ISO, 1997). Its main aim is to give a reference to normalize the inputs and outputs of the process and to make the comparison of similar processes easier (Consoli et al., 1993).

This paper considers three different functional units to which the impacts refer:

- the surface of 1 hectare cultivated per year. This is the most common reference in agriculture to evaluate the input applications and the output performances. In addition, the cultivated hectare of land presents a double functionality: it is both an environmental resource (input system) and an agricultural product (output) relating to its role in environmental protection (Spugnoli et al., 2009);
- 1 kg of grain (dry matter, DM). This represents the functional unit from the farmers' point of view. The production and surface units are widely applied in agricultural LCA (Wegener Sleeswijk et al., 1996; Heijungs et al., 1993);

- 1MJ of biodiesel. This is a functional unit related to the entire bioenergy chain. Following the RES Directive (annex V) and several biofuel studies (Elsayed et al., 2003; Shapouri et al., 2002), this is the main functional unit adopted in the GHG emissions assessment in this paper.

<u>Process boundaries and reference system</u> The process boundaries were fixed at the farm gates. Supposing that the farms have an extraction plant inside, the principal output product is sunflower pure vegetable oil. To evaluate the performance of the examined process, a reference system - i.e. reference values - is needed. The present study considers only the agricultural phase of the biofuel chain and for this reason GWP is compared with the standard emission values adopted in the RES directive for sunflower cultivation: 18 g CO_2eq MJ^{-1}**.** As for the mechanical extraction step of crude vegetable oil, the Directive does not give a reference value, merely indicating the total value of the entire processing phase (oil extraction plus esterification), which amounts to 22 g CO_2eq MJ^{-1} biodiesel. In this study the impact of the extraction step was taken from the assessments of sustainability of the PROBIO Project (Riva et al., 2006), assuming a value of 0.033 MJ MJ^{-1} biodiesel for the consumption of fossil energy and a value of 6.25 g CO_2eq MJ^{-1} biodiesel for GWP.

<u>Impact factors</u> Energy balance and GHG emission assessment were supported by software for the evaluation of agro-energy chains sustainability (So.Fi.A. 3.1 version T), based on Excel® calculation sheets. In the calculation procedure the following process inputs (production factors) were considered: machinery, chemical fertilizers, pesticides, seeds, energy vectors, labor. Primary energy consumption and GHG emission values per input unit at farm gate (production and transport) were taken from "Harmonisation of environmental Life Cycle Analysis assessment for agriculture" (Audsley et al., 1997). Regarding labor, the value of energy cost was taken from Spugnoli and Zoli (1985). Following the indications of the IPCC (IPCC, 2006), the N_2O emissions due to the use of nitrogen fertilizers and the degradation of crop residues were also considered for the calculation of CO_2eq. In both cases the calculation of CO_2eq is obtained by multiplying the nitrogen content by a factor of 4.65. As for N-fertilizers this factor is already included in the value reported in Table 2. Although Annex V of Dir 2009/28/EC excludes from the assessment the emissions associated with the production of agricultural machinery, they were considered in this study, with the purpose of evaluating their importance. The assumed impacts for every unit of process inputs are reported in Table 2.

Table 2. Input taken into account during sunflower cultivation and related impact parameters.

Input categories	Inputs	Unit	Energy MJ/unit	CO_2eq kg/unit
Farm machinery - Tractors	Wheel tractor with roll bar 40-60 kW	h	46.39	3.04
	Wheel tractor with cab 40-60 kW	h	49.71	3.26
	Caterpillar tractor 80-100 kW	h	56.49	3.71
	Wheel tractor 220kW	h	74.05	4.89
Farm machinery - Tillage	Ripper	h	29.47	2.00
	Three-body plough	h	83.51	5.68
	Tine harrow	h	29.47	2.00
	Disc harrow	h	19.65	1.34
	Rotary harrow	h	29.47	2.00

	Trencher	h	27.02	1.84
	Steerage hoe	h	24.56	1.67
Farm machinery - Fertilization/Sowing	Fertilizer spreader	h	24.27	1.67
	Precision seed drill	h	46.71	3.21
Farm machinery – Weed control	Boom sprayer	h	13.65	0.94
Farm machinery - Harvest	Combine harvester 120-160 kW	h	281.83	18.78
Simple nitrogen fertilizers	Nitrogen from residues	kg	-	4.65
	Urea (46-0-0)	kg	31.62	1.33
	Ammonium nitrate (26-0-0)	kg	12.75	1.59
Complex fertilizers	N-P fertilizer (11-25-0)	kg	8.36	0.49
	Diammonium phosphate (18-46-0)	kg	15.26	1.72
Pesticides	Global® (oxifluorfen 22%)*	l c. p.†	75.57	3.41
	Goal® (oxifluorfen 41%)*	l c. p.†	140.83	6.35
Seeds	Sunflower seed	kg	6.93	0.50
Fuels	Agricultural diesel	kg	46.87	3.60
Labor	Unskilled worker	h	7.30	-

* This is considered equivalent to isoproturon
† c. p. = commercial product

It is important to point out that the choice of coefficients applied to calculate energy balance and GHG released during input production is one of the main causes of result variability (Reap et al., 2008b). The coefficients reported in Audsley et al. (1997), perhaps not the latest but widely shared, were therefore applied in this study.

Allocation methods The allocation procedure of co-products, which makes it possible to divide the environmental burdens in a multi-output process, is one of the weak points in biofuel LCA (Gnansounou et al., 2009; Reap et al., 2008a). According to ISO 14041 (ISO 1998, 2006), allocation should be avoided, where possible. Where allocation cannot be avoided and no relationship between inputs and outputs can be established, impacts should be partitioned proportionally to mass basis, energy content or market value of co-products (Ekvall and Finnveden 2001; Wegener Sleeswijk et al., 1996). In this study, aiming to stress the influence of allocation procedures, various procedures were applied to allocate the sunflower oilcake co-product: a) system boundaries expansion applying the substitution method, regarding the use of oilcake as animal feed (indicated as S-1), as solid fuel in substitution of coal (S-2), and as fertilizer (S-3); b) allocation proportional to mass (indicated as A-1), energy content (A-2) and co-product market value (A-3).

<u>Substitution method</u> This is based on the assessment of “avoided impacts” (Azapagic and Clift, 1999). It consists in identifying the product that a co-product of the system can replace (what and how much) and evaluating the effects in terms of impacts avoided as a result of such replacement. In S-1, 1 kg of sunflower oilcake substitutes 0.45 kg of soybean meal (44% protein) imported from Argentina. The equivalence is related to protein content (Riva et al., 2006). The avoided impacts of 1 kg of soybean meal were obtained from Dalgaard et al. (2008). In S-2, 1 kg of sunflower oilcake substitutes 0.70 kg of coal. The equivalence is related to the Lower Heating Value (LHV) of oilcake and coal, 21.21 MJ kg^{-1} (Scrosta, 2008) and 28.04 MJ kg^{-1} (Styles and Jones, 2007) respectively. In S-3, oilcake is used as a fertilizer. The substitution was based on the contents of N and P in 1 kg of sunflower oilcake, equal to 0.05 kg N and 0.008 kg P (Lazzeri et al., 2009).

In S-1, soybean meal substitution implies a reduction of its production and consequently a reduction in soybean oil, which must also be substituted. Considering that soybean oil, like sunflower oil, is used for energy purposes, it is possible to assume an increase of the same amount in sunflower oil production. In theory, this increase implies a corresponding increase in oilcake production, causing an endless iterative loop. In practice, stopping at the second iteration is considered satisfactory, as done in this study. In the S-2 substitution system it was assumed that coal replacement only resulted in a reduction of coal extraction; the corresponding impact reduction was therefore considered. As in S-2, in S-3 it was assumed that the only consequence of the use of oilcake as a fertilizer is a correspondent reduction of fertilizer production and of the related impacts.

Proportional allocation method The allocation in relation to the mass of co-products (A-1) considers a loss of 2% during farm oil extraction; 39% of this mass is oil and 61% oilcake. Energy allocation (A-2) is the main allocation procedure applied in biofuel studies, for example by the USDA (Shapouri et al., 2002) or the Argonne National Laboratory (Wang, 2005). This is also the procedure indicated in the RES directive. The allocation was based on energy content of sunflower oil and oilcake assumed equal to 37.07 and 21.21 MJ kg^{-1}, respectively (Scrosta, 2008). In economic value allocation (A-3), the allocation is made in proportion to the market price (Wang, 2005; Shapouri et al., 2002). The sunflower pure oil and oilcake economic values used in this study are average market prices reported in Italian statistics for 2007: 0.736 € kg^{-1} (Camera di Commercio di Verona, 2007) and 0.172 € kg^{-1} (Camera di Commercio di Treviso, 2007) respectively.

RESULTS AND DISCUSSION

Impacts of the agricultural phase The ED and GWP specific values referring to the functional units (1 ha area, 1 kg grain, 1MJ biodiesel) together with grain and biodiesel yield are reported in Table 3. The results show that the performance of Farm 1 is clearly the worst. That is because Farm 1 not only has a lower yield but also higher inputs. However, in both cases the GWP impact referring to 1 MJ of biodiesel goes well beyond the reference limit considered in this study (24.25 g CO_2eq MJ^{-1}). In the best case, the GWP of the agricultural phase was 50.62 g CO_2eq MJ^{-1}. This value was calculated allocating the whole GWP impact to biodiesel, without considering the co-products use, and it considered both sunflower cultivation and oil extraction phases.

Table 3. Farm yields and impacts considering only the main product.

Impacts	Unit	FARM 1	FARM 2
Grain yield (DM)	kg ha^{-1}	1700	1998
Biodiesel yield	kg ha^{-1}	623	732
ED/S	MJ ha^{-1}	15270	12889
ED/P – Grain (DM)	MJ kg^{-1}	8.98	6.45
ED/P - Biodiesel	MJ MJ^{-1}	0.66	0.48
GWP/S	kg CO_2eq ha^{-1}	1593	1372
GWP/P –Grain (DM)	kg CO_2eq kg^{-1}	0.94	0.69
GWP/P - Biodiesel	g CO_2eq MJ^{-1}	69.07	50.62

The impacts of the different production factors on the ED and GWP of the sunflower cultivation phase are reported in Table 4. The column “Other” comprises labor, seed and pesticides. The low requirement of pesticides in sunflower cultivation determines a low incidence on GWP for this parameter, even though pesticides have to be considered with great attention due to their generally high impact.

Table 4. Effect of production factors on ED and GWP of the sunflower cultivation phase. Data refer to the functional unit of 1 hectare of land.

	Impacts	Machinery		Fuels		Fertilizers		Other		TOTAL
FARM 1	ED (MJ)	812.9	5.6%	6320.9	43.5%	7251.2	49.9%	138.8	1.0%	14523.7
	GWP (g CO_2eq)	54.2	3.7%	485.8	33.5%	906.3	62.4%	5.1	0.3%	1451.5
FARM 2	ED (MJ)	665.6	5.5%	6155.0	51.2%	4964.9	41.3%	226.6	1.9%	12012.1
	GWP (g CO_2eq)	44.3	3.7%	473.1	39.2%	678.7	56.3%	9.4	0.8%	1205.5

It has to be emphasized that while fuels and fertilizers contributed similarly to the energy costs in ED calculation, fertilizers had a greater impact than fuels in GWP calculation. The majority of fertilizer emissions is due to nitrogen emissions, representing 89% for Farm 1 and 82% for Farm 2 of the total emission of fertilizers. This result is not surprising considering that, in addition to production emissions, nitrogen fertilizers are also responsible for the direct emissions of N_2O after distribution in open field, estimated by IPCC methodology (IPCC, 2006) at 4.65 kg CO_2eq (kg N)$^{-1}$. A sensitivity analysis shows that total in-field emissions of N_2O (which also include the nitrogen present in crop residues) represent an important part of the total GHGs released during the sunflower cultivation phase (39% of the total for Farm 1 and 37% for Farm 2).

Effects of allocation methods The results of allocation methods considering sunflower oilcake as a co-product as well as the main product (biodiesel) are reported in Table 5. The three methods of substitution concern the use of oilcake as animal feed (S-1), as fuel (S-2) and as fertilizer (S-3). Allocation is made based on: A-1 mass, A-2 energy content and A-3 economic value. The results are compared with the values of the "No allocation" case, which is without shared-out impacts. The data reported in Table 5 are calculated excluding the impacts of agricultural machinery production, as indicated in the RES Directive.

Table 5. Results of different allocation methods on ED and GWP. Data refer to the functional unit of 1 MJ of biodiesel. The GWP reduction is evaluated with respect to the "No allocation" case.

Allocation methods	FARM 1			FARM 2		
	ED MJ	GWP g CO_2eq	GWP reduction %	ED MJ	GWP g CO_2eq	GWP reduction %
No allocation	0.63	66.72	-	0.45	48.96	-
S-1	0.50	59.80	10	0.29	38.93	20
S-2	-0.78	-25.49	138	-0.96	-43.16	188
S-3	0.46	58.83	12	0.29	41.49	15
A-1	0.25	26.55	60	0.18	19.49	60
A-2	0.32	33.57	50	0.23	24.62	50
A-3	0.47	49.74	25	0.34	36.52	25

Substitution as animal feed did not determine significant benefits in environmental balance. This result is due to the low emissions of 1kg of soybean meal, equal to 0.721 kg CO_2eq (Dalgaard et al., 2008), produced in Argentina, where soybean is generally cultivated extensively with low input cultivation techniques. Moreover, the main reason for such a result is the low substitution ratio considering the same protein content: 1 kg of sunflower oilcake substitutes only 0.45 kg of soybean meal. The substitution method that gave the best results among the considered alternatives was the substitution of oilcake as fossil fuel, in agreement with other studies (Gnansounou et al., 2009). The substitution with coal determined an emission credit in both farms. The results were particularly positive because oilcake is characterized by a high LHV (21.21 MJ kg^{-1}), due to the considerable content of residual oil. In addition, coal has a relatively high impact on GWP, equal to 2.75 kg CO_2eq kg^{-1} (Styles and Jones, 2007). The S-3 method (substitution as fertilizer) gave the worst results for Farm 2. This result was due to the low content of fertilising elements (5% of N and 0.8% P). On the other hand, the nitrogen in oilcake can replace an equal amount of chemical fertilizer distributed to the subsequent rotation crop in pre-plant fertilization (Zaccardelli et al., 2009), reducing the chemical inputs during cultivation. The replaced N-fertilizer is characterized by relatively high GHG production emissions, equal to 2.90 kg CO_2eq $(kg\ N)^{-1}$ (Audsley et al., 1997). It must also be considered that this substitution hypothesis did not take into account the carbon that is incorporated year after year as organic matter in the soil and that could be stored in part as stable carbon, improving soil fertility and structure.

Among the allocation methods, A-1 (allocation on mass basis) was the most advantageous while the allocation on economic value basis (A-3) permitted a low reduction of GWP impact. This result was partially due to the low oilcake price (0.172 € kg^{-1}) that reflects the lack of co-product exploitation. Finally, the allocation method on energy content basis (A-2) permitted a significant GWP impact reduction (Table 5) but not sufficient to satisfy the reference value adopted in the present study (24.25 g CO_2eq MJ^{-1}), even if for Farm 2 the result is very close. Considering that this allocation method was the one adopted in the RES Directive, the minimum yield per hectare of sunflower that could make it possible to satisfy the limit value assumed for the agricultural phase was calculated. The results showed that the grain yield should be 2367 and 2041 kg DM ha^{-1}, i.e. a 39% higher yield for Farm 1 and only 2% higher for Farm 2.

Among the allocation methods evaluated, only the substitution of oilcake as coal (S-2) satisfied the limit assumed for the agricultural phase in Farm 1. For Farm 2, the limit was satisfied also by A-1 while the impact on GWP is only 2%higher in the method A-2.

CONCLUSIONS The results show that the ED and GWP impacts are quite high in both farms. For GWP impact the respect of the default value for sunflower biodiesel cultivation phase (18g CO_2eq MJ^{-1}) is impossible if the oilcake use is not taken into account. Fossil energy consumption and CO_2eq emission restraint are limited by the high input required for sunflower cultivation. Another reason for such a low performance is that the exploited biomass represents only a small portion of the plant (sunflower oil is 10% of the total DM biomass). However, oleaginous crops can contribute to the improvement of soil fertility when included in crop rotations. The advantage in terms of carbon stocking when the oilcake is used as fertilizer should also be considered. The enrichment of the soil organic matter is a key aspect of soil management in Italy where there is a serious lack of organic matter. Taking the C content in oilcake (and also in crop residues) into account could positively modify the CO_2eq balance. Further evaluations on this topic are being carried out by our research group. In short, low input techniques and virtuous co-product exploitation are fundamental goals in achieving environmental sustainability of biofuel chain. As a conclusion, we can state that, within the constraints for CO_2eq emissions indicated by the EU, in Central Italy only a major revision of farm practices, aimed primarily at reducing the use of N-fertilizer, can allow the sunflower to be suitable for biodiesel production.

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