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The role of co-products in biorefinery sustainability: energy allocation *versus* substitution method in rapeseed and carinata biodiesel chains

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ABSTRACT

The paper analyzes biodiesel chains of rapeseed (*Brassica napus*) and carinata (*Brassica carinata*) cultivated in Central and Southern Italy, assessing the impact on Global Warming Potential by means of the Life Cycle Assessment methodology. The production chains differed in use of the oilcake, as animal feed for rapeseed and as biofumigant for *B. carinata*. The allocation of emissions across co-products was first calculated on the basis of their energy content according to the criterion proposed by European Commission for biofuel production. The resulting impacts were then compared to those obtained through the substitution approach (system expansion method), which considers emissions that are saved by replacing the equivalent conventional product with co-product bio-based materials i.e. soybean meals, nematicidal fumigants, fertilizers and glycerol. The results showed that this method is sensitive to pointing out the importance of the valorization of co-products to the sustainability of bioenergy supply chain. Among the different options taken into consideration, in the case of the *B. carinata* biodiesel chain, the substitution of conventional fumigants and fertilizers with biofumigants and amendments is able to determine a global net saving of 134 g CO_2eq per MJ of biodiesel, reversing the sustainability assessment obtained through the energy allocation method. Overall, the results suggest that, when planning future biorefineries, environmental assessment should take the substitution approach into account in order for valorization of co-products and diversification of processes to be rewarded.

1. Introduction

Environmental assessment is a key issue in the definition of strategies for sustainable biorefineries integrated into the territory (Luguel, 2011; Sandèn and Petterson, 2013; Kajaste, 2014). The first chain which demanded a definition of harmonized sustainability criteria was that of biofuel. Despite several studies (Chiaramonti and Recchia, 2010; Fahd et al., 2012; Menten et al., 2013; Ekman et al., 2013), the official methodology for environmental assessment of the biofuel chain is still focused on the main stream with poor valorization of different by-products. In Directive 2009/28/EC (Renewable Energy Directive, RED), the European Community, in fact, indicated that by 2020 every Member State must use sustainable fuels derived from renewable sources in 10% in the transport sector. The RED defined sustainability criteria based on the impact of Global Warming Potential (GWP) owing to Greenhouse Gas (GHG) emissions, by comparing biofuel emissions to those derived from fossil fuels, with the aim of avoiding carbon stock depletion and consequential increase of global warming. The GHG emission saving (calculated according to RED) deriving from the use of biofuels and bioliquids taken into account for: (i) compliance with the requirement concerning national targets, (ii) energy obligations and (iii) eligibility for financial support must be at least 35% (increasing at 50% since 2017 and 60% since 2018).

In this context, the production of biofuel from dedicated crops in the biodiesel chain is strongly penalized by the high emissions of GHG in the agricultural phase (COM, 2010), mainly due to the production and use of diesel and nitrogen (N) fertilization (Buratti et al., 2012). The high environmental costs of the agricultural phase

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make it impossible in several cases to satisfy the RED requirements in terms of GHG reduction (Spugnoli et al., 2012). Nevertheless, the use of oleaginous crops for biodiesel could fulfill the agricultural policy's priority in crop diversification (e.g. "greening" in 2014–2020 CAP reform) by breaking away from cereal monoculture, particularly in the Mediterranean Region. For oleaginous crops, apart from the evaluation of emission saving from soil carbon accumulation via improved agricultural management, the valorization of co-products (i.e. defatted oilseed meals and glycerol) is the main way to reduce the GHG emissions related to the biodiesel production chain.

This paper aims to explain how the valorization of co-products within a fair biorefinery approach can overturn the sustainability assessment of a supply chain. A fair biorefinery approach, in fact, concerns the production of a main product through the valorization of a co-product with the aim of minimizing or avoiding waste production, within a sphere of circular economy (Mirabella et al., 2014). To this purpose a well-established impact calculation methodology, i.e. the GWP of the biodiesel production based on energy allocation of co-products, according to RED, was compared with the method of system expansion. This method is based on the identification of the conventional products to be substituted (actual use and related amounts) by co-products, and on the evaluation of the impacts that are avoided as a consequence of their substitution (Azapagic and Clift, 1999). This methodology can be also applied to other bio-based co-products in an integrated biorefinery framework, starting from oil-based products that share defatted seed meals, such as biolubricants, lipochemicals or cosmetics.

More specifically, with the two methods, this paper estimates the GWP impact produced by a biodiesel chain based on rapeseed (*Brassica napus* L.) and on carinata (*Brassica carinata* A. Brown, Ethiopian mustard), cultivated in Central and Southern Italy. It would seem possible to generalize the results of the cultivation trials to the Mediterranean Region by virtue of the relatively high number of (i) different open field tests (ii) different climatic conditions, (iii) different years and (iv) different cultivation techniques.

2. Assessment methodology

2.1. Inventory flows

The environmental impact assessment was focused on GWP following the RED requirements for sustainable biofuel: (i) carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) effects were expressed as CO_2 equivalents using the following characterization factors: $CO_2 = 1$, $CH_4 = 23$ and $N_2O = 296$; (ii) the functional unit to which the system impacts referred was as usual the energy unit contained in the biodiesel (one MJ of biodiesel); (iii) the biodiesel chain was considered as formed by four subsystems (or phases): cultivation, oil extraction and refining, esterification, transport and distribution. The values of conversion factors expressing the GHG emission of each production factor unit (namely fertilizers, pesticides, seeds, diesel for the cultivation phase, and electricity for oil extraction) were taken from the JEC E3 database, as suggested by the European harmonized calculations of biofuel (BioGrace, 2014). The N_2O emissions from fertilizer management and degradation of crop residues were taken into account following IPCC (2006). The use of values agreed at international level made it possible to reduce one of the main sources of variability of the LCA results (Reap et al., 2008b) and to potentially reach biofuel sustainability certification. The GHG impact values of the other phases of the analyzed biodiesel chains, relating to oil refining, esterification, transport and distribution, were taken at the default values adopted in the RED because these processes are quite standard. On the contrary, for the cultivation and oil extraction phases, technique, technology and product characteristics are specific and their impact was evaluated by measured experimental data. Chain emission was computed by the software So.Fi.A., developed by CRA-CIN and GESAAF (D'Avino et al., 2011a, 2011b).

2.2. System description

Cultivation impact strongly depends on site-specific crop management and yields. The cultivation data were obtained from 22 open field cultivation trials (11 rapeseed trials and 11 carinata trials), carried out in Tuscany, Sardinia, Apulia and Sicily (Italy) on a minimum surface of one hectare in different years (from 2006 to 2010), within the context of the Italian national project "Bioenergie – Filiera oleaginose" (D'Andrea, 2011). The rapeseed and carinata cultivation techniques can be considered as representative of their cultivation techniques under Mediterranean conditions. For each rapeseed trial a corresponding carinata trial was carried out in the same year and in the same site. The measured inputs, yields and product characterization values are reported in Table 1 as median values and range between higher and lower values.

The experimental results are expressed by median and range values because arithmetic means and standard deviation were considered unsuitable due to non-symmetric probability distribution of the inputs and outputs of each trial. Indeed, for example, during all the 22 cultivation trials, farmers did not normally use K_2O fertilization except in one rapeseed field, where 40 kg ha^{-1} were applied following a specific potassium deficiency; so, in this case means and standard deviation (3.6 ± 12.1) made no sense, whereas median and range values reported in Table 1 were representative of average – and realistic – cultivation technique.

Epigeal and hypogeal biomass per hectare was estimated in three randomized subplots of 0.25 m^2, uprooting plants and cutting at root collar evaluating epigeal biomass after seed removal. N content in residues was estimated in each subplot by the Kjeldahl method. Water, oil and glucosinolate contents in seeds were determined (i) by drying in the oven for 24 h at 105 °C, (ii) by the Soxhlet method and (iii) by following the procedure reported in Lazzeri et al. (2011), respectively. Thereby, for each input, GHG emissions were calculated, added and total GHG emissions for each trial were associated to the corresponding seed yields.

Oil extraction was performed by a pressing plant (two extractions), with a nominal power of 18 kW, a working time of 900 h $year^{-1}$ and a capacity of 160 kg of seeds h^{-1}. The residual oil content in the press cake was 10.1%, confirming that 83% of the total

Table 1
Cultivation inputs and yields together with yield characterization values of 11 rapeseed and 11 corresponding carinata crops carried out in Tuscany, Sardinia, Apulia and Sicily in different cropping years. Inputs and yields were reported as median and range values between trials.

Cultivation data	Unit	Rapeseed	Carinata
Input			
Seeds	kg ha^{-1}	6 (4–10)	9 (6–11)
Pesticide active ingredient	kg ha^{-1}	1 (0–1)	1 (0–1)
Diesel	L ha^{-1}	85 (41–152)	83 (41–152)
N fertilizer	kg ha^{-1}	49 (27–137)	52 (48–165)
P_2O_5 fertilizer	kg ha^{-1}	55 (0–115)	40 (0–115)
K_2O fertilizer	kg ha^{-1}	0 (0–40)	0
DM yields			
Seed yield	10^2 kg ha^{-1}	17 (12–33)	22 (10–39)
Epigeal biomass	10^2 kg ha^{-1}	49 (33–95)	80 (37–108)
Hypogeal biomass	10^2 kg ha^{-1}	7 (7–14)	12 (7–16)
Yield characterization			
Seed glucosinolates	μmol g^{-1}	15 (8–23)	87 (72–107)
DM seed oil	% (w/w)	47 (39–49)	40 (34–45)
DM crop residue nitrogen	g kg^{-1}	5 (4–6)	4 (4–6)

DM, dry matter.