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Life cycle assessment of *Brassica carinata* biomass conversion to bioenergy and platform chemicals

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A R T I C L E I N F O

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A B S T R A C T

The extraction, supply and use of fossil energy carriers and chemicals is a day-by-day increasingly critical issue, linked as it is to severe damages to environment and human health, not to talk of the shrinking availability of fossil fuels worldwide. Therefore, research on suitable alternatives to the extensive use of fossil-based fuels and chemicals is crucial: the potential of *Brassica carinata*, a non-food oil crop, to grow on marginal lands in Campania Region was investigated, focusing on the production of biodiesel from seeds and platform chemicals from agricultural and extraction residues via an innovative conversion route (so-called Biofine process) in a local industry.

The aim of this paper is to evaluate the performance of such an agro-industrial system for biodiesel and bio-chemicals. A comparison with an equivalent system only producing biodiesel and thermal energy is also carried out. A Life Cycle Assessment (LCA) is performed by means of commercial LCA software (Simapro 7.3.0), investigating energy requirements and environmental impacts (global warming, acidification, abiotic depletion, human toxicity, eutrophication and photochemical oxidation). Results show that, in spite of claims of biomass-based "greenness", both systems still rely on large fractions of non-renewable energy sources (around 90% of the total use) and mostly affect the same impact categories (abiotic depletion and global warming). The agricultural phase contributes to the total impact more than the industrial extraction and conversion steps, being the nitrogen fertilizers responsible for most of impacts of both systems. However, the conversion of lignocellulosic residues into chemicals instead of heat, conserves the structural quality of natural polymers in the form of marketable value added products (ethyl levulinate and formic acid), also translating into large energy savings compared to traditional chemical routes.

1. Introduction

The supply of heat and liquid fuels, on the one hand, and of chemicals and materials, on the other hand, is at present mainly hinging on fossil sources (coal, oil, natural gas). Alternative pathways for energy and materials supply are urgently needed due to the long-run unsustainability of non-renewable sources as well as to CO_2-related global warming concerns. Last but not least, it is well known that fossil sources have been among the main causes of political and economic instability worldwide (Correljé and van der Linde, 2006; Lippi and Nobili, 2012).

While a variety of renewable options is available for energy production (solar, wind, geothermal, etc.), the supply of fuels and chemicals can only rely on biomass in alternative to fossil products. Plant extractives and structural biopolymers, such as sugar, starch, lignocellulosic and oil crops, can be used as raw materials to produce several organic compounds, including platform intermediates for chemical synthesis, from which numerous value-added commodity and bulk chemicals can be derived (Sheldon, 2011). First generation substrates (food crops) have been, however, criticized for competing with food production (UN, 2007; IFG, 2007) as well as for showing an insufficient energy return on energy investment, due to the relatively small yield per hectare (Pimentel et al., 1981, 1988; Pimentel, 1991; Giampietro et al., 1997; Ulgiati, 2001).

The employment of second generation feedstocks, such as lignocellulosic biomass, non-food crops or bio-based waste raw materials in general, has been commonly recognized to overcome the food versus fuel conflict (McKendry, 2002), being in line with the innovative concept of integrated biorefineries, namely "the sustainable processing of biomass into a spectrum of value-added products (chemicals, materials, food and feed) and energy (biofuels, power and heat)" (Kamm and Kamm, 2004), similar to

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traditional petroleum refinery. The opportunity of co-producing second generation bio-based chemicals together with biofuels was claimed to be particularly advantageous from both energetic and economic viewpoints (Ohara, 2003; Kamm and Kamm, 2004; Uihlein and Schebek, 2009; Fitzpatrick et al., 2010): the large-scale implementation of such a biorefinery concept would contribute to the substitution of imported crude oil in favor of a more sustainable resource supply, by appropriately selecting local raw materials and by reducing negative environmental impacts. These claims in favor of second generation bioenergy compared to first generation processes still need to be convincingly proved. Several limitations related to agricultural yield, industrial processing and environmental impacts other than CO_2 emissions still apply.

In the last decades, many studies have been carried out about technical, economic and environmental aspects related to the production of biofuels (Sánchez and Cardona, 2008; Dong et al., 2008; Ojeda et al., 2011a,b; Nigam and Singh, 2011; Russo et al., 2012), whereas the extraction of chemicals from biomass still has to be deeper investigated, especially due to the vast range of possible target molecules. A first selection of platform chemicals that could be produced from renewable carbohydrate raw materials was reported by the US Department of Energy in 2004 (NREL; Werpy and Petersen, 2004). More recently, the selection was further restricted to 13 target molecules, including ethanol, lactic acid, succinic acid, 3-hydroxypropionic acid, isoprene, bio-hydrocarbons, furfural, hydroxymethylfurfural, 2,5-furan dicarboxylic acid, levulinic acid, sorbitol, xylitol, glycerol and derivatives (Bozell and Petersen, 2010), thus allowing an easier focus on a limited number of platform chemicals and progresses on their production technologies.

Nevertheless, in order to properly assess the conversion of biomass into bioenergy and biochemicals and avoid mis-calculations and too optimistic claims as with first generation biofuels, Life Cycle Assessment (LCA) has to be regarded as an essential tool for sustainability evaluation of products and processes at larger spatial and time scales (from cradle to grave). LCA helps identify environmental aspects and burdens of any product system over its entire life cycle. A large number of LCA studies evaluated the environmental performances of both first and second generation biofuels (Stoeglehner and Narodoslawsky, 2009; Pereira and Ortega, 2010; Fazio and Monti, 2011), whilst only few published LCA studies concern biorefinery systems with multiple output products (Cherubini and Jungmeier, 2010; Cherubini and Ulgiati, 2010; Ekman and Börjesson, 2011). In particular, the conversion of biomass substrates into platform chemicals by means of Biofine process (Hayes et al., 2005), patented by Biofine Inc. and here proposed as a biorefinery pattern, has not been assessed by means of LCA before.

The aim of this study is to evaluate the environmental, energetic and economic feasibility, in terms of emissions, energy gain and economic income, of a biorefinery-oriented system, with a special focus on the production of value-added chemicals via the Biofine process from an oilseed crop (*Brassica carinata*) grown on marginal land in Campania Region (southern Italy). The assessment refers to the hypothetic case study, thoroughly detailed in the next section, of a multiple production system that simultaneously exploits *Brassica* seeds and lignocellulosic residues for the production of, respectively, biodiesel and ethyl levulinate as main industrial outputs. The proposed scenario is of specific local interest, since the patent of the Biofine process was purchased and implemented by the industrial company Le Calorie Srl in Campania Region (southern Italy). The agricultural phase and the industrial conversion to biodiesel and biochemicals are the key steps accounted for, although the side-production of heat (from combustion of residues in the purely energetic scenario) and electricity (from the combustion of lignin and biochar in the biorefinery pattern) are also considered. Several environmental impact categories are investigated, according to the CML 2001 and Cumulative Energy Demand (CED) methods within the framework of LCA methodology, with reference to the conventional production systems based on fossil sources as benchmark process.

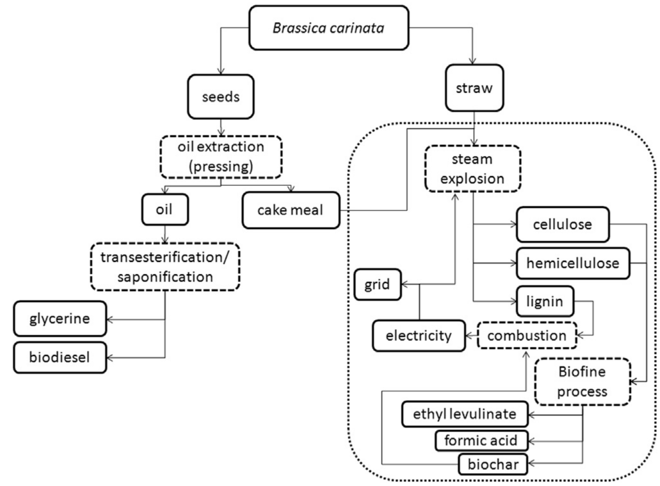

Fig. 1. Schematic flowchart of the investigated *B. carinata* biorefinery system. The dotted frame indicates the process steps leading to platform chemicals, in the biorefinery perspective (see text for details).

2. Materials and methods

The environmental assessment was performed according to the life cycle assessment methodology, described in the standards ISO 14040 and 14044 (ISO, 2006a,b): not only the whole life cycle of a particular product was accounted for in terms of its ecological implications, but also all byproducts arising from any production step.

2.1. Goal definition

The goal of this LCA study is an evaluation of the impacts generated and resource consumption in a biorefinery system producing biodiesel and ethyl levulinate as main products, with heat and electricity as co-products, from *B. carinata* cropped on marginal lands, compared with the conversion of biomass into energy products only (biodiesel and heat). An identification of the most significant and sensitive steps in the production system is also pursued in order to evaluate the most impacting ones and improve their environmental performance by means of careful monitoring and enforcement of strict environmental rules.

The choice to investigate marginal and polluted land in Campania Region for non-food cropping was based on several reasons. First of all, it deals with land unsuitable for food production and therefore cropping it for bioenergy and biochemicals would provide an alternative for the farmers who risk losing their jobs or see their income decreased due to lower market demand on their products. Some farmers keep cropping these portions of land for food, in spite of the fact that they are clearly indicated as polluted (ARPAC, 2010): diverting cropping for food to cropping non-food products would therefore decrease health risks for unaware customers.

Finally, *B. carinata sp* was recognized as a high efficiency accumulator of heavy metals in soils irrigated with sewage effluents