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Agricultural feedstocks of two *Brassica* oilseed crops and energy cogeneration with pure vegetable oil for a sustainable short agro-energy chain in Sicily (Italy)

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ABSTRACT

Potential energy feedstocks from conventional agriculture usually include pure vegetable oil (PVO) and agricultural/forest residues. Their uses can represent a starting point for the development of short agro-energy chains in the south areas of the Mediterranean region. This paper focused on testing and awareness raising of biofuel production for the cogeneration of electricity and heat from PVO of two *Brassica* oilseed crops in Sicily (Italy). The main aims of this study were: i) to evaluate the agronomic performance of rapeseed (*Brassica napus* L. var. *oleifera* D.C.) and Ethiopian mustard (*Brassica carinata* A. Braun) in semi-arid climate condition; ii) to analyze the quality of PVO and the chemical-physical characteristics of pure vegetable oils, defatted seed meals and crop residues of the two species; iii) to define the economic viability of a pilot combined heat and power (CHP) plant operating on PVO. In this study, seed and crop residue yields were determined at the harvesting stage on a harvest area of 10 m^2. For each species, chemical-physical characterizations were carried out using specific protocols. The cogeneration of heat and electricity was carried out using a CHP system with a nominal power of 75 kWh. The final stage of the study focused on the economic viability analysis of the CHP system. Seed yields of rapeseed and Ethiopian mustard were 2.10 and 1.16 t ha^{-1} on average, respectively. Ethiopian mustard obtained the highest performance of aboveground biomass yield (5.31 t ha^{-1}). The fatty acid profiles of the PVO resulted different for the two oilseed crops. Ethiopian mustard had, on average, the highest glucosinolate content in the seeds. The cogenerator showed a consumption of 14.4 kg PVO h^{-1} on average. Cash-flow trend analysis showed good economic benefit for farmers. These results make the two species as promising energy crops for suitable short agro-energy chains in the south Mediterranean areas.

1. Introduction

The existing European Renewable Energy Directive (2009/28/EC) has established that a mandatory 20% share of EU energy consumption must come from renewable energy source by 2020. Agriculture could contribute to the production of bioenergy by the cultivation of energy crops and potential energy feedstocks that usually include vegetable oils and agricultural/forest residues. In the last years, the interest on energy crops has been increased and, as stated by Montemurro et al. (2016), the estimates of land dedicated for bioenergy feedstocks will potentially range from 20 to 60 Mha for the EU25 by 2020 or 2030. Annual herbaceous crops, such as rapeseed, sunflower (*Helianthus annuus* L.) and soybean (*Glycine max* (L.) Merr.) are the most cultivated oilseed crops in Europe (Venturi and Venturi, 2003; Zagada-Lizarazu and Monti, 2011) but their seed and oil yields are highly variable in the European countries mainly due to different climate adaptability of the species, variations in soil quality and agricultural practices. In Italy, *Brassicaceae* oilseed crops have been introduced into traditional cereal cropping systems a long time ago, as rotation crops, and represent an element of yield diversification for farmers (Del Gatto et al., 2015). Particularly, rapeseed and Ethiopian mustard seem well-suited to central-southern areas of Italy as observed by several authors (Copani et al., 2011; Cardone et al., 2003; Lazzeri et al., 2009a; Grassano et al., 2011; Stamigna et al., 2012; Montemurro et al., 2016) although there are significant differences with northern European regions both in terms of seed and oil yields (Rathke et al., 2006; Jankowski et al.,

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2015). Oil is the main product of Ethiopian mustard cultivation and it is well-indicated for biofuels, being rich in erucic and linoleic acids (Cardone et al., 2003; Cosentino et al., 2008; Zanetti et al., 2009). Most of the literature on the energy use of rapeseed and Ethiopian mustard focuses on the production of biodiesel by a transesterification reaction of the oil (Bouaid et al., 2009; Yoo et al., 2010) and bioethanol (González-García et al., 2009). The total costs of biodiesel production are often very high (Del Gatto et al., 2015) and the profit margins for farmers are lower than those for other biodiesel markets even more if the defatted residual meals are not sufficiently valorized. Therefore, the use of pure vegetable oil (PVO) as biofuel and/or for electricity and heat cogeneration could be convenient for farmers despite the few documented information available in the literature (Russo et al., 2012). Considering a short agro-energy chain, PVO could be produced directly at farm level by simple pressing and filtering systems with low transformation costs which provide oil readily available for energy cogeneration plants. In this scenario, the cultivation of oilseed crops, such as rapeseed and Ethiopian mustard, for the production of PVOs tends to gain relevace for many reasons. Lazzeri et al. (2009a) reported how new oilseed crops could contribute at farm scale to agro-biodiversity improvement in rotation with fall/winter cereal species and can improve the quali-quantitative yields of food crops. The same authors highlight that farmers could play two roles becoming at the same time producers and end-users of energy derived from PVOs of oilseed crops, reducing the impacts of the agro-energy chain. Farmers can either consume this energy directly on-farm or sell it to third parties. In this way, it is possible to assert that PVOs represent an element of increasing income for farmers. Other important co-products of the cultivation of oilseed crops are crop residues and defatted seed meals (DSMs). Generally, crop residues such as straw are used on farm with the technique of burial of residues which leads to increase the loss of soil organic substances and the emission of CO_2 with negative effects to the environment, as stated by Zhang et al. (2014). In addition crop residues can represent a potential option for energy production directly on-farm. Fernández et al. (2006) and Alaru et al. (2011) highlighted the energetic valorization of crop residues through combustion process while Bacenetti et al. (2013) and Pagés-Díaz et al. (2014) described the biogas production with the use of residues of different crops. The economicity of a short agro-energy chain could benefit also of the valorization of DSMs both in food, feed, green chemistry sector in a biorefinery chain (Lazzeri et al., 2009a, 2009b; Lomascolo et al., 2012; D'Avino et al., 2015) and in energetic field (Smets et al., 2011). This paper reports results of a two-year trial on two oilseed crops used in a short agro-energy chain carried out in the framework of the "*ANDROMEDA*" Italian project focused on testing and awareness raising of biofuel production for the cogeneration of electricity and heat in Sicily (Italy). The project moved to create a technical, productive and economic model to be applied in several Sicilian areas in order to demonstrate the competitiveness of non-food crops for energy uses compared to food one, especially in view of their agronomically sustainable rotation. The aims of this study were: i) to evaluate the agronomic performance of rapeseed and Ethiopian mustard in Mediterranean climate condition; ii) to analyze the quality of PVOs and the chemical-physical characteristics of PVOs, DSMs and crop residues of the two species; iii) to define the economic viability of a pilot combined heat and power (CHP) plant operating on PVOs.

2. Materials and methods

2.1. Experimental site

The study was carried out from 2012 to 2013 on a traditional cereal livestock farm in Castronovo di Sicilia, a rural community (3000 inhabitants) in the Western Sicily (37°40′44"N − 13°36′12″ E, 677 m a.s.l.). The climate of the area is sub-humid with a mean annual rainfall of about 520 mm, mainly distributed between October and March, and with an average temperature of 14.0 °C. The soil in the area is heavy clay and it is classified as Typic and/or Vertic Xerochrepts (USDA).

2.2. Description of the experimental field and main cultivation practices

Two experimental fields, one for rapeseed and one for Ethiopian mustard, were set up. PR46W14 hybrid of rapeseed and ISCI 7 selection of Ethiopian mustard were used for the tests. A completely randomized block design (Gomez and Gomez, 1984) was used with three replications and a plot area of 15 m^2. The agronomic practices in the study were the same for both the species. Soil was ploughed at 35 cm depth and then harrowed in order to provide a good seedbed. The sowing date was 10 November 2012 for both the species. A density of 75–80 germinable seeds m^{-2} was used with rows spaced 15 cm apart. Before sowing, 220 kg ha^{-1} of phosphorus fertilizer was applied. A total of 150 kg ha^{-1} of nitrogen fertilizer was applied, 50 kg ha^{-1} during sowing and 100 kg ha^{-1} prior of stem elongation. Weed control was chemically performed using fluazifop-*p*-butyl 13.40% at a rate of 1 L ha^{-1} in emergence stage. During flowering stage, *Meligethes aeneus* F. was controlled using imidacloprid 19.42% at a rate of 2 L ha^{-1}. The harvest date was 10 July 2013 for rapeseed and 21 July for Ethiopian mustard. Harvest was carried out when the seed moisture content was lower than 14%. Both species were harvested using a combine harvester equipped with a wheat-cutting bar.

2.3. Climatic data

Data on rainfall and temperatures were collected from a meteorological station belonging to the Sicilian Agro-Meteorological Information Service situated close to the experimental site. The station was synchronized with GMT in order to operate using synoptic forecast models. It was equipped with a MTX datalogger (model WST1800) and various sensors: wind speed sensor MTX (model Robinson cup VDI with an optoelectronic transducer), global radiation sensor (model Philipp Schenk – 8102 thermopile pyranometer) to measure cumulative direct and diffuse solar irradiance, temperature sensor MTX (model TAM platinum PT100 thermal-resistance with anti-radiation screen), relative humidity sensor – MTX (model UAM with capacitive transducer with hygroscopic polymer films and anti-radiation screen), rainfall sensor MTX (model PPR with a tipping bucket rain gauge), and leaf wetness sensor MTX (model BFO with PCB). This equipment provided data on the main meteorological parameters.

2.4. Agronomic and chemical-physical aspects

The main phenological stages of the two species were observed: emergence, leaf development, stem elongation, flowering, development of fruit, ripening and senescence, according to BBCH scale (Lancashire, 1991). Seed and crop residues yields were determined at the harvesting stage on a harvest area of 10 m^2. On a sample of 10 plants, plant height, number of siliques per plant, silique length, number of the seeds per silique and 1000-seed weight (TSW) were recorded. In order to estimate the dry abovegound biomass, samples of each vegetable fraction of plant (leaves, stems, seeds and siliques) were dried at 60 °C in an oven, until constant weight. Pure vegetable oils and DSMs were obtained using a small continuous seed crusher machine (Bracco Company model Elle.Gi type 0.90) of 2.2 kW electric power, three-phase voltage of 380 V and with a capacity of 30 kg of seed h^{-1}. A total of 3 samples for each feedstock (seed, DSM and straw) were analysed to determine the chemical-physical characteristics. Total contents of carbon, hydrogen and nitrogen (C-H-N) of seeds and DSMs were determined using elemental analyzer LECO CHN TruSpec according to the American Society for Testing Materials (ASTM D5373). Glucosinolates (GLs) content of seeds and DSMs were determined following the ISO 9167-1 method with some minor modifications. The moisture was determined according to AOAC (1990). The fatty acids were extracted from ground