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Potential environmental impact of bioethanol production chain from fiber sorghum to be used in passenger cars

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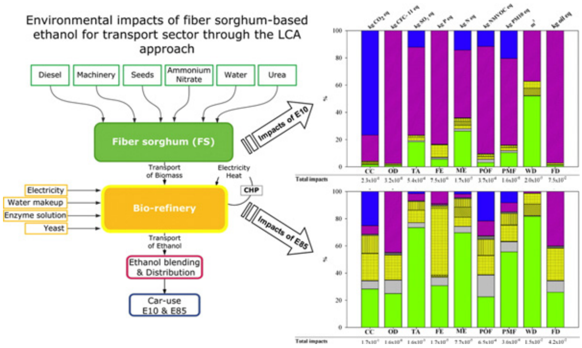
HIGHLIGHTS

- Environmental impacts of fiber sorghum based E10 and E85 blends were investigated.
- A two step LCA was applied: “cradle-to-farm gate” and “cradle-to-wheels”.
- Petrol and the linked tailpipe emissions were hotspots for E10 environmental profile.
- For E85 the major drivers were feedstock production and the imported electricity.
- Compared to gasoline, E85 mitigated climate change, ozone and fossil depletions.

GRAPHICAL ABSTRACT



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ABSTRACT

A life cycle assessment (LCA) was applied to assess the environmental load of a prospective local bioethanol (EtOH) production system in Southern Italy by using lignocellulosic Fiber sorghum (FS) feedstock. A two steps analysis was carried out considering: (i) a “*cradle-to-farm gate*” LCA to investigate thoroughly the FS cultivation on hilly marginal land and (ii) a “*cradle-to-wheels*” system boundary encompassing the environmental pressure of the whole EtOH supply-use chain. Primary data related to lignocellulosic biomass production were combined with experimental feedstock conversion processes through advanced second generation technology. The purpose was the evaluation of the environmental performance of different EtOH-gasoline mixtures in midsize passenger cars: E10 (10% of EtOH and 90% of gasoline) and E85 (85% of EtOH and 15% of gasoline). N fertilization appeared as the prevailing contributor of the crop phase. The “*cradle-to-wheels*” results concerning E10 passenger car disclosed that the main hotspots were represented by the input of low sulphur petrol (66%) and the linked tailpipe emissions (15%), for almost all the impact categories. Otherwise, for E85 flex-fuel vehicle, the major drivers were represented by the feedstock production (46%) and the imported electricity used in the conversion facility (18%).

The FS EtOH blends entailed potential environmental benefits compared with the fossil counterpart (gasoline) for climate change, ozone and fossil depletions. Otherwise, they evidenced a worse profile in terms of acidification, eutrophication and particulate matter formation. Within the context of a the prospective territorial bio-

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refinery network, the comparison of the annual FS bioethanol based systems with similar EtOH scenarios from giant reed perennial crops highlighted: (i) the importance to optimize the N-management for FS feedstock cultivation and (ii) the need to increase the use of the renewable energy carriers along the industrial conversion pathway.

1. Introduction

There is an increasing interest in cropping systems (not in competition with food) capable to provide energy (Berndes et al., 2003; Sims et al., 2006) and building blocks materials (Cherubini, 2010; Cherubini and Jungmeier, 2010; Forte et al., 2016) as alternatives to fossil fuel-based energy carriers and chemicals. In this context, the exploitation of dedicated cultivated crops on marginal lands for bioenergy or biomaterial production could represent a valid alternative for reducing conflicts among food, energy and environment (Solinas et al., 2015), also offering larger technical potential compared to other biomass resources such as agricultural and forest residues, animal manure and organic wastes (Chum et al., 2011).

According to the EU policy and the Italian national regulations, dedicated energy crops on marginal lands are foreseen as an effective source of renewable carbon to emerging second-generation biofuel supply chains for the replacement of conventional fossil fuels (Directive 2009/28/EC; D. Lgs. 03/03/2011 n.28; COM15 final, 2014; P8_TA-PROV(2015)0100; DM Sviluppo Economico 10/01/2015). In this regard, high yielding lignocellulosic biomass feedstock can, simultaneously, maximize the bioethanol (EtOH) output and minimize the competition with other land use (Salvi et al., 2010; Cadoux et al., 2014; Mandade et al., 2015).

Life cycle assessment (LCA) studies aimed to evaluate the environmental load of lignocellulosic EtOH for transport found out a remarkable reduction in greenhouse gases (GHGs) emissions and fossil energy consumption for second generation biofuels in replacement of fossil counterparts (Somerville et al., 2010; Whitaker et al., 2010; Cherubini and Strømman, 2011; Belboom et al., 2015; Morales et al., 2015; Murphy and Kendall, 2015; Zucaro et al., 2016a). However, relevant tradeoffs may occur as increased environmental impacts in terms of eutrophication and acidification (Bai et al., 2010; González-García et al., 2009, 2012; Morales et al., 2015; Mbonimpa et al., 2016; Zucaro et al., 2016a).

Moreover, there is the need to further clarify the nexus between the agronomic performance and the environmental impacts of different alternative candidate lignocellulosic biomasses (Cadoux et al., 2014; Murphy and Kendall, 2015; Zucaro et al., 2016b). Compared to perennials, annual crops may offer higher flexibility (i.e. double cropping, rotation systems, etc.) and lower investment risk thanks to their fast growth rate and high yield potential on marginal land (Monti and Venturi, 2003; Barbanti et al., 2006; Wang et al., 2015).

On this matter, an increasing interest is currently focused on dedicated biomass sorghum for cellulose-based EtOH (Spellman and Bieber, 2011; Cadoux et al., 2014). The lignocellulosic sorghum is characterized by a predominant composition in structural carbohydrates (cellulose, hemicelluloses and lignin) allowing competitive yield of second generation ethanol coupled with electricity cogeneration through lignin combustion (Spellman and Bieber, 2011; Stefaniak et al., 2012; Cadoux et al., 2014; May et al., 2016). Besides the high biomass productivity, the fiber sorghum (FS) cultivation for bioenergy/biomaterial purpose displays many advantages in terms of agronomic performance: adaptability to different soil types, tolerance to arid conditions, modest water and nutrient requirements, short growth cycle with maturity reached in 90 to 180 days (Amaducci et al., 2004; Barbanti et al., 2006; Pantaleo et al., 2009; Fazio and Monti, 2011; Cadoux et al., 2014).

Up to now, LCA studies highlighted a better environmental profile for bioenergy production systems from perennial crops compared with annual crops (Adler et al., 2007; Hillier et al., 2009; Monti et al., 2009). A recent comparative analysis focused on the GHG profile of six bioenergy crops in northern France (miscanthus - *Miscanthus* × *giganteus*, switchgrass - *Panicum virgatum*, fescue - *Festuca arundinacea*, alfalfa - *Medicago sativa*, triticale - *Triticale* × *Triticosecale*, and fiber sorghum - *Sorghum bicolor* L.) confirmed the best compromise of perennials between low fertilizer input and GHG saving, through the higher productivity per hectare (Cadoux et al., 2014). However, under the investigated temperate climate conditions, the annual fiber sorghum growing period was likely limited, resulting in restrained dry biomass yield (Cadoux et al., 2014).

Different results might be gained for cellulosic sorghum based EtOH under Mediterranean conditions, where competitive sorghum biomass yields of about 20–30 t ha^{-1} yr^{-1} have been reported thanks to the optimal radiation interception and plant resistance to drought conditions (Pantaleo et al., 2009; Buratti and Fantozzi, 2010; Saita et al., 2011; Cosentino et al., 2012; Zucaro et al., 2015).

Currently, no LCA studies applied to bio-EtOH based transport scenario are available for FS feedstock grown in the Mediterranean context. A preliminary LCA analysis at the farm gate, pointed up a general better environmental performance for the perennial *Arundo donax* L. (giant reed) biomass in comparison with the fiber sorghum feedstock in Southern Italy (Zucaro et al., 2015). However, the evaluation of giant reed was referred to a year of full productivity (Zucaro et al., 2015). This might have overstated the average productivity along the whole life cycle (Fagnano et al., 2015; Forte et al., 2015; Zucaro et al., 2016a, b), amplifying the yield-scaled environmental benefits versus the annual crop. Additionally, there is the need to encompass the potential different feedstock conversion efficiencies at the industrial facility.

Therefore, the aim of this study was to: (i) analyse the environmental pressure of lignocellulosic bio-ETOH fuel for passenger cars, produced from FS feedstock by means of advanced second generation conversion technologies, with a special focus on the crop phase of the sorghum cultivation on the hilly marginal lands of Campania region (Southern Italy); and (ii) discuss, further, the results in relation to the fossil reference system (conventional gasoline midsize passenger cars) and similar bio-based lignocellulosic EtOH production chains.

2. Material and methods

The LCA addresses the environmental issues and quantifies the potential environmental impacts of a product or a process in a life cycle perspective (ISO 14040, 2006; ISO 14044, 2006). This study performed an environment sustainability assessment based on an attributional LCA approach, in order to verify the feasibility of the second generation bioethanol (EtOH) for the transport sector in Campania Region (Southern Italy). The present work is the first attempt to assess the environmental load of a hypothetical territorial biorefinery based on FS lignocellulosic feedstocks and an advanced conversion technologies to obtain biofuels and bio-chemicals. This LCA was focused on the production and use (in midsized passenger cars) of bio-EtOH fuel considering: (i) the extraction of raw materials, (ii) the refining and production processes, (iii) the use phase, (iv) the possible recycling and the waste disposal processes.