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Life Cycle Assessment of high ligno-cellulosic biomass pyrolysis coupled with anaerobic digestion

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HIGHLIGHTS

- Environmental impacts of corn stovers pyrolysis and anaerobic digestion are valued.
- Biochar is considered as solid fuel for coal power plants or as soil conditioner.
- All results are compared against a corresponding fossil-fuel based scenario.
- Results are encouraging although trade-offs are highlighted.

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ABSTRACT

A Life Cycle Assessment is conducted on pyrolysis coupled to anaerobic digestion to treat corn stovers and to obtain bioenergy and biochar. The analysis takes into account the feedstock treatment process, the fate of products and the indirect effects due to crop residue removal. The biochar is considered to be used as solid fuel for coal power plants or as soil conditioner. All results are compared with a corresponding fossil-fuel-based scenario. It is shown that the proposed system always enables relevant primary energy savings of non-renewable sources and a strong reduction of greenhouse gases emissions without worsening the abiotic resources depletion. Conversely, the study points out that the use of corn stovers for mulch is critical when considering acidification and eutrophication impacts. Therefore, removal of corn stovers from the fields must be planned carefully.

1. Introduction

Today transition from a fossil-based economy to a bio-economy (European Commission, 2012) is justified by the need of an integrated response to several global mega-trends such as: food security, the need of strengthening energy security, increasing demand of biological resources for bio-based products, GHG emission reduction, the need of moving toward a zero-waste society, environmental sustainability of primary production systems, increasing land use competition (Nita et al., 2013). Sustainable bio-refineries can play an important role to address concerns about climate change and security of energy supply, while contributing to economic growth and employment, particularly in rural areas (European Commission, 2014). According to the Impact Assessment to the 2030 Climate and Energy Framework, biomass use in the heat and power sectors is expected to further increase in the medium term, following the EU effort to move to a low-carbon economy by the middle of the century. Residual biomasses – such as manure, pruning, straw or other by-products of farming – are a low cost feedstock source that represents an untapped source for energy production. Moreover, the use of residual non-edible biomass is less controversial than harvested biomass, which raises environmental concerns or issues related to competition with food needs (FAO, 2010, 2012; HLPE, 2013). These concerns and issues have resulted in growing interest in alternative, non-edible biomass resources.

Corn stovers – consisting of cobs, ear husks, stalks and leaves of maize – are abundantly present and very interesting due to their energy content. Corn stovers can be left in the fields after the harvest and used for soil mulching, disposed of, or burnt directly on the field. Corn stovers, typically composed of 35–40% cellulose, 20–25% hemicellulose, and 15–20% lignin, are recalcitrant to aerobic and anaerobic bioconversion, because of the high ligno-cellulosic content and this characteristic represents the major

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obstacle to a cost-effective exploitation. Lignin, the most abundant aromatic biopolymer on Earth, is extremely recalcitrant to degradation and preliminary treatments are necessary in order to facilitate its degradation by bacteria.

Intermediate pyrolysis consists in the controlled heating (at temperatures between 350 and 600 °C) of biomass in an inert atmosphere, obtaining gas, liquid (bio-oil) and a carbonaceous residue (char). In turn, these pyrolysis products can be upgraded to fuels/materials or can be burnt to produce thermal energy. Besides chemical and thermochemical processes, which include hydrotreating/cracking or gasification of bio-oil for syngas production, a recent approach is the coupling of pyrolysis with a biological upgrading system, by hybrid techniques (Jarboe et al., 2011). In principle, coupling anaerobic digestion (which produces biogas) with a thermic de-polimerizing system, such as pyrolysis, allows to overcome the recalcitrant feature of certain feedstock. Therefore, it could be a relatively simple and low-cost solution to overcome the problems which affect both technologies. In particular, the conversion to biogas allows the use of mixed microbial consortia which can operate with low quality bio-oil and gas – especially with high water content or with inorganic contaminants – and produces a biogas which is compatible with existing power generating facilities. This solution has been proven as an alternative to catalytic methanation for converting syngas into methane (Guiot et al., 2011) and allows the treatment of the whole gas/bio-oil mix at low temperature (Lewis, 2012) without the need of tar reforming and syngas purification. Preliminary data showed that, once the microbial consortium has adapted, it is possible to digest the bio-oil from intermediate pyrolysis anaerobically with satisfactory yield (Torri and Fabbri, 2012).

Research within the Interdepartmental Centre for Industrial Research (CIRI) Energy and Environment focuses on technologies for the pre-treatment of biomasses before their anaerobic digestion (DA) (Torri and Fabbri, 2014). In this context the goal of the research is to evaluate, firstly on a small scale (Bandini et al., 2014) and subsequently on a larger prototype scale, the environmental performances of pyrolysis coupled to anaerobic digestion for the processing of corn stover. Combination of pyrolytic and anaerobic digestion techniques is named PYDA in the following. This study aims to assess the potential environmental impact and benefits of the large scale prototype (hereafter named PYRO2012) in order to support and inform the development of this process for the exploitation of residual biomasses with high lignocellulosic content. The study applies an attributional Life Cycle Assessment (LCA) adopting a 'cradle-to-grave' perspective.

2. Materials and methods

2.1. Experimental plant

The experimental data used in this study have been obtained by a pilot scale pyrolyzer (described below) and lab scale anaerobic digestion (AD) system running in batch operation: bio-oil and gas outputs are stored into frozen bottles and tedlar bags and then inserted into the AD device. Anaerobic digestion tests of oil and syngas were performed off-line as shown in Torri and Fabbri (2014) using 1 L pressurized reactor (pyrolysis liquid) and 100 ml syringes (gas). This batch procedure provided the data concerning the pyrolysis–anaerobic digestion coupling.

The pyrolysis reactor is essentially constituted by a hopper, a 100 mm cylindrical pyrolysis chamber, a tank for the collection of the biochar and a scrubber/heat exchanger for the collection of oil, a tee for gas sampling, a hydraulic seal system consisting of a steel bubbler with 1 m depth water and a controlled torch at the end of the system. The pyrolysis reactor is equipped with an electric heating system and a motorized auger (which is coaxial with the reaction chamber) and is flushed by 1000 ml min^{-1} of nitrogen for safety reasons. The biomass is progressively taken by the auger from the hopper, through the loading channel, and then conveyed through the pyrolysis chamber (T = 400 °C, residence time = 10 min). Pyrolysis vapors are collected in the heat exchanger/scrubber, where a peristaltic pump continuously takes the oil from the bottom and carries it up to the heat exchanger inlet.

In order to obtain samples and pyrolysis data (e.g. energy consumption), an intermediate pyrolysis plant with a throughput of 10 kg h^{-1} was built and operated semi-continuously in 10 tests, for a total test time of 60 h. During the middle portion of the test (excluding the first and last hours of start-up and shut-down), yield and actual energetic consumption were measured upstream by means of an electricity meter.

2.2. LCA method

Life Cycle Assessment (LCA) is the method chosen for assessing the environmental performances of PYDA. The LCA of a product or process is generally performed in order to identify the 'hot spots' in the life cycle in order to reduce consumption of energy and raw materials, and emission/waste production, as well as to identify possible improvements towards the achievement of a more environmentally sustainable result. When dealing with experimental methods which are in progress, LCA can support, in an iterative way, the undergoing research: by giving a highlight on the most impacting processes in the system, it points to where more progress is needed; by defining thresholds (i.e. minimum performances required for having a net energy gain) it can identify some basic performances which have to be achieved before moving to any scaling-up phase. When evaluating different scenarios for product development, a prospective or comparative Life Cycle Assessment is realized, which analyses possible future changes between alternative product systems or configurations (Azapagic and Clift, 1999).

The LCA method is standardized by ISO 14040 and 14044 (ISO, 2006a,b) and comprises four phases: (1) goal and scope definition; (2) inventory analysis; (3) impact assessment; (4) interpretation. Below, data used and approaches applied in each of these phases are described.

2.2.1. Goal and scope definition

Goal and scope focus on environmental performances of the PYDA system for the treatment of corn stovers while exclude the assessment of its economic potential.

The EU Renewable Energy Directive (European Union, 2009) assigns agricultural residues and wastes "zero life-cycle greenhouse gas emissions up to the process of collection of those materials"; this principle has been adopted with respect to Global Warming Potential (GWP) and extended to the outstanding impact categories such as eutrophication potential, abiotic resources depletion, etc. (see below Life Cycle Impact Assessment). In order to define the system boundaries, particular attention has been paid to the removal and use of stovers. Elimination of stovers from the field has been considered to require a fertilizer offset since corn stovers are usually left on field for soil mulching thanks to their nitrogen, phosphorous and potassium content. As a further indirect consequence, fertilizer emissions due to the offsetting of fertilizers have been considered inside the system boundaries. These fertilizers emissions are mainly due to the production of nitrous oxide which in turn is due to nitrification and denitrification processes (FAO, 1996).

Therefore the system boundaries of the study include the following processes: (1) fertilizer offset; (2) fertilizer offset emissions, which includes emissions to air due to fertilizer application as well