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Environmental assessment of thermo-chemical processes for bio-ethylene production in comparison with bio-chemical and fossil-based ethylene

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ABSTRACT

The use of biomass for production of chemicals is gaining interest because of its potential to contribute towards a reduction in greenhouse gas emissions and other environmental benefits linked to the substitution of fossil resources. But, conversely to biofuels, studies focusing on environmental impacts of biomass-derived chemicals are scarce. This paper uses life cycle assessment to evaluate the environmental sustainability of bio-ethylene from poplar produced by the following three thermo-chemical routes: direct and indirect dehydration of ethanol and production of olefins via dimethyl ether. The indirect route is the best option for most impact categories for all three allocation methods considered: system expansion, economic and energy basis. However, the dimethyl ether-to-olefins route has the lowest global warming potential. In comparison to ethylene produced bio-chemically from sugar beet, the thermo-chemical indirect route has lower impacts for all categories except human, terrestrial and freshwater toxicities. All three thermo-chemical alternatives show a significant reduction in global warming potential (up to 105% in the case of dimethyl ether-to-olefins) and depletion of fossil fuels when compared to conventional ethylene production from fossil fuels. However, the results also suggest that bio-ethylene produced by any of the three thermo-chemical routes would lead to a significant increase in most other impact categories relative to fossil fuels. Therefore, while trying to reduce greenhouse gas emissions, the overall environmental sustainability of bio-ethylene suffers from the increase in other environmental impacts.

1. Introduction

The European chemicals industry is committed to a gradual increase in the utilization of renewable feedstocks, with the objective of producing 25% of biomass-derived chemicals in 2030 (DSBC, 2012). Biomass-derived chemicals act as a storage of biogenic carbon (Haro et al., 2014) and could potentially have negative net greenhouse gas emissions (The Royal Society, 2016). This makes them an appealing target for reducing the impact on climate change from the chemicals industry. Among the candidates for producing bio-chemicals, ethylene stands out as the largest chemical commodity with the global demand of 150 million tonnes in 2016 (Mitsubishi Chemical, 2017). Ethylene is currently largely produced by steam cracking using different hydrocarbon feedstocks (ethane, propane, naphtha and gas oils), although the use of ethane is being favoured, especially in Europe (Ethylene Profile, 2015).

Even though bio-ethylene production is still far from playing an important role in the near future, it can complement production of fossil-based olefins (Amghizar et al., 2017; Braskem Company, 2017). Compared to other biomass-derived chemicals, the production of bio-ethylene has an advantage that it can be introduced directly into existing value chains, infrastructure and markets (Arvidsson, 2016). Ethylene can be produced from biomass following two different pathways: bio-chemical and thermo-

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chemical. In the former, ethanol produced from the fermentation of sugars is dehydrated into ethylene. The Brazilian company Braskem is already producing 200,000 t/y of polymer-grade bio-ethylene using sugarcane bio-ethanol as an intermediate (Braskem Company, 2017).

In the thermo-chemical pathway, lignocellulosic biomass is converted into ethylene prior to thermal treatment (pyrolysis and/or gasification) and further chemical conversion of produced syngas into ethylene. There are two alternatives for the chemical conversion, either the production of methanol/dimethyl ether (DME) or ethanol as chemical intermediates. In the case of methanol/DME, a methanol-to-olefins reactor is used. For ethanol, the same dehydration process as in the bio-chemical pathway is utilized. Several studies have evaluated techno-economic feasibility of ethylene production via the bio-chemical route, including Kamzon et al. (2016), Becerra et al. (2017) and Nitzsche et al. (2016). Equivalent studies of thermo-chemical pathways have also been carried out (Haro et al., 2013; McKechnie et al., 2015; Sharifzadeh et al., 2015). In this study, we focus on the thermo-chemical route to evaluate the environmental sustainability of producing bio-ethylene from biomass. The results are compared with bio-chemical ethylene produced by dehydration of first-generation bio-ethanol and with ethylene obtained by steam cracking of fossil resources. The following three main alternative pathways are considered: direct ethanol dehydration, indirect ethanol dehydration and DME-to-olefins. Therefore, the scope of the work covers the most promising alternatives for bio-ethylene production via thermo-chemical conversion (Haro et al., 2013).

In contrast to biofuels, there are scarce examples of life cycle assessment (LCA) studies of biomass-derived chemicals. Most existing studies are focused on specialty chemicals produced via the bio-chemical pathway (e.g. Fiorentino et al., 2017) and only a few on chemical commodities like ethylene (e.g. Cheali et al., 2015). Studies of life cycle impacts of ethylene production using the thermo-chemical pathway are rare and the number of impacts considered is limited. For example, Karka et al. (2017) considered only three categories: cumulative energy demand, global warming potential and water consumption. A couple of other studies discussed the key environmental issues in the production of bio-ethylene focusing on second-generation ethanol (Belboom and Léonard, 2016; Liptow et al., 2013). First-generation bio-chemical ethanol was studied by Ghanta et al. (2014) who considered corn as a feedstock in a US context while Tsiropoulos et al. (2015) evaluated the use of sugarcane in Brazil and India. Sugarcane from Brazil was also considered by Kikuchi et al. (2017) for the production of ethanol in Japan, alongside the use of domestic sugarcane-molasses. Other studies assessed the economic and environmental implications of using bio-ethanol for ethylene production instead of utilizing it as a transportation fuel (McKechnie et al., 2015; Posen et al., 2015). Finally, Horváth et al. (2017) analysed the carbon efficiency of the conversion of bio-ethanol into different chemicals, including ethylene.

Therefore, there is a lack of comprehensive studies of environmental impacts of thermo-chemical production of ethylene from biomass. This study aims to fill this knowledge gap. The results are compared to the impacts from ethylene produced by bio-chemical conversion as well as with ethylene produced from fossil feedstocks to provide a comprehensive multi-criteria analysis of the environmental performance of bio-ethylene. As far as we are aware, this is the first study of its kind internationally.

2. Methodology

The study involves a comparative attributional LCA, based on the guidelines of the ISO 14040/44 standards (2006a, 2006b). The goal and scope of the study are described next, followed by the inventory data and an overview of the impact assessment method used in the study.

2.1. Goal and scope

The main goal of the study is to estimate and compare life cycle environmental impacts of the three alternative methods for producing bio-ethylene from biomass via thermo-chemical conversion: direct ethanol dehydration (Case 1); indirect ethanol dehydration (Case 2); and DME to olefins (Case 3). A further goal is to compare these thermo-chemical routes with ethylene produced from first-generation ethanol via the bio-chemical route and with ethylene from fossil-based resources.

As indicated in Fig. 1, the scope of the study is from 'cradle to gate', with two main stages considered: biomass supply (cultivation, collection and transportation to the processing plant); and production of bio-ethylene and its co-products. The use of bio-ethylene and the co-products, as well as their distribution, are excluded from the system boundaries. The construction and decommissioning of the production plant are also excluded as the impacts of infrastructure per unit of product are negligible over the (long) lifespan of industrial plants (Reyes Valle et al., 2015).

The functional unit is defined as the production of 1 tonne of ethylene.

2.2. System description

The plant size chosen is equivalent to 500 MWth in terms of the energy content of the feedstock processed, based on the higher heating value (HHV). This plant size is typically considered in studies of biomass-to-liquids (BTL) plants (Villanueva et al., 2011). The type of biomass processed in the plant is the same for each of the three cases considered. However, the amount of biomass required per tonne of ethylene produced and the output of the co-products vary depending of the production route due to the different efficiency and selectivity of the three routes. The feedstock is poplar as detailed in the next section.

2.2.1. Feedstock supply

Poplar is selected as the feedstock, which has recently attracted significant interest as an energy crop (Guo et al., 2014). The production plant is assumed to be based in the Duero Valley (*Castilla y León*, Spain) as there is extensive cultivation of poplar there due to favourable climatic conditions. For these reasons, land use change is not considered.

The life cycle of a poplar crop spans 16 years. In the first year, land preparation and the planting of cuttings take place. This is followed by three tree-growing cycles of five years each (Gasol et al., 2009), with the trees being cut to the ground after each cycle. At the end of the third cycle, the trunks are treated with insecticide to remove the roots and, after three months, new cuttings are planted. The average production of biomass is 216 t/ha on a dry basis for the three cycles as a whole. Further description of the feedstock supply can be found in Reyes Valle et al. (2015).

2.2.2. Case 1: direct ethanol dehydration

This process involves three main steps:

i) bioslurry production from biomass (Fig. 2);
ii) production of ethanol from bioslurry by direct route through gasification and catalytic conversion of syngas (Fig. 3); and