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Life cycle impact assessment of bio-based plastics from sugarcane ethanol

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ABSTRACT

The increasing production of bio-based plastics calls for thorough environmental assessments. Using life cycle assessment, this study compares European supply of fully bio-based high-density polyethylene and partially bio-based polyethylene terephthalate from Brazilian and Indian sugarcane ethanol with production of their petrochemical counterparts in Europe. Bio-based polyethylene results in greenhouse gas emissions of around -0.75 kg $CO_{2eq}/kg_{polyethylene}$, i.e. 140% lower than petrochemical polyethylene; savings on non-renewable energy use are approximately 65%. Greenhouse gas emissions of partially bio-based polyethylene terephthalate are similar to petrochemical production (±10%) and non-renewable energy use is lower by up to 10%, partly due to the low bio-based content of the polymer. Assuming that process energy is provided by combined heat and power reduces the greenhouse gas emissions of partially bio-based polyethylene terephthalate production to a range from −4% (higher) to 15% (lower) compared to petrochemical polyethylene terephthalate depending on the methodological choices made. Production from Brazilian ethanol leads to slightly higher impacts than production from Indian ethanol due to dampening effects of allocation on Indian ethanol produced from sugarcane molasses, different sugarcane pre-harvesting practices and inter-continental transport of Brazilian ethanol to India. Internal technical improvements such as fuel switch, new plants and best available technology offer savings up to 30% in greenhouse gas emissions compared to current production of petrochemical polyethylene terephthalate. The combination of some of these measures and the use of biomass for the supply of process steam can reduce the greenhouse gas emissions even further. In human health and ecosystem quality, the impact of the bio-based polymers is up to 2 orders of magnitude higher, primarily due to pesticide use, pre-harvesting burning practices in Brazil and land occupation. When improvements are assumed across the supply chain, such as pesticide control and elimination of burning practices, the impact of the bio-based polymers can be significantly reduced. Realising such improvements will minimise the greenhouse gas and other emissions and resource use associated with bio-based polyethylene terephthalate and will allow to alleviate further pressure on fragile ecosystems.

Abbreviations: BAT, best available technology; CHP, combined heat and power; EQ, ecosystem quality; FIT, feed in tariff; GHG, greenhouse gas; HDPE, high-density polyethylene; HH, human health; LCA, life cycle assessment; LDPE, low-density polyethylene; LLDPE, linear low-density polyethylene; MEG, monoethylene glycol; NREU, non-renewable energy use; Pchem, petrochemical; PE, polyethylene; PET, polyethylene terephthalate; PTA, purified terephthalic acid.

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1. Introduction

Since 1980, petrochemical plastics production increased by an average compound annual growth rate of about 5%, resulting in a global production volume of 288 million tonnes in 2012 (PlasticsEurope, 2013). This production accounts for 5% of the global total primary energy supply (BP, 2013; PlasticsEurope, 2013).[5] In Europe, low-density, linear low-density and high-density polyethylene (LDPE, LLDPE and HDPE, respectively) and polyethylene terephthalate (PET) together represent 36% of plastics demand (PlasticsEurope, 2013).

It is known that the use of renewable resources for applications other than fuels, such as chemicals, oleochemicals, paper and textiles, generally offers higher value added (Nova Institut, 2010). Recently, the use of bio-based plastics for packaging has received a lot of attention due to emerging technological options (Shen et al., 2010). Polylactic acid, bio-based polyethylene (bio-PE), and partially bio-based PET (bio-PET) are notable examples. In 2011, bio-PE and bio-PET represented 56% of the global bioplastics' production capacity reaching 650 ktonnes (European Bioplastics, 2012). The capacity is expected to further increase since several producers have commissioned new production plants (JBF, 2012; TTS, 2011). Daioglou et al. (2014) estimate that the global feedstock energy demand for chemicals and refinery products is expected to increase from 30 EJ today to over 100 EJ by 2100. Biomass can supply over 40% of the total primary energy required for non-energy purposes and thus reduce greenhouse gas emissions by 20% in 2100 (Daioglou et al., 2014). Bio-based products and plastics could hence become an important strategy in the transition process towards sustainable bio-based economies (EC, 2009, 2011; EU, 2011). To ensure that adequate decisions are made, it is essential to assess the potential environmental impacts of the entire process chain taking into consideration local production practices and boundary conditions.

The purpose of this study is to assess the environmental impacts of bio-PE and bio-PET from sugarcane ethanol. The selected products represent a large share of current bio-based plastics production capacity and will continue to do so in the short and medium term (Shen et al., 2010). While numerous studies have been published on biofuel production from various feedstocks (e.g. Börjesson and Tufvesson, 2011; von Blottnitz and Curran, 2007), to our knowledge, there is only one peer-reviewed article that assesses the environmental impacts of bio-LDPE (Liptow and Tillman, 2012). However, Brazilian sugarcane ethanol data and data on ethanol conversion to bio-ethylene need to be updated. Polymer producers also publish environmental profiles of their bio-based products without, however, disclosing detailed background information (Hunter et al., 2008). Other studies, in which ethylene is a precursor, do not report environmental impacts of bio-ethylene, but aggregated results for the final polymer (bio-PVC; Alvarenga et al., 2013). Chen and Patel (2012) used literature data to prepare a rough estimate of non-renewable energy use and greenhouse gas emissions for bio-PET from sugarcane and maize. However, process data on ethanol dehydration need to be revisited and, for a comprehensive analysis, it is important to assess additional environmental impacts on ecosystem quality, human health, water-use and land use.

In the following, we describe the production of bio-PE and bio-PET from sugarcane ethanol. We then present the methodology used to assess their environmental performance, and compare the results with the production of their petrochemical counterparts in Europe.

2. Process description

Both bio-PE and bio-PET are currently produced from first generation ethanol, i.e. ethanol derived from food crops such as sugarcane. Ethanol is subsequently catalytically dehydrated to ethylene and a) is polymerised to polyethylene or b) is oxidised to ethylene oxide and then hydrolysed to bio-based mono-ethylene glycol (bio-MEG), the bio-based component of bio-PET. Regardless whether the feedstock is bio-based or petrochemical, further conversion of ethylene to these polymers remains the same. The comparability of bio-PE and bio-PET with their petrochemical counterparts is ensured since they are identical polymers. Although ethanol is produced from various food crops such as sugarcane, maize and wheat, we concentrate on production from sugarcane since it is currently the only feedstock used to produce bio-PE and bio-PET. Also, we focus on Brazilian and Indian production because they are the world's largest sugarcane and sugarcane ethanol producers and today's production of bio-PE and bio-PET is established in Brazil and India, respectively (de Jong et al., 2012).

2.1. Sugarcane ethanol production in Brazil and India

The production chain of ethanol in Brazil and India is described in detail in Tsiropoulos et al. (2014). This section focuses on main differences between ethanol production in south-central Brazil and Uttar Pradesh, India. Brazilian sugarcane cultivation offers high yields (around 85 t_{cane}/ha) and is highly mechanised; pre-harvesting burning practices are partly applied but they are gradually being phased out. In India, agricultural practices rely mainly on human and animal labour, yields are significantly lower (around 55 t_{cane}/ha) and irrigation is required. In Brazil, fresh sugarcane juice is directly fermented and distilled to ethanol whereas in India only sugarcane molasses are used.

In both countries, ethanol production yields co-products, which are used internally and reduce inputs (e.g. fertilisers), make the process less dependent on external energy sources and provide surplus electricity and biomass. During sugarcane juice extraction, juice is separated from the fibrous stalks and the obtained shredded bagasse is used in co-generation facilities to produce steam and electricity to meet process energy requirements. An increasing number of mills both in Brazil and in India generate surplus electricity, which they sell to the national grid. The remaining bagasse is typically sold as a solid biofuel or as feedstock for the paper industry (ISMA, 2011a,b; Seabra et al., 2011). Residues of juice filtration, typically referred to as filtercake or mud, are mixed with ashes from boilers and are returned to sugarcane fields as fertilisers. The distillation generates a significant amount of wastewater (stillage). In Brazil, after cooling in open ponds, stillage is distributed onto the fields and valuable nutrients are recycled (Lisboa et al., 2011). In India, stillage is typically treated in anaerobic digesters to generate biogas; the biogas is used in co-generation facilities and contributes to on-site energy supply (Tewari et al., 2007). Depending on filtercake availability a number of distilleries use part of the stillage to produce bio-compost, which is either sold or offered to farmers for free (ISMA, 2012).

2.2. Bio-PE production

Historically, bio-based ethylene was derived from ethanol dehydration. However, after the mid-1940s, with the rise of the petrochemical industry, steam cracking of petroleum liquids and heavier fractions of natural gas became the dominant processes for

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[5] Based on total global primary energy supply of 522 EJ (87% is fossil-based; BP, 2013). The contribution of petrochemical plastics (288 Mtonnes, 2012) is calculated based on the weighted average specific energy consumption of plastics (76.7 GJ/tonne), of which approximately 46% is process energy requirements.