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Evaluation of the environmental performance of alternatives for polystyrene production in Brazil

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ABSTRACT

The global demand for polystyrene is supposed to reach an overall baseline of 23.5 million tons by 2020. The market has experienced the effects of such growth, especially regarding the environmental performance of the production processes. In Brazil, renewable assets have been used to overcome the adverse consequences of this expansion. This study evaluates this issue for the production of Brazilian polystyrene resins, general-purpose polystyrene (GPPS) and high-impact polystyrene (HIPS). The effects of replacing fossil ethylene with a biobased alternative are also investigated. Life Cycle Assessment is applied for ten scenarios, with different technological approaches for renewable ethylene production and an alternative for obtaining bioethanol, which considers the export of electricity. The fossil GPPS and HIPS show a better performance than the partially renewable sources in terms of Climate Change (CC), Terrestrial Acidification (TA), Photochemical Oxidant Formation (POF), and Water Depletion (WD). The exception is Fossil Depletion (FD), a somewhat predictable result. The main environmental loads associated with the renewable options are related to the sugarcane production. Polybutadiene fails to provide greater additional impact to HIPS when compared to GPPS. With regard to obtaining ethylene from ethanol, Adiabatic Dehydration (AD) technology consumes less sugarcane than Adiabatic Dehydration at High Pressure (ADHP), which leads to gains in TA and POF. In contrast, ADHP was more eco-friendly for WD because of its lower water losses and in terms of CC because of the advantageous balance of fossil CO_{2eq} at the agricultural stage and the lower consumption of natural gas in ethylene production. The electricity export is an auspicious environmental opportunity because it can counterbalance some of the negative impacts associated with the renewable route. According to a "cradle-to-grave" perspective, the partially renewable resins show a more favorable balance of carbon. This difference increases when sequestration and biogenic carbon emissions are considered.

1. Introduction

Polystyrene (PS) is a thermoplastic polymer produced from styrene, a petroleum-derived liquid hydrocarbon. The homopolymers of styrene have a sparkling appearance and are often referred to as crystal or general purpose polystyrene (GPPS). Because of the brittleness of GPPS, styrene can also be polymerized in the presence of polybutadiene to produce a more resistant resin called high-impact polystyrene (HIPS). GPPS and HIPS have a wide range of applications that include packaging, electronic equipment, furniture, machinery, and transportation (PlasticsEurope, 2008).

The global demand for PS has a compound annual growth rate (CAGR) of 1.4% per decade since 2000, which resulted in 14.9 million tons being required in 2010. In the coming years, this market expects to have an even more impressive growth and thereby reach an overall demand of 23.5 million tons by 2020 (GBI, 2012). Companies have examined the consequences of such an expansion, especially with regard to the environmental performance of PS production. In many cases, Life Cycle Assessment (LCA) has been used for these evaluations (ACC, 2011; Madival et al., 2009; PlasticsEurope, 2008; Suwanmanee et al., 2013; Zabaniotou and Kassidi, 2003). When applied to different polymers (GPPS, HIPS, the Polylactic acid — PLA, the Polyethylene terephthalate — PET, etc.), LCA results have shown that the production stage appears to be the main source of concern in environmental terms because it is a step that is highly dependent on energy sources, as noted by Suwanmanee et al. (2013).

The market concern with environmental issues has motivated companies from the polymeric sector to seek alternatives that make their products rely less on fossil resources and become more environmentally sustainable. It is thus that the prospect of reversing to renewable origins started to develop and the potential environmental benefits of these amendments were examined (Gironi and Piemonte, 2011; Harst and Potting, 2013; Leceta et al., 2014; Shen et al., 2010; Weiss et al., 2012;

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Yates and Barlow, 2013). Once again, the use of fossil resources did not appear to be a cause of worsened environmental impact profiles.

In Brazil, the incorporation of renewable assets in polymer production takes place, on an economical scale, during the production of "Green Polyethylene", in which ethylene (C_2H_4) is obtained from sugarcane ethanol (Morschbacker, 2009). Although ethanol dehydration technology has been dominant in Brazil since the early 1980s, only in the twenty-first century did the Brazilian petrochemical companies show an effective interest in the process because of the decreasing cost of sugarcane on the internal market and the rising price of oil worldwide (Iles and Martin, 2013). With this market consolidation, companies have attempted the same route employed for the production of other resins, namely the 'Polystyrene Partially Renewable' approach. However, the real effect of renewable sources on the environmental impact of polymer production has not been clearly reported in the literature.

This study evaluates the environmental performance of the production of GPPS and HIPS in accordance with the conditions present in Brazil. HIPS is included in the study to investigate the changes in environmental profile caused by polybutadiene. In view of the current technological trends in polymer production, the environmental effects of replacing fossil C_2H_4 with a renewable alternative obtained from sugarcane are also discussed under two perspectives: (i) one comprehending only the chain of production of the two resins ("cradle-to-gate"); and (ii) a wider perspective that considers the whole life cycle ("cradle-to-grave"). Filling this gap is very important in a country like Brazil, where the production of polymer resins tends to increase due to the recent discovery of oil in the pre-salt layer, so that the sector can position itself regarding the supply on both national and external markets.

2. Methodology

Attributional LCA, applied according to a "cradle-to-gate" approach, is used to determine the environmental performance of the products under analysis. Table 1 summarizes the GPPS and HIPS formulations commonly found on the market, which are also used to represent the PS resins.

Fig. 1 describes the ten possible scenarios for processing GPPS and HIPS that we evaluated. The analysis consists of the direct comparison of environmental performance results for resins of the same modality.

Scenarios S1 and S6 include the production of fossil GPPS and HIPS. Therefore, the C_2H_4 and benzene (C_6H_6) used for the production of the styrene monomer and polybutadiene to be incorporated into the HIPS are obtained from crude oil and natural gas. Scenarios S2–S10 use C_2H_4 obtained from sugarcane ethanol. In S2 and S7, the C_2H_4 is obtained by adiabatic dehydrogenation. The utilities – heat and electricity – required for ethanol production are produced by cogeneration from sugarcane bagasse. For S3 and S8, the manufacturing of ethylene occurs at high pressure. This alternative saves energy compared to the previous process.

Ethanol production in S4 and S9 provides a surplus of electricity because the cogeneration operates at high pressure, thus generating a byproduct to be exported for the electric grid. In these scenarios, C_2H_4 is still obtained by adiabatic dehydrogenation. In S5 and S10, the synthesis of C_2H_4 is carried out at high pressure and electricity export takes place. For all the scenarios described above, the Life Cycle modeling (LC-modeling) takes into account the average technologies used in Brazil.

Table 1
Formulation and physical properties of GPPS and HIPS resins.

Major components of the formulation	Typical value (%)	
	GPPS	HIPS
Ethylene (C_2H_4)	74.4	69.1
Benzene (C_6H_6)	25.6	23.8
Polybutadiene $(C_4H_6)_n$	–	7.1

3. Description of process technologies

3.1. Production of GPPS and HIPS from fossil chemicals

The Brazilian mix of crude oil makes up 81% of the domestic production of fossil fuels (~92% offshore). The remainder is imported from Africa and the Middle East (EPE, 2013). The average refining procedure consists of crude oil desalting, atmospheric and vacuum distillations, catalytic cracking, and hydrotreating (ANP, 2012).

Regarding natural gas, over 58% of the Brazilian demand is catered by extraction from petroleum gas fields. The remaining 42% is imported from Bolivia (EPE, 2013). Fossil ethylene is formed by the steam cracking (750–875 °C) of a solution containing natural gas and naphtha produced from crude oil refining (Zimmermann and Walzl, 2005). In Brazil, C_6H_6 is mainly obtained through catalytic reforming (Parker, 2013), a technological route in which naphtha is blended with hydrogen and then exposed to a chlorinated catalyst at 500 °C and 15–50 bar. C_6H_6 and C_2H_4 are converted into C_8H_{10} by catalytic alkylation with a synthetic zeolite. The dehydrogenation of C_8H_{10} produces styrene monomers, which are submitted to free-radical polymerization to yield GPPS (Fig. 2).

The synthesis of HIPS starts by dissolving polybutadiene (C_4H_6) in a mixture of C_8H_8 and additives (diluents, chain-transfer agents, and initiators). With the onset of polymerization, the PS forms a separate phase (Mahl et al., 2005).

3.2. Adiabatic Dehydration of ethanol (AD)

Ethylene production from the catalytic Adiabatic Dehydration (AD) of ethanol was modeled based on the technological approach provided by Barrocas et al. (1980), Baratelli (1981), and Kagyrmanova et al. (2011).

Ethanol is vaporized in a heat exchanger and mixed with steam (1.5 kg/kg C_2H_4). The gaseous solution is heated in a furnace – with an energy consumption of 6.4 MJ/kg C_2H_4 – and fed into the adiabatic reactor (Fig. 3). This value is somewhat higher than the result provided by the dataset "Ethylene production from cane based ethanol. ESA-DBP" from CPM Database (5.6 MJ/kg C_2H_4), which also describes the environmental burdens for production of ethylene from Adiabatic Dehydration of ethanol for the Brazilian conditions (Liptow and Tillman, 2009).

The dehydration process is endothermic. C_2H_4 goes through a condensation tower and a drying process before it can be marketed (99.3%$_{vv}$). The conversion rate of ethanol into ethylene surpasses 98%.

3.3. Adiabatic Dehydration of ethanol at High Pressure (ADHP)

Adiabatic Dehydration at High Pressure (ADHP) is a variation of the previously described process. The transformation occurs in a set of adiabatic fixed-bed reactors at 380–420 °C and 4.0 MPa in the presence of the γ-Al_2O_3 catalyst (Fig. 4). After dehydration, the product is purified by adsorption in a zeolite sorbent and undergoes cryogenic distillation. Compared to the AD technology, this alternative generates C_2H_4 at a higher purity grade (99.96%$_{vv}$) and lower energy consumption – 1.2 MJ/kg C_2H_4 – but with a slightly lower C_2H_6O conversion efficiency (95%). The energy saving is due to the reaction products being obtained at high pressure, which makes recompressing prior to entering the separation tower unnecessary. The ADHP process was modeled based on parameters and information derived from Barrocas and Baratelli (1983), Barrocas et al. (1980) and Coupard et al. (2013).

3.4. Obtaining ethanol from sugarcane

The production of hydrated ethanol from sugarcane is depicted in Fig. 5. The model for the agricultural stage considers the technological procedures practiced in the state of São Paulo, which provided 59% of the total Brazilian sugarcane production between 2005 and 2013 with an average agricultural productivity of 85.6 t/ha (CONAB, 2014).