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Bi-dimensional sustainability analysis of a multi-feed biorefinery design for biofuels co-production from lignocellulosic residues and agro-industrial wastes

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ABSTRACT

This paper presents a multi-feed biorefinery design (MPB10) as a solution for producing bioethanol from lignocellulosic residues and simultaneously treating agro-industrial wastes (cheese whey and tequila vinasses). MPB10 exhibits a higher process complexity than simpler conventional lignocellulosic biofuel biorefineries. However, the design increases the overall energy productivity and achieves similar environmental and economic sustainability values than a single-feedstock biorefinery producing lignocellulosic ethanol and electricity (SPB).

According to the bi-dimensional sustainability method employed in this work, the most important sustainability indicators were the End-use Energy Ratio (EER) for the environmental domain and Yield together with Total Production Cost (TPC) per energy unit produced for the economic domain. MPB10 scored 6% and 18% higher values for the first two indicators than its SPB counterpart with the added benefit of solving a severe environmental pollution problem. Nevertheless, MPB10 TPC per energy-unit and per litre of bioethanol are 6% and 30% higher than SPB, respectively.

1. Introduction

Biofuels from lignocellulosic feedstock will play an important role in the short-term as fossil fuel substitutes for transport (Tanaka, 2011). Different government directives have been already proposed to promote and support the production and use of liquid biofuels in the autotransport and aviation sectors. For instance, the US Renewable Fuels Standard (RFS) established that 60 billion litres of the total renewable fuels to be used by 2022 in the US must come from lignocellulosic biomass (US Environmental Protection Agency, 2006), and at the time of writing, the European Community suggests a 0.5% contribution from second-generation (2G) biofuels to the autotransport sector by 2020 (European Union Council, 2015). Some biorefining technologies based on biochemical platforms have reached sufficient maturity for their deployment at commercial scale (Stephen et al., 2011; Tanaka, 2011), corroborated by the recent opening of 3 biorefineries using 2G feedstock (McCue, 2013; Lane, 2014b,a).

However, the increase of lignocellulosic biomass demand will bring, in the medium term, its revaluation and a shift in availability with its consequent impact on the economics of biofuels production. For instance, Sanchez et al. (2013) showed the effect of using lignocellulosic agro-residues with different plant capacities and polysaccharide concentrations (proportional to feedstock prices) on the Total Production Cost (TPC) and energy efficiency of biochemical biorefineries (Kamm et al., 2010). Plant capacities of around 500 ton dry basis (DB)/day were established as the minimum size in order to maintain a TPC no larger than 20% above competitive TPCs achieved in large-scale plants. For those biorefineries with highly efficient biochemical transformation

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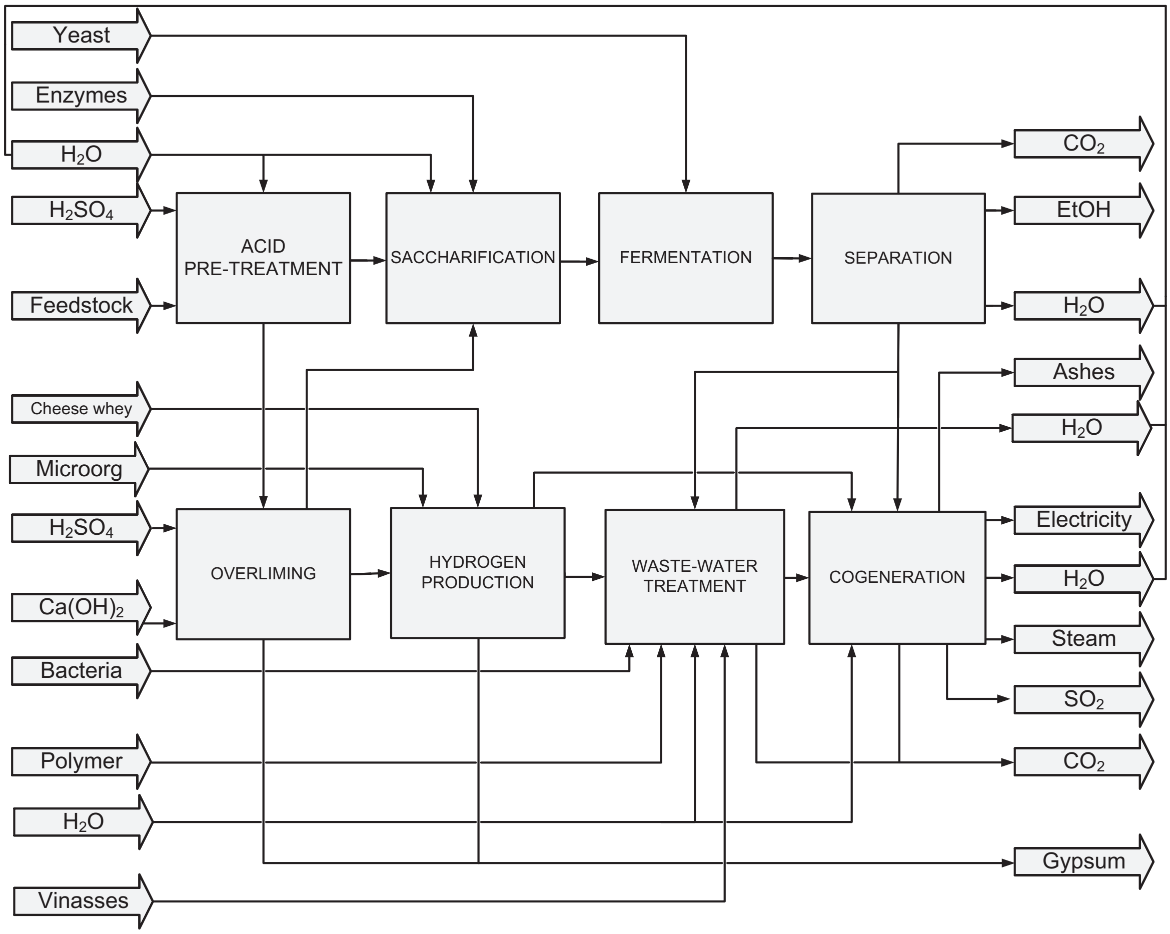

Fig. 1 – MPB10 block diagram.

steps, alternatives for increasing plant profitability or improving environmental sustainability are related to either the use of multiple feedstock, reductions in direct operating/capital costs, or improvements in process tasks not directly related to biofuels production, such as efficient process water usage, CO_2 re-utilization, or (heat and electricity) co-generation (Sanchez et al., 2014).

This paper presents a biorefinery design that exploits the use of multiple raw-materials for producing energy in the form of biofuels and electricity and, simultaneously, providing a solution for the environmental pollution caused by local agro-industrial wastes. The biorefinery produces bioethanol from wheat straw in a pretreatment-saccharification-fermentation train as its main product and uses waste streams from the dairy (cheese whey) and tequila (vinasses) industries as raw materials for enhanced electricity production, making the biorefinery almost self-sufficient in electricity. Biohydrogen is produced in a dark fermentation stage from the cheese whey waste and a stream of pentoses-rich hydrolysates derived from the pretreatment stage. Produced acetates and butyrates are sent, together with the vinasses stream, to a wastewater treatment (WWT) stage improving biogas production. Both biohydrogen and biogas, as well as lignin and biomass residues from the bioethanol separation stage, are employed as fuel for electricity production in the co-generation stage. Under this multi-feed scheme, water consumption and TPC per unit of energy produced are smaller than single-feed biochemical biorefineries found in the literature (e.g. (Aden et al., 2002; Hamelinck et al., 2005; Kaparaju et al., 2009; Kazi et al., 2010). This biorefinery would be hypothetically located in a specific agro-industrial region of western Mexico with sufficient supplies within a 80 km radius of the main feedstock (Sanchez et al., 2013) and waste streams for a 500 ton DB/day capacity plant. Available amounts of cheese whey and highly pollutant tequila vinasses wastes in this region are approximately 100 ton/day (50%, w/w) (Valencia and Ramirez, 2009; Lugardo, 2013) and 3900 ton/day (Lopez-Lopez et al., 2010), respectively. Vinasses treatment and its associated biogas production is currently being adopted by most large-scale tequila producers. However, small and medium size tequila factories may not have access to these technologies. The use of a multi-feed biorefinery that could be used at a regional level to deal with this environmental problem and simultaneously provides other benefits (such as energy production) could be an affordable solution.

This 500 ton DB/day multi-feed biorefinery (termed MPB10) was designed to be as economically and environmentally sustainable as a similar (but less complex) single-feed biorefinery (SPB) producing bioethanol from the same feedstock (i.e., wheat straw) with a competitive TPC. Economic and environmental metrics and indicators taken from the chosen sustainability analysis method were employed as design guidelines for MPB10 focusing on improving energy productivity and reducing water consumption whilst maintaining the amount of bioethanol produced as close as possible to SPB production. The social domain of the sustainability analysis was not considered since it falls beyond the authors' expertise. The resulting MPB10 design matches the economic, environmental and global performance of SPB. This is achieved by employing a small fraction (10%) of the pretreatment liquid hydrolysates (8 ton/day) rich in pentoses in the dark fermentation stage, sufficient to treat 50 ton/day of cheese whey (half of the amount available in the region) with a 3.3:1 lactose:pentose mass ratio, higher than the minimum ratio required to guarantee maximum acetic and butyric acids, as well as biohydrogen production in the dark fermentation stage than with cheese whey or wheat straw hydrolysates alone (Lopez-Hidalgo et al., 2013). Regarding vinasses, 10% of the available amount (390 ton/day, equivalent to the production of a medium size tequila factory) is fed into the biorefinery WWT stage, achieving the same output-COD value as SPB.

The following section presents a brief description of the MPB10 design as well as its single-feed biorefinery (SPB) counterpart, including the calculation of their corresponding Biorefinery Complexity Indices (BCI) as a way of quantitatively comparing the process complexity of