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Estimating the environmental impacts of a brewery waste–based biorefinery: Bio-ethanol and xylooligosaccharides joint production case study

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ABSTRACT

In the food industry, the brewing sector holds a strategic economic position since beer is the most consumed alcoholic beverage in the world. Brewing process involves the production of a large amount of lignocellulosic residues such as barley straw from cereal cultivation and brewer's spent grains. This study was aimed at developing a full-scale biorefinery system for generating bio-ethanol and xylooligosaccharides (XOS) considering the mentioned residues as feedstock. Life Cycle Asssessment (LCA) methodology was used to investigate the environmental consequences of the biorefinery system paying special attention into mass and energy balances in each production section to gather representative inventory data. Biorefinery system was divided in five areas: i) reconditioning and storage, ii) autohydrolysis pretreatment, iii) XOS purification, iv) fermentation and v) bioethanol purification. LCA results identified two environmental hotspots all over the whole biorefinery chain: the production of steam required to achieve the large autohydrolysis temperature (responsible for contributions higher than 50% in categories such as acidification and global warming potential) and the production of enzymes required in the simultaneous saccharification and fermentation (> 95% of contributions to terrestrial and marine aquatic ecotoxicity potentials). Since enzymes production involves high energy intensive background processes, the most straightforward improvement challenge should be focused on the production of steam. An alternative biorefinery scenario using wood chips as fuel source to produce heating requirements instead of the conventional natural gas was environmentally evaluated reporting improvements ranging from 44% to 72% in the categories directly affected by this hotspot.

1. Introduction

The depletion of fossil fuels, the increasing concerns regarding climate change effects and the need of an environmental-friendly economy are forcing the interest towards the development of technologies based on renewable sources to produce bio-chemicals (e.g., plastics, foams, building blocks, polymers) and bio-energy (Sanders et al., 2007). In this sense, biomass plays a key role for the sustainable global development (Sanders et al., 2012). The main use of biomass is for food and feed, however, valorization of biomass-based waste is focused the research and development since it could be used in other large scale applications and the no-competition with food/feed is guaranteed (Liu et al., 2012; Kolfschoten et al., 2014). Moreover, other derived achievements from biomass-based economies have been identified such as regional energy security and rural economies improvement (Liu et al., 2012). The implementation of biorefinery approach is attaining special attention not only from an environmental perspective but also because biorefineries offer unprecedented opportunities (Liu et al., 2012; Sanders et al., 2012). The biomass-based feedstocks can be deconstructed into multiple high-added value products depending on the selected strategy (Borrega et al., 2011; Horhammer et al., 2011; Liu et al., 2012; Kolfschoten et al., 2014; Vargas et al., 2015). Thus, the valorization sequence selected will considerably affects not only to the type of yielding products but also their yield and inputs/energy requirement.

Regarding potential feedstocks used in biorefineries, there is a considerable interest in straw, a lignocellulosic by-product. Cereal straw is an agricultural residue from harvesting, which has traditionally been incorporated into the soil as nutrients and carbon supplier, directly burnt for heating purposes or used as animal beeding (Soon and Lupwayi, 2012). Nevertheless, it has attracted the attention from cellulosic ethanol industry by environmental and cost-effective issues (Kumar et al., 2016; Neves et al., 2016; Vargas et al., 2016).

Barley (*Hordeum vulgare*) is an abundant cereal in the world and it is

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one of the ten most common crops (Krawczyk et al., 2008), being Spain placed in the fifth position in terms of global production volume (Vargas et al., 2015). One of the main barley-demanding industries is the brewing industry, where the grain is the main raw material. The high starch content and the good adherence of the husks to the grain body even after malting and milling are the rationale behind barley use in beer production (Pascari et al., 2018). Beer is the most consumed alcoholic beverage in the world (Pascari et al., 2018) so, the demand for barley grain is outstanding. According to the beer production process (Mussatto, 2014; Pascari et al., 2018), the brewer's spent grains (BSG) constituted by the husk and seed coat layers are the main residue from the brewing process (~20 kg of wet brewer's spent grains are produced per 100 L of beer produced) as well as lacks economically feasible applications (Mussatto, 2014; Rojas-Chamorro et al., 2018). Moreover, cereal cultivation stage involves the co-production of straw – up to 0.53 kg straw per kg grain (Larsen et al., 2012; Vargas et al., 2015). Both (spent grains and straw) are an important and cheap source of lignocellulosic material with high carbohydrate content, so multiple potential applications such as second generation bio-ethanol and high-added value products could be identified (Vargas et al., 2015, 2016).

Having a look into lignocellulosic structure, it is constituted by cellulose, hemicelluloses and lignin as principal components. The cellulose, through enzymatic hydrolysis and fermentation, it might be converted to liquid fuels such as bioethanol. The hemicelluloses are considered an important source of valuable compounds as xylooligosaccharides (XOS), useful in food and pharmaceutical industries. XOS (considered novel non-digestible oligosaccharides with prebiotic potential, immunostimulating effect, anti-allergy, anti-infection and anti-inflammatory properties) are made up of β-(1,4)-linked xylose units (Chung et al., 2007; Meyer et al., 2015; Reis et al., 2014). The lignin can be used for the obtaining of high added-value products, such as resin precursors, heavy metal sequestrant, antimicrobial agents, aromatic compounds, syngas products, among others (Dávila et al., 2017). Therefore, this work deals with the large scale design and optimization of an industrial process for both barley straw and BSG valorization following a biorefinery scheme. The valorization sequence chosen for analysis includes a first step of hydrothermal pretreatment, with recovery of valuable hemicellulose-derived compounds in a separate liquid stream, and other step of simultaneous saccharification and fermentation (SSF) of the solid stream to obtain high bio-ethanol concentrations. The biorefinery scheme has been assessed from an environmental following the LCA methodology and considering a cradle-to-gate approach. To our knowledge, there is no peer-review studies available in the literature that analyse the joint production of bio-ethanol and XOS from alternative feedstocks. In the following, the production process at large scale of bio-ethanol and XOS is described in detail paying special attention to the design process.

2. Methodology

2.1. Life cycle assessment

Life Cycle Assessment (LCA) is considered one of the most developed tools for looking holistically at the environmental consequences linked to the life cycle of production processes, products or services. In this sense, it is widely used by environmental professionals and policy makers for the systematic evaluation of the environmental dimension of sustainability. Numerous studies focused on chemical and waste management processes have been environmentally assessed following the ISO (2006) guidelines (Burgess and Brennan, 2001; Kralisch et al., 2014; Al-Salem et al., 2014; Deorsola et al., 2012). In addition, several authors have explored the implementation of LCA methodology in environmental studies of biorefineries (Mu et al., 2010; Neupane et al., 2013; Gilani and Stuart, 2015). Therefore, its applicability in this area is justified.

2.2. Goal and scope definition

The goal of this LCA study is to provide a full overview regarding the production of both bio-ethanol and XOS under a biorefinery scheme as well as to determine its environmental performance. To do so, the biorefinery process has been modelled at full-scale process based on laboratory-scale data (Vargas et al., 2015, 2016). The scale-up of chemical processes requires a certain understanding of the involved steps (Piccinno et al., 2016). Therefore, the framework proposed by Piccinno et al. (2016; 2018) for scaling-up chemical production systems for LCA studies from laboratory-scale data has been followed in detail. An attributional cradle-to-gate approach has been contemplated in this research study, considering barley straw and BSG from brewery industry as key raw materials.

Since an attributional approach has been considered, the impacts have been estimated from the processes and material/energy flows used directly in the bio-ethanol and XOS life cycle. Therefore, energy and mass balances have been performed for the modelling of the full-scale biorefinery plant with the aim of gathering all the required data for the Life Cycle Inventory stage.

As difference to laboratory processes which are often far from being optimized (mostly in terms of resource consumption and energy efficiency) as well as they do not have the benefit of economies of scale (Piccinno et al., 2018), scale up production processes give a first approach to identify bottlenecks that should need to be improved in perspective of a possible industrial production. Therefore, a contribution analysis of the different production sections has been performed with the aim of identifying the environmental hotspots.

2.3. Functional unit and allocation procedure

LCAs are often performed using a functional unit that refers to the product obtained in the production system. However, biorefineries commonly yield on multiple co-products. In biorefinery systems the choice of method for allocating environmental impacts between the co-products is a common challenge (Cherubini et al., 2011; Sandin et al., 2015) since it can considerably influence decision-making strategies. In addition, allocation problems arise when it is not feasible to split involved processes or areas between the co-products. Thus, two approaches have been considered in this study to report the environmental impacts derived from the biorefinery under study.

1 Approach avoiding allocation: the functional unit is considered as the portfolio of co-products (i.e., bio-ethanol and xylooligosaccharides) that are generated in the valorization route (Gilani and Stuart, 2015). Thus, environmental impacts are calculated for a reference flow of 74.22 tonnes of lignocellulosic stream that enters in the valorization pathway and corresponds with a production batch.
2 Approach including allocation: the environmental impacts of the biorefinery are allocated to the co-products using a partitioning method based on the economic value (market value) of co-products. This perspective is deemed reasonable since both are target products for the biorefinery. The partitioning has been applied to areas connected to both products such as raw material reconditioning and storage (area 1) and autohydrolysis pretreatment (area 2). Regarding ancillary activities (solid and liquid waste management) and on-site emissions derived from the valorization strategies, it has been possible to identify which flow correspond to each co-product and thus, partitioning has not been required. This overriding approach is acknowledged by ISO 14044 (ISO, 2006).

2.4. Description of the full-scale bio-ethanol and XOS production biorefinery

The raw material considered in this biorefinery is based on the combination of barley straw from cereal cultivation stage and the BSG