Isobutene production from wheat straw in a biorefinery perspective: A life cycle analysis

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1. Introduction

Today there is a scientific consensus that global warming is caused by human actions. Therefore, the concern for the reduction of greenhouse gas emissions must shift the global energy matrix towards renewable technologies to promote a key sector in sustainable development (Longati et al., 2018). In this sense, biorefinery systems play a relevant role in the energy sources of a green carbon economy since these systems can produce both biofuel and bioelectricity (Khatiwada et al., 2016). This study focuses on the life cycle environmental assessment of isobutene production through the valorisation of wheat straw in a biorefinery perspective. Thus, this study aims to determine those factors that may restrict the environmental viability of the biorefinery process, establishing initial pathways in the development of the conceptual design. In addition, the identification of environmental hotspots in the bio-based isobutene production system is carried out, with the objective of reducing the environmental impacts of these stages by proposing improvement plans to achieve a sustainable biorefinery system.

2. Materials and methods

The Life Cycle Assessment (LCA) methodology is used to determine the environmental main contributors in the production of bio-based isobutene. LCA is a comprehensive methodology for the systematic assessment of the environmental impacts of a service or production system throughout all stages of its life cycle (ISO, 2006a). To determine the environmental profile of wheat straw-based isobutene, this study follows the ISO 14040 and 14044 guidelines (ISO, 2006a; 2006b), according to a cradle-to gate approach. The functional unit used to quantify the environmental impacts corresponds to 1 kg of isobutene with 99.6% purity. The biorefinery system was simulated in Superpro designer® v11 software (Intelligen, 2021), and the process simulation considers a biorefinery plant that is supplied with 32,000 $t\cdot yr^{-1}$ of wheat straw and operates for 360 $days\cdot yr^{-1}$ (8,640 $hr\cdot yr^{-1}$). At the cultivation stage, an economic allocation is used to distribute the environmental burdens between wheat grain and straw. Moreover, the inventory data for the background processes are obtained from the Ecoinvent® v3.6 database (Wernet et al., 2016).

The bio-based isobutene production comprises five sections. The first stage is the pretreatment of biomass with a hydrolysis step followed by a steam explosion. The second stage corresponds to an enzymatic hydrolysis process, which is carried out at 50°Cusing 20 $mg\cdot gr^{-1}$ of cellulose of Cellic® CTec3 cellulase (Novozymes, Bagsvard, Denmark) at 20% wt of total solids loading. The third stage is fermentation, in which the culture medium is sterilized, and the nutrients are added to the glucose-rich stream. The fourth stage corresponds to the isobutene recovery, in which distillation and adsorption processes are carried out to obtain an isobutene production of 99.6% purity. The last stage corresponds to a cogeneration system (CHP), in which the residual biomass from the previous stages is sent to an anaerobic digestion process to produce biogas, which is sent to the CHP system to produce high-pressure steam for the pretreatment stage, and the electricity required by the biorefinery plant, while the excess electricity produced is supplied to the grid.

To assess the environmental impacts, the characterization factors of the ReCiPe endpoint V1.04 Hierarchist method (Huijbregts et al., 2016) and the software SimaPro 9.2 (Pré Sustainability, 2021) are used. Thus, the damage categories are human health (DALY), ecosystems ($species\cdot yr^{-1}$) and resources (USD2013). In this sense, the use of endpoints in environmental assessment convey relevant information about the characterization flows to the decision maker (Ismaeel, 2018).

3. Results and discussion

Table 1 presents the environmental profile of the isobutene production based on wheat straw while Figure 1 shows the contribution of the life-cycle stages in the environmental impacts generated by the biorefinery system. According to this figure, the pre-treatment stage is the main contributor in all damage categories with a contribution above 40%. The great contribution of pre-treatment is due to wheat production in human health and ecosystems (above 70%), meanwhile in the resources category, the steam production is the main contributor (55%). Moreover, a marginal percentage of environmental credits is obtained due to the avoided electricity production, because of the excess of energy produced by the biorefinery system.

Table 1. Characterization results of the 1 kg of isobutene production

Damage category	Unit	Total
Human health	DALY	9.15E-06
Ecosystems	species·yr^{-1}	3.16E-08
Resources	USD2013	3.01E-01

Regarding the single score indicator (mPt) to support the decision-making process in the design development of this biorefinery approach, a value of 174 mPt is obtained. Pre-treatment appears as the relevant contributor with 80.9 mPt, followed by enzymatic hydrolysis and fermentation stages with 48.7 and 41.4 mPt, respectively.

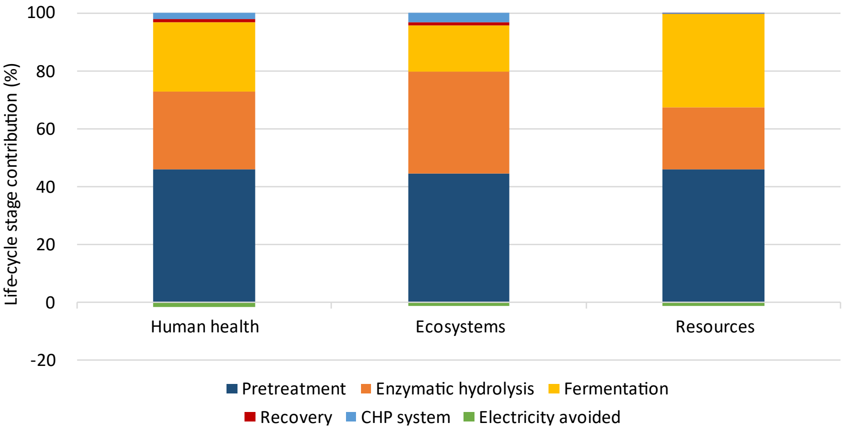

Figure 1. Life-cycle stages contribution of the bio-based isobutene production

4. Conclusion

The use of lignocellulosic feedstock as a carbon source in the large-scale fermentation processes represents a suitable option for isobutene production. In this way, the biorefinery approach emerges as a promising strategy to achieve low carbon energy production. However, improvement actions are required to mitigate the environmental impacts contribution of pre-treatment and enzymatic hydrolysis stages to achieve even better results in the environmental performance of the biorefinery system.

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