Identifying the environmental hotspots in the production of xylitol to be used as a phase change material

Humberto Santos[1], Silvia Guillen Lambea[1]

Afiliación: Grupo de Ingeniería Térmica y Sistemas Energéticos (GITSE)
Instituto de Investigación en Ingeniería de Aragón (I3A)
Universidad de Zaragoza, Mariano Esquillor s/n, 50018, Zaragoza, Spain.
Tel. +34-976762707, e-mail: *hdasilva@unizar.es*

Abstract

The objective of this work is to investigate the environmental hotspots in the production of the phase change material xylitol. Results showed that biotechnological production (BP) has lower environmental impacts than chemical production (CP). Energy is the environmental hotspot for the BP, and energy and nickel for the CP.

Introduction

Lignocellulosic biomass contains mainly three components; cellulose, hemicellulose and lignin, from which hemicellulose is the source of xylose, subsequently turned into xylitol [1]. Although xylitol is well known in the food and pharmaceutical industries, it also has potential application as phase change material (PCM) in thermal energy storage (TES) systems [2] due to its properties [3].

Regarded as a PCM, it was reported in the literature that xylitol has a melting temperature of 93 ˚C and a latent heat of 240 kJ.kg^{-1} [4].

Life cycle assessment (LCA) has become one of the most used tools to investigate a life cycle impact of a product or service. LCA quantifies the environmental impacts of the complete life cycle of a product. This methodology allows one to investigate the environmental impacts of a PCM during their life cycle and understand what the main contributors during its production are, use and end of life.

Thus, this work is in line with initiatives to decarbonize the energy sector by using thermal energy storage systems and the objective is to compare the environmental impacts in the chemical and biotechnological production processes of xylitol and identify the environmental hotspots.

Methodology

The methodology adopted consisted of collecting literature data of the xylitol production pathways, which are the chemical and biotechnological processes.

Data are selected for LCA inventory and a cradle-to-gate environmental assessment of the two production pathways is conducted for the same product system (raw materials/biomass harvesting, transportation and manufacturing) using SimaPro 9.4v as LCA software, Ecoinvent 3.8v as database and ReCiPe 2016 Midpoint (H) as LCIA method. The approach used in this paper followed the LCA guidelines of the International Organization for Standardization (ISO) in which LCA is subdivided into four steps: (I) goal and scope definition; (II) inventory analysis (LCI); (III) life cycle impact assessment (LCIA), and (IV) interpretation. The biotechnological process manufacturing has the following inputs: water, sulfuric acid, quicklime and energy. On the other hand, the chemical process has the same inputs as in the biotechnological process plus the usage of hydrogen and nickel as catalyst. The Functional Unit (FU) is 1 kg of xylitol.

Results and discussion

Four impact category indicators are analyzed: Global Warming Potential (GWP) given in kg CO_{2eq}, Terrestrial Ecotoxicity Potential (TETP) in kg 1,4-DCB, Land Occupation potential in m^{2}a crop eq, and Water Consumption Potential (WCP) in m^3.

In the overall process, considering the unit processes of farming, transportation and manufacturing, the total GWP is 2.20 kg CO_{2eq}, TETP is 11.50 kg 1,4-DCB, LOP is 2.16 m^{2}yr annual crop land, and WCP is 0.97 m^3. Fig. 1(a) shows the contribution of the three unit processes, and for GWP, for instance, manufacturing is responsible for more than 75%. On the other hand, manufacturing had a lower contribution to WCP.

As the manufacturing (BP) is the unit process contributing the most, it is detailed as follows. The total impacts for GWP, TETP, LOP and WCP are 1.74 kg CO_{2eq}, 9.50 kg 1,4-DCB, 2.12 m^{2}yr annual crop land, and 0.31 m^3, respectively. From Fig. 1 (b), more than 75% of these impacts is due to energy use, except in the TETP because sulfuric acid accounts for more than 25%. Oppositely, the environmental impacts for GWP and TETP are higher for the CP, although they follow the same trend as in the BP. Overall, GWP, TETP, LOP and WCP accounts for 8.84 kg CO_{2eq}, 144.02 kg 1,4-DCB, 0.69 m^{2}yr annual crop land, and 0.98 m^3, respectively. From Fig. 1(c), in the three first impacts, more than 90% are from the manufacturing stage, with exception of the WCP in which more than 75% is due to the practices in farming. The manufacturing process is thus analyzed in more detail to understand what the contributors are. For the manufacturing (CP) the GWP, TETP, LOP and WCP were found to be 8.24 kg CO_{2eq}, 141.73 kg 1,4-DCB, 0.64 m^2yr annual crop land, and 0.21 m^3, respectively. In Fig. 1 (d) however, one can see that there are two more inputs, hydrogen gas and nickel. The first one has negligible impact. Nickel, on the other hand, together with the energy use, account for most of each impact indicator. In GWP, for instance, they are responsible for more than 75%.

Xylitol is a bio-based material, regardless of the production process chosen, it will possess a great advantage over other PCMs, especially those obtained from fossil fuels such as paraffin waxes. Regarding the production pathway, it is seen that in GWP and TETP the BP becomes more attractive than the CP. Regarding the energy usage, it comes from two distinct sources: electricity and thermal energy in the form of steam. The electricity accounts for less than 10% in GWP and TETP indicators, and the remaining attributed to the steam. However, in the WCP, electricity accounts for nearly 90%.

Conclusions

Taking GWP as a target, the manufacturing stage contributes the most compared to transportation and farming. The biotechnological process presents 4 times less global warming potential compared to the chemical process, being more attractive to produce xylitol.

Energy is the key contributor in the manufacturing of the BP, while energy and nickel are the environmental hotspots in the CP.

Acknowledgement

We acknowledge the project TED2021-131061B-C31 supported by Ministry of Science, Innovation and Universities of Spain MCIN/AEI/10.13039/501100011033, and grant RYC2021-034265-I both funded by MCIN/AEI/10.13039/501100011033 and "European Union NextGenerationEU/PRTR".

References

[1]. VENKATESWAR RAO, L., GOLI, J. K., GENTELA, J., and KOTI, S. Bioconversion of lignocellulosic biomass to xylitol: An overview. *Bioresource Technology*. 2016, 213, 299–310. Available from doi: 10.1016/j.biortech.2016.04.092.

[2]. ANISH, R., MARIAPPAN, V., JOYBARI, M. M., and ABDULATEEF, A. M. Performance comparison of the thermal behavior of xylitol and erythritol in a double spiral coil latent heat storage system. *Thermal Science and Engineering Progress*. 2020, 15. Available from doi: 10.1016/j.tsep.2019.100441.

[3]. HÖHLEIN, S., KÖNIG-HAAGEN, A., and BRÜGGEMANN, D. Thermophysical characterization of MgCl2·6H2O, xylitol and erythritol as phase change materials (PCM) for latent heat thermal energy storage (LHTES). *Materials*. 2017, 10(4). Available from doi: 10.3390/ma10040444.

[4] DIARCE, G., GANDARIAS, I., CAMPOS-CELADOR, A., GARCÍA-ROMERO, A., and GRIESSER, U. J. Eutectic mixtures of sugar alcohols for thermal energy storage in the 50-90°C temperature range. *Solar Energy Materials and Solar Cells*. 2015, 134, 215–226. Available from doi: 10.1016/j.solmat.2014.11.050.

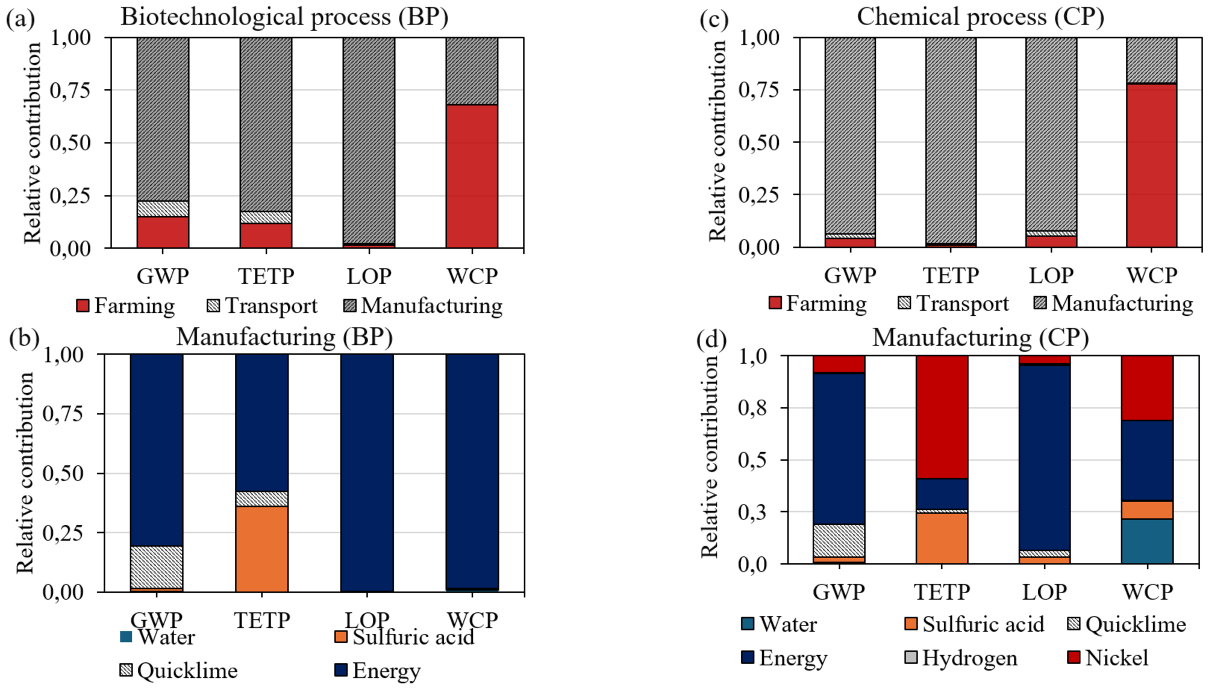

Fig. 1. Environmental impacts of (a) biotechnological process (BP); (b) manufactuting stage (BP); (c) chemical process (CP); and (d) manufacturing stage (CP). Units: GWP-kg CO_{2eq}, TETP-kg 1,4-DCB, LOP-m^2a crop eq, WCP-m^3