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Environmental performance of new processes for the production of fructo- and galacto-oligosaccharides (FOS and GOS)

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Abstract

The prebiotics like FOS and GOS are receiving special attention in the food industry due to their health benefits. They can be produced by enzymatic synthesis by using disaccharides or other substrates as raw materials or by extraction and hydrolysis from different natural sources (roots, legumes). The environmental footprints of these different production schemes are lacking to provide guidance for the ecodesign of such new production processes.

In this work, Life Cycle Assessment (LCA) was undertaken to analyze and compare the production of FOS and GOS by enzymatic synthesis from glucose (to get FOS) or lactose (to get GOS) and hydrolytic production from extraction of yacon potato (to get FOS) or chickpea (to get GOS).

A cradle-to-gate approach was considered in the two scenarios under assessment (the phases of use and/or final disposal of FOS/GOS were not considered). The functional unit was defined as 100 g of FOS/GOS produced. LCAs were performed using data collected at the laboratory scale, supplemented with data from Ecoinvent database. SimaPro was used for the LCA modeling with the midpoint impact EF2.0 characterization method.

Results showed that the main environmental hotspot was the production of yacon potato or chickpea used in the hydrolysis process. For this reason, the hydrolytic process caused higher environmental burdens than the enzymatic synthesis process. Chickpea production causing more impacts than yacon potato production, GOS production generated more environmental impacts than FOS production. When produced by enzymatic synthesis, FOS and GOS were the sources of similar environmental impacts.

From a process point of view, special attention must be paid on three specific stages of production: time of synthesis, freeze-drying and purification of the final product. The environmental load of these stages was associated to high energy consumption and huge amount of ethanol requirement.

The results from this study helped to identify the stages requiring special efforts to ecodesign the production of FOS and GOS at pilot scale in the future. Further research should primarily be focused in the reduction of the biomass used and corresponding solid waste generated during the hydrolytic production. Furthermore, environmental assessment should be included at each development of the process to ensure its efficient eco-design.

Keywords: *prebiotics; innovative production processes; Life Cycle Assessment; food engineering*

1. Introduction

Fructo and galacto-oligosaccharides (FOS and GOS, respectively) are attracting increasing interest as prebiotic functional food ingredients as they may confer health benefits on the host, mainly associated with the modulation of microbiota. However, their benefits go beyond their prebiotic properties, as they are low caloric sweeteners, give a feeling of satiety, contribute to body weight control, relieve constipation, have a low glycemic index and are not cariogenic. Therefore, FOS and GOS are increasingly used in the formulation of dairy products, beverages, bakery products, and some sweets, converting them in functional foods. Moreover, they are extensively employed in infant formula to stimulate the development of newborns microbiota.

As FOS and GOS can be incorporated into many products, their demand has exponentially increased worldwide over time. From a technological point of view, these prebiotics can be produced by enzymatic synthesis (by fructosyltransferase or β-galactosidase enzymes) using disaccharides or other substrates as raw materials or by extraction and hydrolysis (hydrothermal process) from different natural sources mainly from roots (of chicory, artichoke, yacon potato, dahlia or agave) and legume seeds (such as soybean, lupin, lentil, chickpea, pea and cowpea) (Martins et al., 2019).

To the best of our knowledge, no environmental study has been published with special focus on the environmental footprints of different production schemes of FOS and GOS. In this work, the assessment of the environmental impacts associated to the enzymatic synthesis and hydrolytic production of FOS and GOS was performed. To this aim, a Life Cycle Assessment (LCA) was undertaken to analyse two scenarios based on different processes considering sucrose, lactose, yacon potato and chickpea seeds as raw materials. The environmental hotspots were identified on the basis of experimental results carried out at laboratory scale.

2. Material and methods

2.1. Goal and scope definition

The aim of this study was to assess and compare the environmental performance by Life Cycle Assessment of FOS and GOS production by enzymatic synthesis or hydrolysis from different substrates (sucrose and lactose for enzymatic synthesis of FOS and GOS, respectively; hydrolysis of yacon potato and chickpea seeds to obtain FOS and GOS, respectively).

A cradle-to-gate approach was considered in enzymatic and hydrolysis scenarios under assessment, *i.e.*, considering production of sucrose/lactose and yacon potatoe/chickpea seeds, the extraction or substrate preparation to produce the required inputs and the production of FOS/GOS but not the phases of use and/or final disposal of FOS/GOS. This perspective was assumed since FOS and GOS are intermediates and not final products. Among the processes considered throughout the production life cycles, centrifugation, purification, freezing and freeze-drying were performed after the extraction phase. The detailed production processes and the system perimeters are presented on **Figure 1**.

To allow comparisons between the systems under study, the functional unit was defined as 100 g of FOS/GOS produced by enzymatic synthesis or hydrolysis.

2.2. Life Cycle Inventory

Inventory data for the foreground system (direct inputs and outputs for each stage) such as electricity requirements (estimated with power and operational data from the different units: reactors, centrifuges, rotary evaporator, heating plates and freeze-dryers) as well as the use of chemicals, enzymes and water were average data of the laboratory scale.

The background data were taken from Ecoinvent database v3.5 (2018) by using the cut off system model. The laboratory scale process was located at CIDCA-CONICET (La Plata, Argentina) and University of Madeira (Madeira, Portugal), so the average electricity generation and imports/exports from Argentina and Portugal have been considered as GLOBAL in terms of geographical precision in the database.

2.3. Impact characterization

Environmental impacts were quantified with the Environmental Footprint method version 2.0 implemented in Simapro software (v9.0.0.35). This method has been selected as recommended by the EU for product environmental footprint (Fazio et al., 2018). Midpoint impact categories have been considered.

3. Results and Discussion

3.1. Process stages contributions

Enzymatic synthesis. The hotspots associated with enzymatic synthesis were related to the enzymatic synthesis itself and the purification stages, both for FOS and GOS production which presented similar environmental impacts. Enzymatic synthesis was responsible of about 60 ± 15 % of the impacts on all impact categories, while purification was responsible of about 20 ± 15 % of the impacts on all impacts categories. The impact of enzymatic synthesis was mainly due to electricity, requiring a reactor at 50°C during 24 hours and subsequently enzyme inactivation at 95°C. The impact of the purification was mainly due to the use of 1.5 kg of ethanol to obtain the final product rich on FOS or GOS and with low content of monosaccharides. The other steps required the lowest amounts of electricity and no material inputs. Therefore, their contributions to the environmental profile were negligible regardless the impact category.

Hydrolysis. The hotspots associated with hydrolysis were related to the substrate extraction and the freeze-drying although we obtained differences on the relative values and categories. For FOS production, substrate extraction contributed to 39 ± 20 % and freeze-drying to 26 ± 14 % of the impacts. For GOS production, substrate extraction contributed to 57 ± 28 % and freeze-drying to 16 ± 13 % of the impacts. For both FOS and GOS production purification contributed to about 16 ± 12 % of the impacts. Freeze-drying contribution was due to electricity consumption it required, and purification contribution was due to ethanol consumption, as for enzymatic synthesis. The contribution of the substrate extraction step was due to the production process of yacon potato and chickpeas together with solid waste generated after extraction of FOS/GOS from these raw materials. As for enzymatic synthesis, the contributions of the other process steps were negligible.

3.2. Comparisons between the different process scenarios

Figure 2 presents the comparison of the environmental impacts between the processes of enzymatic synthesis and hydrolysis, for both FOS and GOS. A remarkable difference could be noticed between the two processes: enzymatic synthesis caused significantly less environmental damages, both for FOS and GOS and on all impact categories (except for non-cancer human health effects and freshwater ecotoxicity, but the difference in these cases is very low). This should be directly related with differences on the production systems and the substrates used, as detailed above. Although the two processes share a number of stages in common (cleaning, centrifugation, storage and purification), a significant difference between them was observed in the first stage, *i.e.*, the enzymatic synthesis of FOS/GOS from sucrose/lactose or their extraction from biomass (yacon potato/chickpea).

From the energy use point of view, energy consumption were comparable for both enzymatic synthesis and hydrolysis and could not explain the differences observed on **Figure 2**. Enzymatic synthesis implied an enzymatic step based on the use of a cocktail of enzymes with temperatures around 50 °C during 24 hours of reaction and 95 °C for enzyme inactivation. On the other side, hydrolysis included a hydrothermal process under non isothermal conditions, carried out at temperatures between 50 °C and 100 °C but only for 2 hours, requiring rather low energy amount. However, hydrolysis process also involved the additional step of freeze-drying during storage, increasing significantly the electricity requirements of the whole process.

Finally, the total difference on the environmental impacts was mainly due to the huge difference in the amounts of raw materials required for the two scenarios: around 500 g of sucrose / lactose for enzymatic synthesis *vs* more than 5 kg of yacon potato/chickpea for hydrolysis. The interrelated consequence was the high amount of solid wastes generated in hydrolysis processes, also causing an environmental load. Accordingly, hydrolysis reported the worst environmental results.

Among the two hydrolysis processes, the production of FOS caused less impact than the production of GOS, except for water scarcity and mineral and metal use. In accordance of statements above, it was due to the more important environmental impact associated to chickpea production than the environmental impact of yacon potato production.

No literature data are available on these systems for comparison. However, such a study does not claim providing precise environmental impacts of the processes, especially because the study has been conducted at a laboratory scale, which can be far away from an industrial process. Nevertheless, such an approach highlights areas of concern in the further development of the processes, and should be used iteratively at each development stage in order to check if environmental burdens have been decreased by new developments and not transferred to another step of the system. Such an iterative approach could ensure eco-design of the production processes.

4. Conclusions

The production of prebiotics like FOS and GOS is receiving special attention in the food industry due to their health benefits. This study analyzed by LCA two different scenarios at laboratory scale for producing FOS and GOS original mixtures.

Hydrolysis process generated more environmental impacts than enzymatic synthesis. With regards to the production processes themselves, special attention must be paid on three specific stages: time of synthesis, freeze-drying and purification of the final product. The enzymatic based synthesis involved the utilization of enzymes whose production and use require large times of incubation (energy consumption). The hydrolytic production was carried out at high temperatures and lower times than the enzymatic synthesis, requiring less energy. However, the use of freeze-drying in the storage step equaled electricity expenditure for both processes. The environmental load associated to the purification step was due to the huge amount of ethanol used. Nevertheless, the use of huge amount of raw materials in the hydrolysis process induced the highest environmental load which finally widely overcame the environmental burdens associated with energy or ethanol used.

The results from this study helped to identify the stages requiring special efforts to ecodesign the production of FOS and GOS at pilot and industrial scale in the future. Further research should be focused in the reduction of the biomass used and corresponding solid waste generated during the hydrolytic production. Further developments should also include systematically environmental assessment at each development stage to ensure the eco-design of the process, and considering not only the production processes but also their use, and more globally their whole life cycle.

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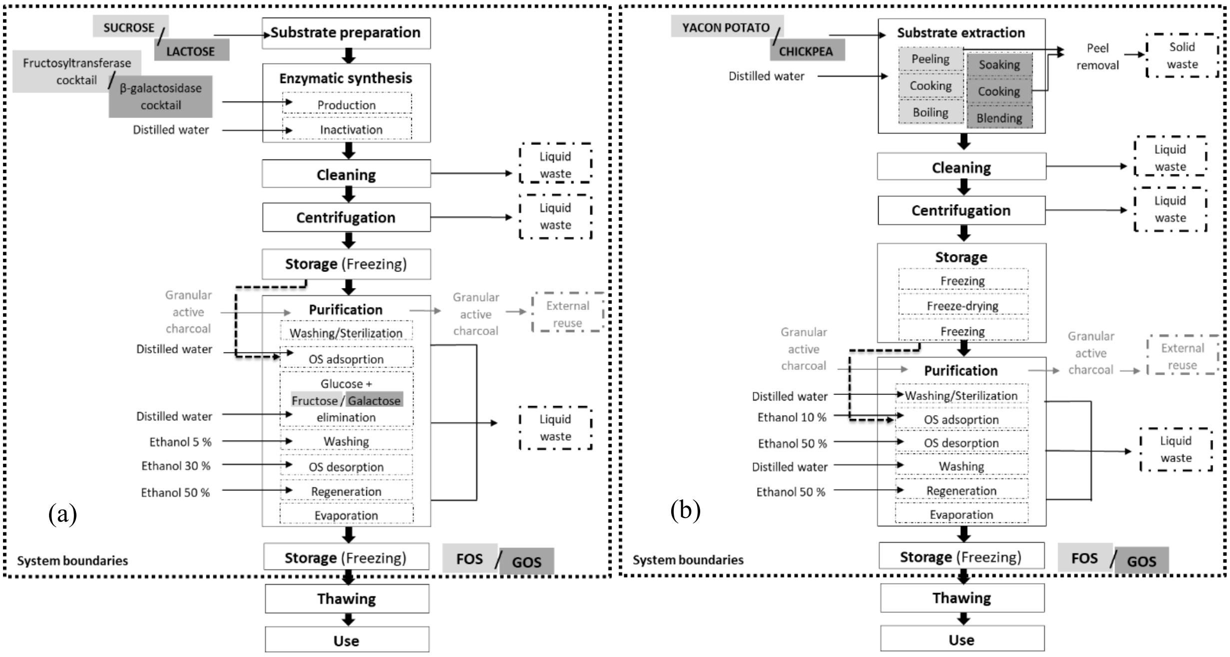

Figure 1. FOS and GOS production processes by enzymatic synthesis (a) or hydrolysis (b).

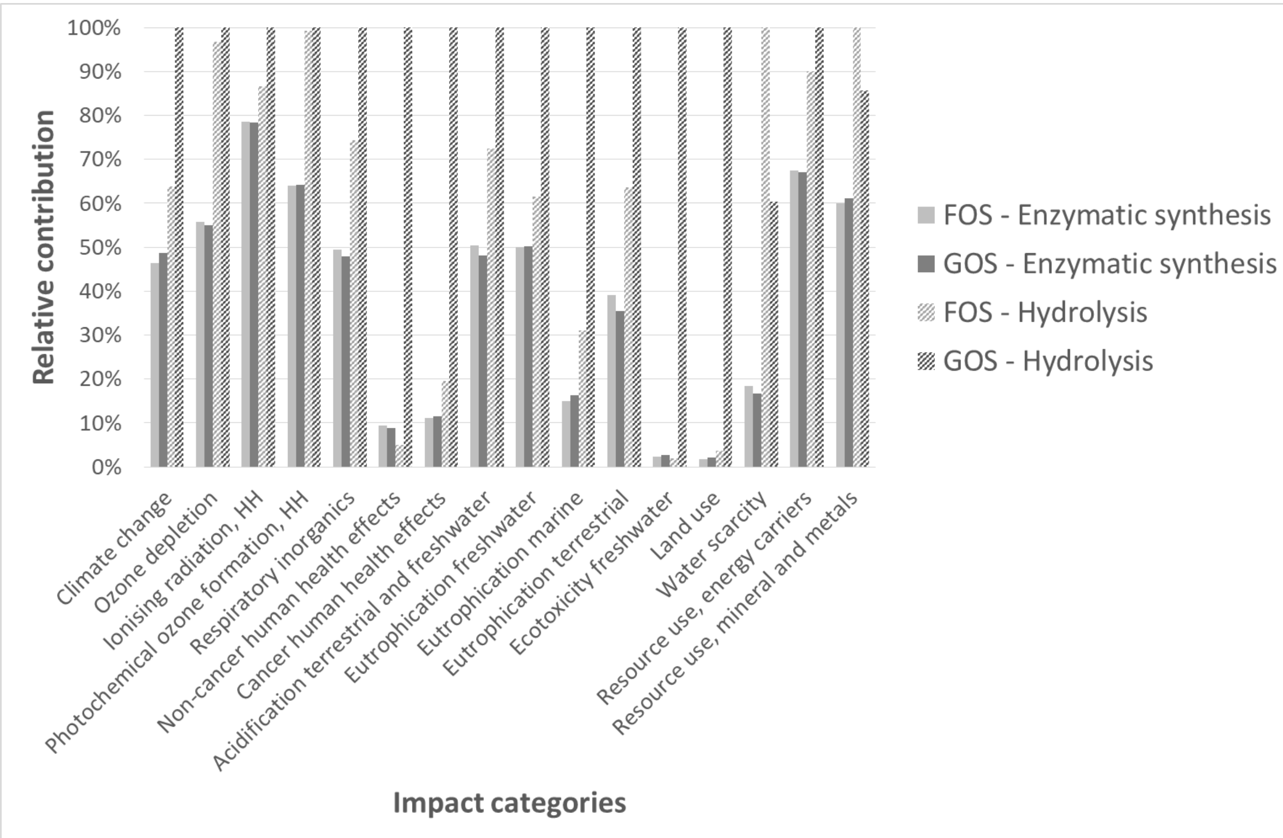

Figure 2. Comparison of the environmental impacts computed by LCA (EF2.0 method) between the processes of enzymatic synthesis and hydrolysis, for both FOS and GOS.