Process simulation for xylitol production from brewer's spent grain in a Colombian biorefinery. Part 1: Xylose production from arabinoxilans extracted by the alkaline pretreatment of BSG

Simulación de proceso para la producción de xilitol a partir de bagazo de cebada en una biorrefinería en Colombia. Parte 1: producción de xilosa a partir de arabinoxilanos extraídos en el pretratamiento alcalino de BSG

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ABSTRACT

This work presents the simulation in Aspen Plus® of a process to obtain arabinoxylans (AX) from Brewer's Spent Grain (BSG), which is the major byproduct of the brewing industry. The process is divided into two stages: alkaline pretreatment and enzymatic hydrolysis. These stages cover the extraction of proteins and AX from BSG using an alkaline pretreatment and enzymatic hydrolysis of the AX separated from the liquid stream to obtain xylose, i.e. the substrate required for the fermentation to xylitol. Simulation results show that xylose obtained corresponds to 8,5 % of the dry weight of the raw material, obtaining a yield of 58 %. Several streams of byproducts were obtained, such as proteins, polypeptides, amino acids, phenolic compounds and lignocellulosic residues that can be valorized in other processes. Simulation was performed in the context of a biorefinery in Colombia.

Keywords: Simulation, brewer's spent grain, xylitol, biorefinery.

RESUMEN

Este trabajo presenta la simulación en Aspen Plus® del proceso para obtener arabinoxilanos (AX) a partir de bagazo de cebada, principal subproducto de la industria cervecera. El proceso se divide en dos etapas: pretratamiento alcalino e hidrólisis enzimática. En la primera etapa, se logra la extracción de proteínas y AX de la cascarilla de cebada y en la segunda etapa, se hidrolizan enzimáticamente los AX separados de la corriente líquida hasta obtenerse xilosa, el sustrato requerido para el xilitol. Los resultados de la simulación mostraron que la xilosa obtenida corresponde al 8,5 % del peso de la materia prima, obteniéndose un rendimiento del 58 %. Adicionalmente se obtienen varias corrientes de subproductos como proteínas, polipéptidos, aminoácidos, compuestos fenólicos y residuos concentrados en lignina y celulosa, los cuales se pueden valorizar en otros procesos. La simulación del proceso se realizó en el contexto de una biorrefinería en Colombia.

Palabras clave: Simulación, cascarilla de cebada, xilitol, biorrefinería.

Introduction

Currently, global economy is based mainly on products derived from fossil resources. Most of the basic and intermediate chemical products are produced using crude oil and natural gas as feedstock. However, considering sustainability principles and objectives formulated by United Nations (UN), several countries have promulgated policies to reduce the negative effects of greenhouse gases emissions on global warming, simultaneously helping to mitigate the economic instability due to the volatility of crude oil price. Those policies have fostered research projects and industrial production that valorize non-fossil sources as raw material for food, feed, energy, chemicals and materials.

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Among the different effects of the development of biorefineries, the implementation of new production methods, as intensified technologies and bioprocesses, is noticeable (Hermann, Blok, and Patel, 2007). The increasing number of industries based on bioprocess has been the precursor of a new and more competitive market of bio-based products. Thus, the renewal of technologies based on fossil resources is imminent to promote the production of new products with characteristics different to those of the chemicals nowadays available. These new products should satisfy the new requirements of consumers who consider sustainability as a key factor in the decision-making process (Jong, Higson, Walsh, and Wellisch, 2011).

The industrial trend to implement sustainable processes, using renewable raw materials (biomass and residues) and producing bio-based products, has favored the development of the biorefinery concept. This concept intends to cover all the available technologies for the treatment of biomass, taking advantage of its wide range of possibilities for the generation of products with high added value (Cherubini, 2010). Although some bio-based products can be fabricated by simple processes, the same product can be obtained by integrated processes in biorefineries where energy, chemicals and materials can be produced simultaneously in a sustainable way (Jong *et al.*, 2011).

The main challenge of biorefineries is to find the biomass with the composition and characteristics required by its products and processes. This fact has led the bio-based chemical industry to seek allies in other manufacture sectors and find organic byproducts that can be used as raw material. In this context, brewery is one of the industries present worldwide and recognized for its large number of organic byproducts (Xiros and Christakopoulos, 2012).

Beer is an alcoholic beverage produced by the fermentation of sugars extracted from barley, whose aroma and flavor are given by hops. In Colombia, the brewing industry is one of the most important economic sectors, mainly due to the high demand of this product. In 2016, national production of beer reached 19,1 million hectoliters, which generated a high amount of organic solid byproducts corresponding to yeast, hops and, in greater proportion, to brewer's spent grain, commonly known as BSG. Usually, a brewery produces approximately 20 kilograms of wet BSG per hectoliter of beer, i.e. about 85 % of the total byproducts of the process (Reinold, 1997). Therefore, BSG is the most important residue in breweries.

Multiple research projects have investigated the use and valorization of BSG. Considering its properties and composition, a large number of potential products can be obtained. BSG has been assessed as feedstock for biotechnological processes, production of energy, supplementary food and feed, construction materials, coal production, fertilizers, among many others (Mussatto, Dragone and Roberto, 2006). The most advanced studies correspond to the use of BSG as a raw material in various chemical processes, e. g. phenolic antioxidant compounds, lactic acid,

ethanol and xylitol (Meneses, Martins, Teixeira, and Mussatto, 2013; Mussatto and Roberto, 2008).

Xylitol is a five-carbon polyol, commonly employed in food and pharmaceutical industry as sweetener. It does not require insulin to be metabolized and it has low heat capacity (Ravella, Gallagher, Fish and Prakasham, 2012). For these properties, xylitol is generally used as sweetener agent in foods aimed at diabetic consumers. In consequence, its production and commercial use have greatly increased in the last decade. Currently, world xylitol production is about 160 000 t per year, equivalent to USD \$ 670 million, and by 2020 it is expected that the production increases up to 242 000 t, equivalent to USD 1 billion (Ravella *et al.*, 2012).

Several studies have been published about the feasibility of biorefineries based on different processes for the production of xylitol from BSG as main raw material. Dávila, Rosenberg and Cardona (2016) reported a study of a biorefinery for the production of xylitol, ethanol and polyhydroxybutyrate from BSG. They established the feasibility for different process configurations with and without heat integration. Likewise, Mussatto, Moncada, Roberto and Cardona (2013) presented various researches using BSG for the production of xylitol. Results of these studies were applied in a techno-economic analysis for a BSG biorefinery located in Brazil, where the technological and environmental feasibility of the project was evaluated.

This work presents the simulation in Aspen Plus V9® of xylose production process from BSG. Xylose is the main sugar for xylitol production. The process for xylitol production includes three main stages: (1) alkaline pretreatment for AX extraction from BSG, (2) enzymatic hydrolysis of AX for xylose production and (3) xylose fermentation. This article presents the simulation of the first two stages. Process simulation was performed with the aim to carry out a feasibility study of a biorefinery in the Colombian context.

Process Description

As mentioned previously, the simulation presented in this work corresponds to the first part of a process designed to produce xylitol from BSG. This process pretreatment had as main objective the conditioning of raw material for the fermentation process, specifically xylose production, which is the main substrate for fermentation and production of xylitol. Figure 1 presents the simplified block flow diagram of this part of the process. Pretreatment process starts with conditioning of the raw material. BSG requires wet grinding to reduce its particle size, creating an interfacial area to facilitate the following operations. After grinding, BSG is preheated and fed to the alkaline treatment stage, where it is mixed with a 4M sodium hydroxide solution. Alkaline hydrolysis is performed to separate hemicellulose from cellulose and lignin, and produce and solubilize arabinoxylans (AX). BSG protein is extracted and alkaline hydrolysis takes place. The alkaline pretreatment implicates the saponification of intermolecular ester bonds cross-linking xylan hemicelluloses and other components, and the porosity of the lignocellulosic biomass

increases with the disintegration of the cross-links (Xu and Sun, 2016).

Then, to precipitate proteins and neutralize the NaOH in excess, both in the liquid fraction, a diluted sulfuric acid solution is added to reach pH 3. Protein fraction is separated from the liquid that contains the AX and the degraded lignin by centrifugation. Yield of the precipitation of protein is assumed 100 % for simulation. Then, azeotropic ethanol is added to the liquid fraction to precipitate AX, which are separated from the liquid by centrifugation. Despite its solubility, a fraction of the Na_2SO_4 produced in NaOH neutralization co-precipitates with AX. The degraded lignin remains in the liquid fraction as furan compounds. After washing the solid fraction with ethanol to dissolve the co-precipitated Na_2SO_4, AX are enzymatically hydrolyzed using six pure commercial enzymes simultaneously (endo-1,4-β-xylanases, α-L-arabinofuranidases, β-xylosidases and α-glucuronidases). The purpose is to obtain a mixture of xylose and arabinose that has to be concentrated for the fermentation stage.
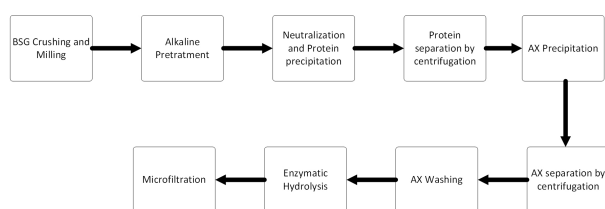

Figure 1. Simplified block diagram of the pretreatment process of BSG to produce xylose.
Source: Authors

Methods and materials

Components required for simulation

Simulation of the process previously described was performed in Aspen Plus V9®. The first step of the simulation was to select the compounds, in the simulator database, that adequately represent the substances involved in the process. BSG from Tocancipá (Colombia) Brewery was supplied by Bavaria S. A. It has ~80 % of moisture, and it is composed of the following five main fractions: hemicellulose (25,13 % dry basis [db]), glucans (18,63 % db), lignin (16,69 % db), protein (14,50 % db) and extractive compounds (22,58 % db) (Rojas-Pérez, 2018). As shown in Table 1, most of the compounds of BSG are not found in Aspen Plus V9® databases. Thus, it was necessary to define them manually, introducing physical and chemical properties available in the literature.

Parameters to define the properties required by the simulator for the different solid compounds were obtained from Wooley and Putsche (1996). Using this information, it was possible to define several solid compounds present in the process, such as cellulose, hemicellulose (kind of arabinoxylans) and lignin, as well as other solids present in the organic material. Additionally, water, ethanol, sodium hydroxide, xylose, arabinose and sodium sulfate were found in the simulator databases. Then, parameters for calculating its properties were taken directly from databases.

Selection of the calculation method

As the phase balance is not relevant for this part of the process, Gil, López, Zapata, Robayo, and Niño (2015) recommended the IDEAL method to perform the simulation. This method is also suitable for processes where unconventional solids are involved, because solid compounds and solubility values are specified by the user based on experimental data.

Then, in the simulation environment – Setup > Specifications section – the METBAR units system was selected. The type of stream selected was MIXCIPSD, because it corresponds to streams where unconventional solids are present and where, in some cases, it is necessary to specify the particle size distribution. This type of stream was chosen because the particle size is an important property for this simulation, considering that grinding and separations are made by the difference of particle size in BSG.

Process simulation specifications

Production capacity: Considering further economic feasibility to be performed according to the results of the simulation, it is necessary to evaluate the process at several production capacities. For this reason, three production capacities were selected regarding breweries located in Colombia:

- 40 000 hectoliters of beer per year that generate approximately 800 t of BSG per year, corresponding to Bogotá Beer Company Brewery – Tocancipá, Cundinamarca.

- 2,3 million hectoliters of beer per year that generate approximately 46 000 t of BSG per year, corresponding to Bavaria Boyacá Brewery – Tibasosa, Boyacá.

- 7,8 million hectoliters of beer per year that generate approximately 156 000 t of BSG per year, corresponding to Bavaria Tocancipá Brewery – Tocancipá, Cundinamarca.

Crushing: Figure 2 shows the crushing block and the streams associated. Grinding is the first stage of the process. The particle size of BSG at the brewery outlet does not facilitate the efficient removal of AX by hydrolysis. Thus, it is necessary to reduce its particle size. To simulate this stage, the input and output particle size distribution of the crushing block, streams 1 and 2 in Figure 2, have to be defined. The input size is specified in the solids sub-stream of the feed stream. An average size of 4mm (4 000 microns) was defined regarding the average size of the barley grain. According to the results of an experimental evaluation performed in this project, BSG must be ground to obtain a mean particle size of 501,2 μm (Rojas-Pérez, 2018).

Table 1. Description of the components used in the process simulation

Component ID	Type	Component name and source of properties	Alias
WATER	Conventional	WATER - Aspen Plus V9 Databases	H_2O
XYLOS-01	Conventional	XYLOSE - Aspen Plus V9 Databases	$C_5H_{10}O_5$-D2
ARABI-01	Conventional	ARABINOSE - Aspen Plus V9 Databases	$C_5H_{10}O_5$-D1
NAOH	Conventional	SODIUM-HYDROXIDE - Aspen Plus V9 Databases	NAOH
XYLAN	Solid	Xylan is considered as a solid throughout the process and never as solution. Additionally, xylan is a polymer, but its molecular weight formula will be taken only as the repeat unit. The other properties are determined on a weight basis and then converted to mole basis for the database, using the molecular weight of a repeat unit (Wooley and Putsche, 1996).	$C_5H_8O_4$
ARABINAN	Solid	Isomer of xylan. The same properties are specified	$C_5H_8O_4$
CELLULOS	Solid	Cellulose is considered as solid throughout the process and never as solution. Additionally, cellulose is a polymer, but its molecular weight formula will be taken only as the repeat unit. The other properties are determined on a weight basis and then converted to mole basis for the database, using the molecular weight of a repeat unit (Wooley and Putsche, 1996)	$C_6H_{10}O_5$
LIGNIN	Solid	Lignin is as solid throughout the process and never as solution (Wooley and Putsche, 1996)	–
ASH	Solid	Ashes contained in the barley are mainly calcium oxides (Mussatto and Roberto, 2005). The compound is defined by the properties of calcium oxide.	CAO
HEMICELU	Solid	Polymer of xylan - arabinan. Properties of xylan are specified.	$C_5H_8O_4$
SULFU-01	Conventional	SULFURIC-ACID - Aspen Plus V9 Databases	H_2SO_4
SODIU-02	Conventional	SODIUM-SULFATE - Aspen Plus V9 Databases	NA_2SO_4
ETHAN-01	Conventional	ETHANOL - Aspen Plus V9 Databases	C_2H_6O-2
PROT-SOL	Solid	Solid protein. Solid type compound. The composition of amino acids present in barley proteins are mainly glutamic acid and glutamine (Linko, Lapvetelainem, Laakso, and Kalio, 1989), thus the compound is defined with the properties of glutamic acid.	$C_5H_9NO_4$
PROTEIN	Conventional	Protein in solution, same properties of glutamic acid. L-GLUTAMIC-ACID	$C_5H_9NO_4$
ENZYME	Solid	The molecular structure, molecular weight, enthalpy of solid formation, heat capacity of solid and density of solid are specified. (Wooley and Putsche, 1996)	–
XYLAN-LQ	Conventional	Xylan in solution. Glutaric acid formation enthalpy is used because it is a compound with the same molecular composition of the xylan monomers (C5H8O4), calorific capacity and density of water, under the assumption that they behave like water because it is a compound that will be very diluted in the process.	$C_5H_8O_4$
ARABN-LQ	Conventional	Arabinan in solution. Same Xylan-LQ specifications.	$C_5H_8O_4$

Source: Authors

Alkaline pretreatment: Figure 3 presents the blocks associated with the alkaline pretreatment. It consists in the use of basic compounds to produce solvation of some polymeric chains present in biomass, increasing its surface area and porosity (Menon and Rao, 2012). The main advantage of this type of treatment is to avoid the formation of furan compounds with inhibitory action during the fermentation stage. Additionally, yield in hemicellulose degradation and pentose formation is high (Bhutto *et al.*, 2017).

The outlet stream of the mill (2 in Figure 2) contains BSG whose particle size has been reduced to facilitate the pretreatment steps. This stream is mixed with a stream of NaOH 4M at 1:14 mass ratio in dry basis of BSG. This relationship was selected according to the results of a previous experimental study performed to determine the effect of some variables on alkaline pretreatment. At that condition, approximately 76 % of the AX contained in the hemicellulose are extracted.

After mixing, the blend was fed to a stirred tank reactor operating at 40 °C. Since the kinetics of the hemicellulose alkaline hydrolysis to AX is unknown, the simulation is developed in a conversion reactor (B2 in Figure 3). Theoretically, in this kind of simulation block, the generation of shorter chains of AX in solution occurs and, likewise, the protein contained in the BSG is solubilized.
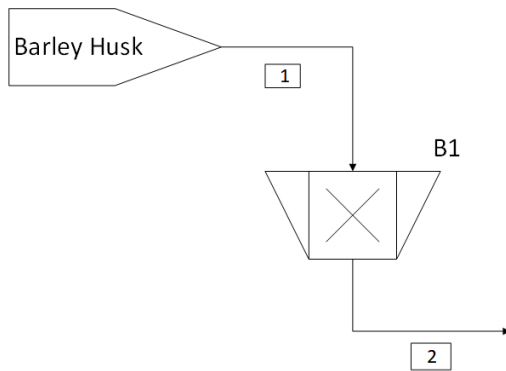
Figure 2. Schematic representation of the crushing block in the Aspen Plus Process Simulator V9® interface.
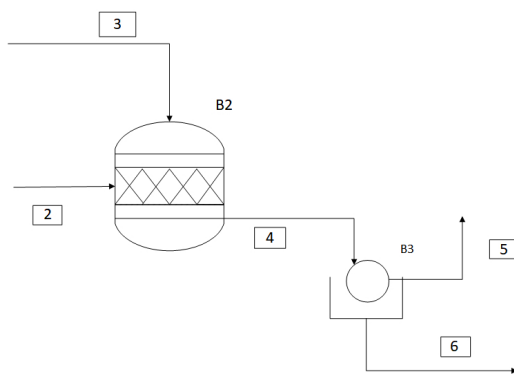**Source:** Authors

Figure 3. Schematic representation of an alkaline pretreatment section in Aspen Plus Process Simulator V9® interface.
Source: Authors

Knowing the composition of hemicellulose of BSG, ~70 % of this fraction corresponds to xylan and 30 % to arabinan. Thus, considering a yield of 76 %, the following reactions are specified in the reactor B2:

1) Generation of xylan in solution from hemicellulose (Conversion of 44,7 % of hemicellulose)

2) Generation of arabinan in solution from hemicellulose (Conversion of 20,3 % of hemicellulose)

3) Protein solid in solution (100 % of Solid Protein)

Finally, a tangential filtration is performed (B3 in Figure 3), where solids are separated from the liquid mixture. The solid stream contains mainly lignin and cellulose compounds and the liquid stream is an aqueous solution of AX and proteins.

Proteins Separation: Figure 3 presents the block associated with proteins separation stage. The liquid stream 6 from the filter B3 is treated in the tank B4 with sulfuric acid stream (7). It is added to neutralize the excess of the NaOH previously used in the alkaline hydrolysis and to bring the solution to the pH of the isoelectric point of the proteins, in order to precipitate them (Vieira *et al.*, 2014). Thus, the acid treatment produces a heterogeneous stream (8) fed to the centrifuge (B5

in Figure 4), where a solid stream (9) containing the protein and a liquid stream (10) containing the AX are obtained.
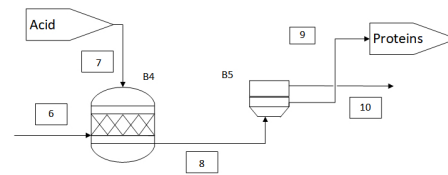

Figure 4. Schematic representation of the protein separation section in the Aspen Plus Process Simulator V9® interface.
Source: Authors

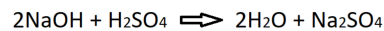The specific reactions for reactor B4 are reported in Figure 5.

$$2NaOH + H_2SO_4 \Rightarrow 2H_2O + Na_2SO_4$$

$$Protein \Rightarrow ProtSol \qquad Protein\ precipitation$$

Figure 5. Reactions specified in the protein precipitation reactor B4.
Source: Authors

Arabinoxylans precipitation and washing: Precipitation of AX is carried out by the addition of ethanol, taking advantage of the low solubility of AX in this solvent. 100 % yield respect to AX precipitation was considered for simulation. Regarding the previous neutralization step, the aqueous stream 10, rich in AX, contains a considerable amount of dissolved Na_2SO_4. Although this salt is soluble in ethanol, a fraction co-precipitates with AX. For this reason, it is necessary to wash the solid AX with ethanol for solubilizing and thus entraining the salt present in the solid.
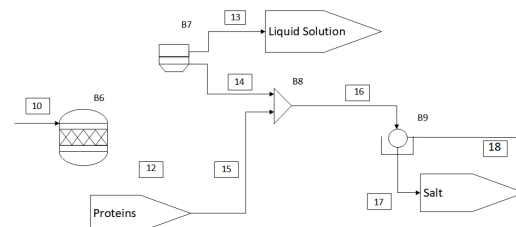
Figure 6. Schematic representation of AX precipitation and washing in the Aspen Plus Process Simulator V9® interface.
Source: Authors

For the simulation of this step, the AX rich liquid stream (10) is mixed with azeotropic ethanol (11) in a volume ratio 1:5 (Reis, Coelho, Coimbra, and Abu-Ghannam, 2015). This condition was selected from previous experimental evaluation. The mixture is sent to a conversion reactor (B6 in Figure 6), where precipitation of AX is specified. The solid-liquid mixture is fed to a centrifuge (B7 in Figure 6) where two phases are separated. Solids stream corresponds to concentrated AX (14). Then, this stream is mixed with azeotropic ethanol (15), to wash the solids and thus remove traces of Na_2SO_4. Finally, the liquid ethanol-salt mixture (stream 16) is separated from the solid AX using a filter (B9 in Figure 6).

Enzymatic Hydrolysis: Once the AX are obtained, enzymatic hydrolysis is carried out. This process is catalyzed by enzymes and the chains of AX are broken in xylose and arabinose.

For the simulation of this stage, two streams are fed to the reactor B10 in Figure 7: one of the streams corresponds to solid AX from filter B9 (18) and the other is the enzyme aqueous solution stream (19), which includes the water required to dilute the substrate to the required conditions. The conditions employed to simulate enzymatic hydrolysis were obtained from experimental tests developed in previous work of the research project (Rojas-Pérez, 2018). Enzymatic hydrolysis is performed at the following conditions: 40 °C, pH 5,5 and AX initial concentration 5 g/L. The reaction was specified in a conversion reactor (B10), where final concentration of xylose and arabinose are 1,31 g/L and 0,44 g/L, respectively. These values correspond to 65 % and 42 % yield, respectively.
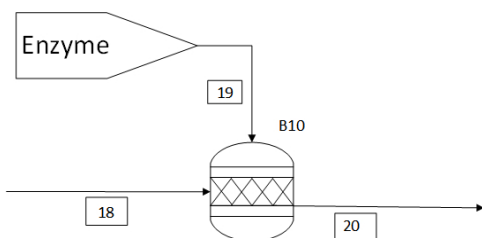

Figure 7. Schematic representation of the hydrolysis reactor in the Aspen Plus Process Simulator V9® interface.
Source: Authors

Results

Results of the simulation validate the process designed. Figure 8 presents the process flow diagram (PFD) and Table 4 shows the material balance for one of the three production capacities studied (156 000 t/year).

As the process for each of the three production cases evaluated was the same, PFD are similar and the differences in mass and energy balances are mainly due to the availability of AX to hydrolyze. Table 2 shows the xylose produced after the process. The final conversion of xylose is close to 8,5 % based on the initial dry weight of BSG, in all the cases. This conversion is mainly linked to yield of the enzymatic hydrolysis, because the conversion of AX into xylose and arabinose is incomplete. In addition to the stream containing xylose and arabinose in the feedstock fermentation section, three byproducts are generated: the solid residue rich in cellulose (stream 5), the protein extracted from BSG (stream 9) and the liquid rich in phenolic compounds, such as p-coumaric and ferulic acids (stream 13).

Table 2. Xylose produced as a function of the BSG production capacity

Brewery	Residual BSG (t/year)	Xylose produced (t/year)
Bavaria Tocancipá	156 000	2 657
Bavaria Tibasosa	46 000	783,5
BBC Tocancipá	800	13,6

Source: Authors

Table 3 shows the net heat duty for the main simulation blocks: Alkaline treatment tank (B2), neutralization and proteins precipitation tank (B4), ethanol mixing tank for AX precipitation (B6) and enzymatic hydrolysis reactor (B10). The only equipment that requires cooling services is the neutralization tank, mainly due to the sudden increase in temperature by the heat of reaction released during the formation of sodium sulfate.
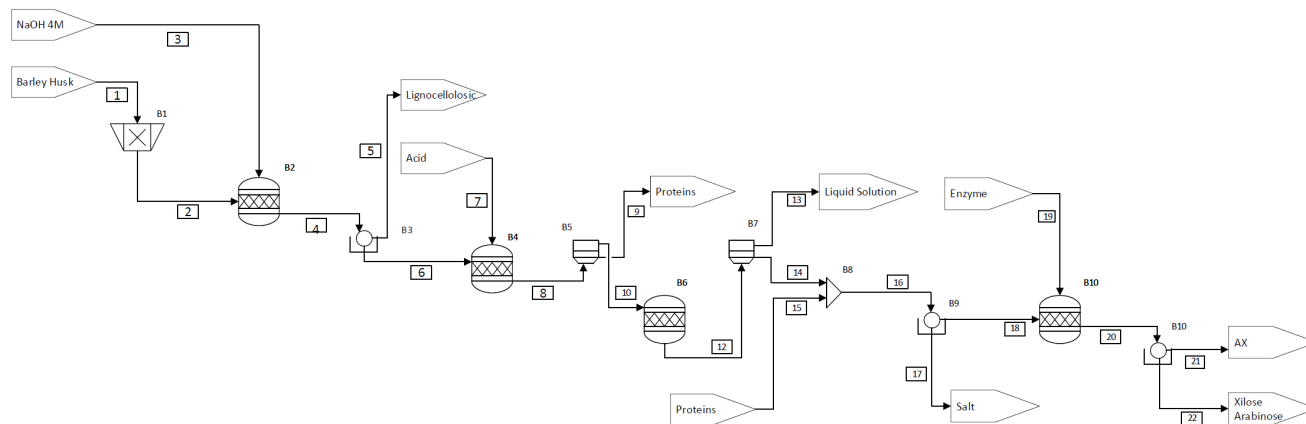

Figure 8. Process Flow Diagram for the simulated process. Residual wet BSG processed 156 000 t/year corresponding to Bavaria Tocancipá Brewery.
Source: Authors

Table 3. Energy consumption associated with the main equipment of the simulation

	B2	B4	B6	B10
Specified temperature (°C)	40	25	25	40
Treatment capacity of BSG (t/year)	**Net heat duty (kW)**			
156 000	902,2	-1 654,8	226,5	22,4
46 000	193,5	-4 879,4	66,8	6,6
800	3,4	-84,9	1,2	0,11

Source: Authors

In this section of the simulation, the detailed sizing of the pretreatment equipment is pending. Pretreatment and fermentation stages of the process are operated in batches, where the size of the equipment and its time of operation depends on the programming of the process and the required lot sizes. These factors will be established when performing the economic feasibility, as well as the detailed sizing.

Conclusions

The technical feasibility of the designed process for obtaining xylitol from BSG has been proved at different production rates through simulation in Aspen Plus. Simulation results show that xylose obtained corresponds to 8,5% of the dry weight of the raw material, obtaining a yield of 58%. Several streams of byproducts were obtained, such as proteins, polypeptides, amino acids, phenolics compounds and lignocellulosic residues that can be valorized in other processes. In the second part of this article, simulation for the three production capacities will be used to perform the economic feasibility assessment.

Acknowledgements

Table 4. Mass balance for the simulated process. Residual wet BSG processed 156 000 t/year corresponding to Bavaria Tocancipá Brewery (Units 1 to 11)

	Units	1	2	3	4	5	6	7	8	9	10	11
From			B1		B2	B3	B3		B4	B5	B5	
To		B1	B2	B2	B3		B4	B4	B5		B6	B6
Temperature	C	25	25	25	40	25	25	25	25	25	25	25
Pressure	atm	1	1	1	1	1	1	1	1	1	1	1
Mass Enthalpy	J/kg	-14 543 075	-14 543 074	-14 544 899	-14 501 577	-10 558 009	-14 670 137	-8 244 437	-14 540 127	-11 300 971	-14 597 035	-6 514 812
Mass Density	kg/m^3	1 054	1 054	1 034	1 031	1 344	1 033	1 740	888	1 080	885	807
Volume Flow	m^3/year	140 359	140 359	498 337	643 715	14 070	623 781	55 330	834 349	1 1843	822 506	3 190 236
Mass Flows	t/year	147 982	147 982	515 424	663 406	18 907	644 498	96 255	74 0754	12 789	72 7964	2 575 454
WATER	t/year	124 800	124 800	438 547	563 347	5 633	557 714	1 925	593 919	5 939	587 980	128 496
XYLOS-01	t/year	0	0	0	0	0	0	0	0	0	0	0
ARABI-01	t/year	0	0	0	0	0	0	0	0	0	0	0
NAOH	t/year	0	0	76 877	76 877	769	76 108	0	0	0	0	0
XYLAN	t/year	0	0	0	0	0	0	0	0	0	0	0
ARABINAN	t/year	0	0	0	0	0	0	0	0	0	0	0
CELLULOS	t/year	4 961	4 961	0	4 961	4 961	0	0	0	0	0	0
LIGNIN	t/year	3 494	3 494	0	3 494	3 494	0	0	0	0	0	0
ASH	t/year	1 092	1 092	0	1 092	1 092	0	0	0	0	0	0
PROTEIN	t/year	0	0	0	5 491	55	5 436	0	0	0	0	0
HEMICELU	t/year	8 143	8 143	0	2 850	2 850	0	0	0	0	0	0
SULFU-01	t/year	0	0	0	0	0	0	94 330	1 016	10	1 006	0
SODIU-02	t/year	0	0	0	0	0	0	0	135 143	1 351	133 791	0
ETHAN-01	t/year	0	0	0	0	0	0	0	0	0	0	2 446 958
PROT-SOL	t/year	5 491	5 491	0	0	0	0	0	5 436	5 436	0	0
ENZYME	t/year	0	0	0	0	0	0	0	0	0	0	0
XYLAN-LQ	t/year	0	0	0	3 640	36	3 604	0	3 604	36	3 568	0
ARABN-LQ	t/year	0	0	0	1 653	17	1 636	0	1 636	16	1 620	0

Source: Authors

Table 5. Mass balance for the simulated process. Residual wet BSG processed 156 000 t/year corresponding to Bavaria Tocancipá Brewery (Units 12 to 22)

	Units	12	13	14	15	16	17	18	19	20	21	22
From		B6	B7	B7		B8	B9	B9		B10	B11	B11
To		B7		B8	B8	B9		B10	B10	B11		
Temperature	C	25	25	25	25	25	25	25	40	40	25	25
Pressure	atm	1	1	1	1	1	1	1	1	1	1	1
Mass Enthalpy	J/kg	-8 293 699	-8 297 667	-7 954 232	-6 514 812	-6 773 438	-6 798 536	-5 810 246	-15 802 087	-15 750 102	-9 029 946	-15 833 083
Mass Density	kg/m^3	822	821	876	807	819	809	1479	979	981	1 303	995
Volume Flow	m^3/year	4 019 870	3 976 313	43 557	215 870	259 437	255 788	3 649	1 067 178	1 070 379	2 484	1 052 209
Mass Flows	t/year	3 303 418	3 265 248	38 170	174 270	212 440	20 7045	5 395	1 064 274	1 069 669	3 428	1 066 241
WATER	t/year	71 6476	70 9311	7 165	8 695	15 860	15 844	16	1 045 160	1 044 767	1 045	1 043 722
XYLOS-01	t/year	0	0	0	0	0	0	0	0	2 635	3	2 633
ARABI-01	t/year	0	0	0	0	0	0	0	0	773	1	772
NAOH	t/year	0	0	0	0	0	0	0	0	0	0	0
XYLAN	t/year	3 568	0	3 568	0	3 568	0	3 568	0	1 249	1 249	0
ARABINAN	t/year	1620	0	1620	0	1620	0	1620	0	940	940	0
CELLULOS	t/year	0	0	0	0	0	0	0	0	0	0	0
LIGNIN	t/year	0	0	0	0	0	0	0	0	0	0	0
ASH	t/year	0	0	0	0	0	0	0	0	0	0	0
PROTEIN	t/year	0	0	0	0	0	0	0	0	0	0	0
HEMICELU	t/year	0	0	0	0	0	0	0	0	0	0	0
SULFU-01	t/year	1 006	995	10	0	10	10	0	0	0	0	0
SODIU-02	t/year	133 791	132 453	1 338	0	1 338	1 337	1	0	1	0	1
ETHAN-01	t/year	2 446 958	2 422 488	24 470	165 575	190 045	189 855	190	0	190	0	190
PROT-SOL	t/year	0	0	0	0	0	0	0	0	0	0	0
ENZYME	t/year	0	0	0	0	0	0	0	19 113	19 113	191	18 922
XYLAN-LQ	t/year	0	0	0	0	0	0	0	0	0	0	0
ARABN-LQ	t/year	0	0	0	0	0	0	0	0	0	0	0

Source: Authors

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