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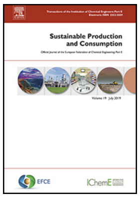

Research article

Process design and scale-up study for the production of polyol-based biopolymers from sawdust

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ABSTRACT

Sawdust is a by-product of the forestry industry which can be used as raw material for the production of added-value bio-based chemicals, leading to the development of a circular economy based on this organic resource. One of the most promising approaches for the reuse of sawdust is the production of polyols, which in turn can be used as raw material for the production of biopolymers. In this work, this process is analyzed to develop a sustainable alternative for the processing of forestry waste, obtaining biodegradable polymers than can be re-incorporated into the production cycle. A conceptual design and scale up of the process for the production of polyols out of sawdust and glycerol is developed based on experimental data. The process has been designed following the premise of being as environmentally sustainable as possible, but using simple equipment feasible to be deployed and operated by the timber facilities. Therefore, sawdust is used as raw material and energy source. The process is modeled using an equation based approach to perform a techno-economic analysis of it. The proportions of sawdust devoted to polyol production and thermal energy generation and power consumption are determined, as well as capital and operating expenses. In addition, a scale-up study to determine the effect of the economies of scale on the economic performance of the process proposed is carried out, as well as a sensitivity analysis in order to assess the influence of the raw materials price on the production cost. The results show that, for usual market prices of glycerol and starch, the production cost ranges from 0.10 to 0.66 USD per kilogram of biopolymer produced.

1. Introduction

Mankind ages have been described by the main materials used by the different societies, such as stone, clay, or iron. Over the last decades, plastics have defined our way of life anticipating a plastic age (Yarsley and Couzens, 1945). Plastics have good properties, including, among many others, resistance to corrosion and low density, providing advantages in many fields such as electronics, automotive and aeronautics industries, and packaging. However, the issues related to their disposable nature and slow decomposition rate are a major environmental concern worldwide, in particular due to the pollution generated in the oceans and their accumulation in living organisms. These problems are magnified by the short life cycle of some of the main applications of plastics. For instance, it is estimated that a third of the plastic production is used in packaging that is rapidly discarded (Thompson et al., 2009). Therefore, bio-based plastics may represent an opportunity to benefit from the advantages of these materials while minimizing their environmental impact. A number of biodegradable plastics already exist, and large scale production processes have been developed for the production of polyhydroxyalkanoate (PHA) (Novak et al., 2015; Peres et al., 2004), polyhydroxybutyrate (PHB) (Prieto et al., 2017), polylactic acid (PLA), polybutylene adipate terephthalate (PBAT), and other polyesters from adipic acid and glycerol (Bueno et al., 2015). In addition, developments based on starch for the production of biodegradable bio-based polymers stand out as having a promising potential (Jiang et al., 2020). Among them, the use of lignocellulosic materials derived from wood based waste streams as precursors, fillers, or functional additives for the production of biopolymers is a novel sustainable manufacturing approach with the potential to extend the ‘cradle-to-grave’ value of initial raw materials (prior to the creation of waste), reduce use of polymer precursor materials, and create new composites with adequate characteristics and functionalities for a variety of appli-

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Nomenclature

Abbreviations

CAPEX	Capital expenses
GDP	Gross domestic product
OPEX	Operating expenses
PBAT	Polybutylene adipate terephthalate
PHB	Polyhydroxybutyrate
PLA	Polylactic acid
PHA	Polyhydroxyalkanoate

Variables

c_{p_j}	Specific heat of component j
m_j^k	Mass flow of component j in stream k
t	Time
x_j^k	Mass fraction of component j in stream k
Capacity	Sawdust processed (kton/year)
H^k	Enthalpy of stream k
T^k	Temperature of stream k
$R_{\text{Glycerol-Sawdust}}$	Glycerol to sawdust feeding ratio

Parameters

$\eta_{\text{Combustion}}$	Combustion efficiency
η_{Drying}	Moisture removal yield
λ_{j}	Latent heat of component j
$h_{\text{j}}^{\text{Combustion}}$	Heat of combustion of component j
T_{Ref}	Reference temperature

cations. One possible way to obtain these high added value polymeric products is the use of precursors or additives obtained from the liquefaction of lignocellulosic materials.

Liquefaction is regarded as an efficient way to convert the biomass into biopolyols with high content of reactive hydroxyl groups. Some of the benefits related to the proposed solution are: i) biomass does not need costly separation and purification prior to the reaction, ii) liquefaction does not need for high pressure and drying post-process, iii) this process requires relatively lower process temperatures compared to other thermo-chemical conversion routes, and iv) biopolyols can be used directly, without any additional reaction or treatment to prepare biodegradable materials. In recent works, Briones and co-workers have successfully reported the liquefaction of several lignocellulosic residues from agricultural activities and industrial and biorefinery byproducts, which are usually discarded or combusted for energy generation, into biopolyols, multifunctional liquids with suitable physical and chemical features for polyurethane synthesis (Briones et al., 2015) and the production of biobased plasticizers (Briones et al., 2020). In order to search for novel applications, a very attractive possibility could be the use of bio-based polyols as fillers or polymer matrix in the production of thermoplastic composites. Additionally, recent developments in the study of wood-based polyols show the potential of this material for other applications, such as the production of wood adhesives (Jiang et al., 2018), additives for epoxy resins (Kumar et al., 2017), and as raw material for polyurethane foams (Zhang et al., 2019), including foams with special properties such as flame retardant foams (Yue et al., 2017).

The aim of this work is to scale up the production of a natural-low cost biopolyol for bio-based polymer elaboration, which shall be obtained through liquefaction processes of radiata pine sawdust (Chile's main forest plantation). The use of lignocellulosic waste as raw material is based on the presence of reactive groups associated with cellulose, hemicellulose, and lignin, such as hydroxyl and phenolic groups, that allow the production of polyol to be subsequently used for the production of the biopolymer. The high functionality of the mixture of polyols makes this material likely to be used for the synthesis of new macromolecular materials. Thus, in this work a process for the production of polyols from sawdust, glycerol and starch is conceptually designed. Additionally, a techno-economic analysis to determine the effect of the economies of scale on the economic performance of the process proposed, and a sensitivity analysis in order to assess the influence of the raw materials price on the production cost, are carried out. Experimental studies on the polymerization process were carried out to determine the conversion of the reaction and data from previous studies are used in order to evaluate the purification capacity.

The paper is organized as follows: Section 2 presents a general description of the process and the modeling details of all stages of the process. Section 3 presents the design and economical evaluation results, using the Chilean regions of Maule, Araucanía, Biobío, and Los Ríos as real cases to evaluate the investment and production costs of the process studied, including a scale-up study and a sensitivity analysis to evaluate the influence of the raw materials price in the production cost. Finally, Section 4 draws the main conclusions.

2. Methods

2.1. Methodology for process design

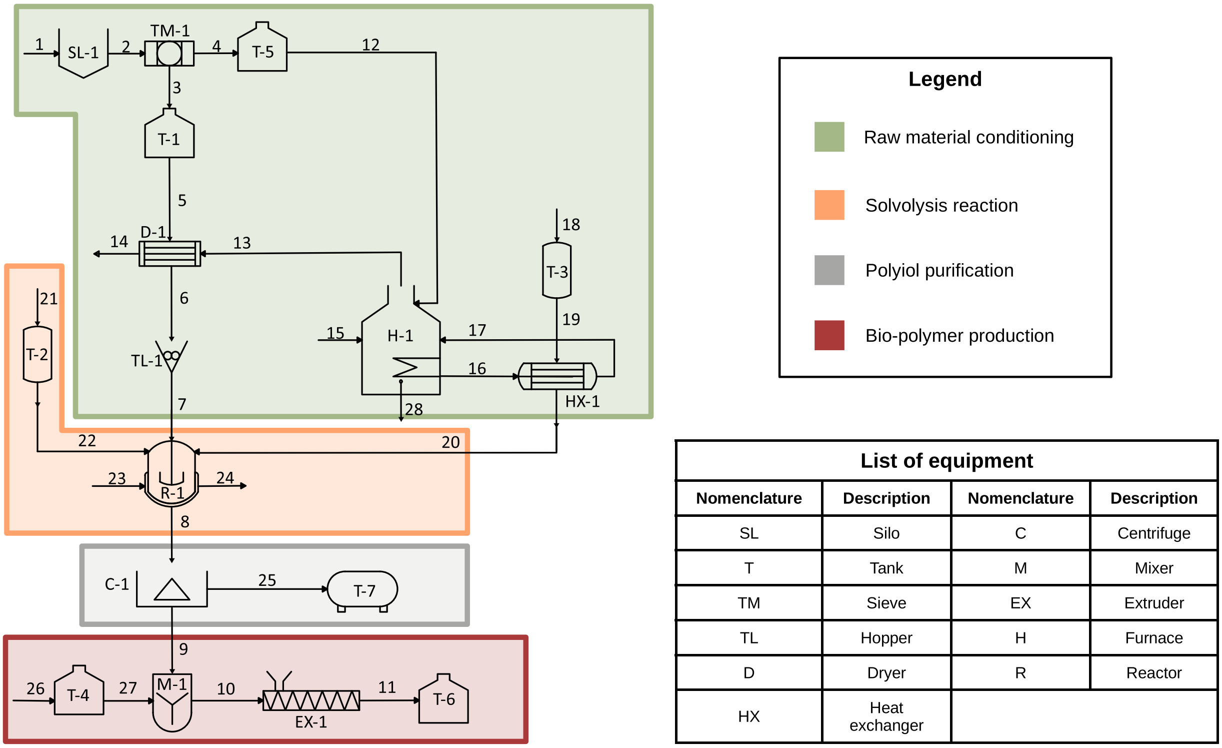
The process for the production of biopolymer from sawdust consists of four stages, i.e., raw material conditioning, solvolysis reaction, polyol purification, and biopolymer preparation, as shown in Fig. 1. In order to develop a completely renewable process, sawdust is used as energy source for the process and as raw material for the production of biopolymer. The sawdust devoted to the production of polyols is introduced in a reactor together with glycerol (R-1), where a solvolysis reaction catalyzed by sulfuric acid is carried out. The mixture of polyols obtained is purified by centrifugation (C-1) to remove the solid residues, and it is sent to a mixer (M-1) for a secondary reaction, the plastification of the mixture of polyols with starch, giving rise to the biopolymer. The biopolymer is extruded to obtain pellets, which in turn can be used as raw material for the production of plastic based pieces.

All the stages involved in the process are modeled through mass and energy balances, using experimental data reported in previous works for the chemical transformations carried out in each stage of the process. A mathematical model of the process is used to determine the energy requirements of each stage, and to carry out a techno-economic and sensitive analysis of the process, determining the capital expenses (CAPEX), operating expenditures (OPEX), and the final price of the biopolymer produced.

2.2. Process design calculations

2.2.1. Raw material conditioning

The first stage of the process consists on the conditioning of the raw materials. The size of sawdust is homogenized using a sieve within a vibrating screen unit (TM-1) to obtain a particle size between 0.3 and 0.6 mm. The energy consumed by the vibrating screen is estimated based on data provided by commercial suppliers (Sinfonia Technology, 2015), which are reported in Table 1s of the Supplementary Material. The sawdust out of size, together with a fraction of the homogenized sawdust, is used for heat generation in a combustion chamber (CC-1) to meet the thermal energy requirements of the process, as shown in Eqs. (1) and (2). In the equations, m_j^k denotes the mass flow of component j in stream k, Q^n the heat flow exchanged in the unit n, and $h_{\text{Sawdust}}^{\text{Combustion}}$ the heat of combustion of sawdust ($-18{,}849$ kJ kg^{-1}). The combustion chamber is modeled as an adiabatic furnace where sawdust is burned with an excess of air of 65%, assuming an efficiency



List of equipment

Nomenclature	Description	Nomenclature	Description
SL	Silo	C	Centrifuge
T	Tank	M	Mixer
TM	Sieve	EX	Extruder
TL	Hopper	H	Furnace
D	Dryer	R	Reactor
HX	Heat exchanger		

Fig. 1. Flowsheet for the production of polyol based biopolymer from sawdust.

($\eta_{\text{Combustion}}$) of 92% (Srinivasa Rao and Venkat Reddy, 2008).

$$m^{1}_{\text{Sawdust}} = m^{3}_{\text{Sawdust}} + m^{4}_{\text{Sawdust}} \quad (1)$$

$$Q^{\text{Combustor}} = -\left(Q^{\text{HX1}} + Q^{\text{Dryer}}\right) = m^{4}_{\text{Sawdust}} \cdot h^{\text{Combustion}}_{\text{Sawdust}} \cdot \eta_{\text{Combustion}} \quad (2)$$

A fraction of energy produced in the combustion is used for the generation of saturated steam, which will be further used to heat up the glycerol used in the solvolysis reaction in a heat exchanger (HX-1). The energy devoted to the generation of steam is computed in Eq. (4), where λ_{Water} denotes the latent heat of water, T^k and H^k the temperature and enthalpy of stream k respectively, and c_{p_j} the specific heat of component j. Enthalpies are calculated using Eq. (3), assuming a reference temperature (T_{Ref}) of 25 °C. The rest of the energy from the combustion, contained in the flue gases, is used for drying the sawdust devoted to the production of polyol (D-1). This process is performed in a rotary dryer assuming a moisture removal yield $\left(\eta_{\text{Drying}}\right)$ of 90%. The increase of the gases mass flow due to the evaporation of sawdust moisture and the increase of temperature of sawdust are assumed negligible. The combustion of sawdust is carried out using air at atmospheric conditions.

$$H^{k} = \sum_{j} m^{k}_{j} \cdot c_{p_j} \cdot \left(T^{k} - T_{\text{Ref}}\right) \quad (3)$$

$$Q^{\text{HX1}} = \lambda_{\text{Water}} \cdot m^{16}_{\text{Water}} = H^{20} - H^{19} \quad (4)$$

The fraction of homogenized sawdust devoted to the production of energy is a function of the energy required for the heating of glycerol, Eq. (4), and sawdust drying, Eq. (5).

$$Q^{\text{Dryer}} = \lambda_{\text{Water}} \cdot m^{\text{Vaporized}}_{\text{Water}} = \left(H^{14} - H^{13}\right) \quad (5)$$

As shown in Eq. (2), the energy required for the heating of glycerol and sawdust drying is a function of the fraction of sawdust devoted to the production of polyol, since it determines the amount of glycerol to be heated, Eq. (6), and the water to be removed from sawdust, Eq. (7), which in turn determines the fraction of sawdust devoted to the production of energy through the Eq. (1), $m^{\text{To polyol}}_{\text{Sawdust}}$: $m^{\text{Processed}}_{\text{Sawdust}} m^{\text{To energy}}_{\text{Sawdust}}$: $m^{\text{Processed}}_{\text{Sawdust}}$. $R_{\text{Glycerol-Sawdust}}$ denotes the glycerol to sawdust feeding ratio, defined in Section 2.2.2.

$$m^{19}_{\text{Glycerol}} = m^{3}_{\text{Sawdust}} \cdot R_{\text{Glycerol-Sawdust}} \quad (6)$$

$$m^{\text{Vaporized}}_{\text{Water}} = \eta_{\text{Drying}} \cdot m^{3}_{\text{Sawdust}} \cdot x^{3}_{\text{Moisture}} \quad (7)$$

The temperature of glycerol is raised beyond the reaction temperature so that, when it is mixed with the other components involved in the solvolysis reaction (i.e. sawdust and sulfuric acid) in the reactor (R-1), a fraction of the heat is transferred to these components, reaching the reaction temperature, 150 °C. Therefore, the energy balance performed to determine the temperature of glycerol includes the sensible heat transferred by the glycerol to sawdust and sulfuric acid in the reactor, and the heat transferred from the saturated steam to glycerol, Eq. (5). Considering the glycerol to sawdust and glycerol to sulfuric acid ratios involved in the process (described in Section 2.2.2), the glycerol needs to be heated to a temperature $\left(T^{20}\right)$ of 163 °C. A detailed description of the design and sizing of the vibrating sieve, dryer, combustion chamber, and the heat exchanger HX-1 can be found in Sections A1.1, A1.2, A1.3 and 1.4 of the Supplementary Material respectively.

2.2.2. Solvolysis reaction

In the reaction stage (R-1), the sawdust is introduced in a batch stirred reactor together with glycerol and sulfuric acid as catalyst. A solvent to biomass ratio $\left(R_{\text{Glycerol-Sawdust}}\right)$ of 5.4:1 (Briones et al., 2012), and a solvent to catalizer ratio of 45:1 are considered for this stage (CIPA, 2017). Sawdust and sulfuric acid are fed at atmospheric temperature, while the glycerol is heated up to 163 °C as described previously. These three components are placed in the reactor, giving raise to a transfer of heat from the glycerol to the rest of components, so that the mixture reach the reaction temperature

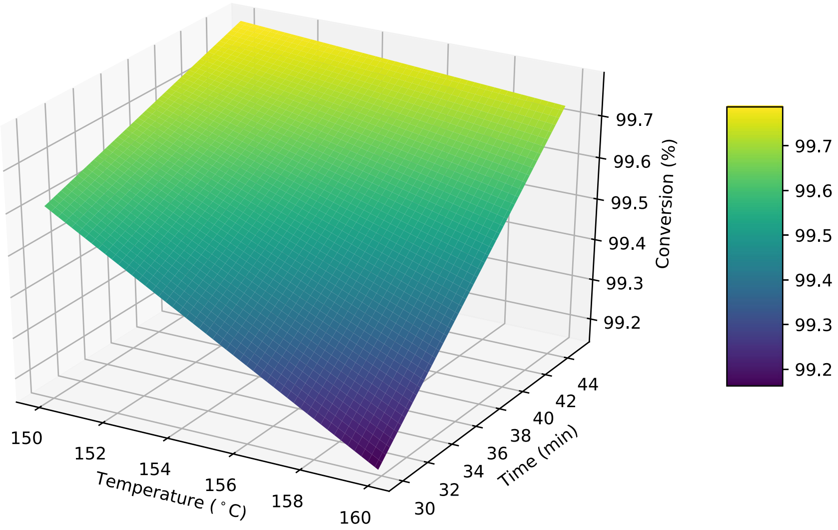


Fig. 2. Conversion of sawdust as a function of the operating temperature and time.

(150 °C). The liquefaction of sawdust is carried out in the reactor at a temperature of 150 °C and atmospheric pressure. The mass balances for the reactor are shown in Section A1.5.1 of the Supplementary Material.

Glycerol is a solvent which decomposes the biomass, breaking its structure and producing highly reactive molecules that recombine with other biomass molecules or with molecules from the solvent, obtaining a mixture of polyols. The selection of glycerol as solvent is a critical factor to achieve high biomass liquefaction yields. In addition, since the solvent is a major constitutive element of the mixture of polyols obtained, the choice of solvent used also determines the properties of the polymers based on polyols (Hu et al., 2014). The different structure of lignocellulosic components results in different liquefaction rates. Hemicellulose, lignin and amorphous cellulose are degraded in the first stages of the liquefaction process, while crystalline forms of cellulose, with a more packed structure that difficulties the contact with the solvent, require longer degradation times (Hu et al., 2014). The reaction is exothermic, with a reaction heat of −186.72 kJ/kg, based on previously performed experiments (CIPA, 2017). Therefore, the thermal energy generated as a consequence of the solvolysis reaction has to be removed using the cooling jacket of the reactor (streams 23 and 24) to keep the reaction temperature constant over time. Water at a temperature of 20 °C is used as coolant, setting the maximum temperature raise of the refrigeration water equal to 10 °C. For sawdust, the reaction time considered is 45 min, based on experimental data (CIPA, 2017). The energy balances for the reactor are reported in Section A1.5.2 of the Supplementary Material.

The experimental data show that reaction yield is a function of time and temperature, as shown in Fig. 2, developing a correlation to estimate the conversion as a function of these parameters, Eq. (8) (CIPA, 2017). For a reaction temperature of 150 °C and a reaction time of 45 min results in a conversion rate of 99.8 %. A selectivity of 100% has been assumed (CIPA, 2017). A detailed description of the procedure followed for the design of the reactor R-1 can be found in Section A1.5.3 of the Supplementary Material.

$$\text{Conversion} = 118.3 - 0.127 \cdot T(^\circ\text{C}) - 0.393 \cdot t(\text{min}) + 0.0027 \cdot T(^\circ\text{C}) \cdot t(\text{min}) \tag{8}$$

2.2.3. Polyol purification

The third stage comprises the purification of the polyols obtained in the previous stage. The stream leaving the reactor is composed of a mixture of polyols, the in-excess glycerol, sulfuric acid, residual moisture, and solid impurities contained in the sawdust. The separation of these components is carried out through centrifugation (C-1), separating the polyols from the other components. Two streams at room conditions are obtained after centrifugation, a stream containing the purified polyol with traces of water, glycerol and sulfuric acid, and a waste stream containing the rest of components. It is considered that the waste stream containing the glycerol, sulfuric acid, residual moisture, and solid impurities drags a fraction of the polyols during the separation process equal to 10 % of the polyol produced. The mass and energy balances, and the design procedure for the centrifuge C-1 is collected in Section A1.6 of the Supplementary Material.

2.2.4. Biopolymer preparation

The fourth stage consists on the production of a biopolymer combining the polyol with starch. Starch can be produced from biomass such as cooking corn or from algae. However, the production process of starch is out of the scope of this work. The polyol acts as plastifier agent, cross-linking the starch molecules to produce a biopolymer. The plasticization reaction is carried out combining starch and polyol in a ratio of 2.63:1 in a mixer (M-1) with constant agitation during the reaction time. The process is carried out at atmospheric conditions, with a mixing time of 30 min (Briones et al., 2015). The mass balances and design of the mixer M-1 is collected in Section A1.7 of the Supplementary Material.

The polymer produced is extruded to obtain pellets (EX-1), which are a versatile intermediate product that can be used for the production of the final polymer products in different formats such as films or laminated products. A screw extruder for the production of the biopolymer pellets has been considered. The estimation of the energy consumed by the extruder is based on data provided by commercial suppliers (Bausano, 2020; Beier, 2020; Kairong Group, 2020; Wuhe Machinery Co., 2020). These values, are reported in Table 6s of the Supplementary Material.

2.3. Methodology for economic assessment

The estimation of the investment cost is based on the cost of the equipment, using the factorial method proposed by Towler and Sinnott (2012). The estimation of the equipment cost relies on the size of process units, which is estimated through a preliminary design of each unit reported in the Section A1 of the Supplementary Material. Equipment cost is estimated based on

Table 1
Factors for investment cost estimation.

Direct investment costs (% over equipment cost)		Indirect investment costs (% over direct investment costs)	
Equipment erection	40	Design and engineering	20
Piping	40	Contractor's fee	5
Instrumentation	15	Contingency	10
Electrical	10		
Buildings	10		
Utilities	45		
Site development	2		
Ancillary buildings	20		

Table 2
Price of raw materials.

Raw material	Price (USD/ton)
Sawdust	75
Sulfuric acid	300
Glycerol	650
Starch	333

the correlations developed by Martín and Grossmann (2011) and Max et al. (2003) reported in Section A2 of the Supplementary Material, updating the value of the money to 2019. The value of the different factors are collected in Table 1.

The operating costs include raw materials, utilities, labor, and amortization of the investment. The prices of the raw materials considered are collected in Table 2. For the sake of brevity, we refer the reader to the Supplementary Material for a detailed description the correlations used for the estimation of the equipment cost and a detailed description of the procedure to estimate the operating costs.

2.4. Chilean forestry industry

Based on the process described previously, the deployment of facilities to process the sawdust waste in the four Chilean regions with the largest timber wood industry has been evaluated, i.e. Maule, Biobío, Araucanía, and Los Ríos regions (Instituto Forestal, 2020c), shown in Fig. 3. These regions have been selected since the timber industry has a high importance in their economies regarding both the regional gross domestic product (GDP) and the employed workforce in the forestry sector (Instituto Forestal, 2018; 2020a; 2020b; 2020c). These data, as well as sawnwood production and sawdust waste generation per region, are given in in Table 3.

3. Results and discussion

The process described in previous sections has been scaled-up for the processing of the sawdust waste produced in the Araucanía, Biobío, Los Ríos and Maule Chilean regions. The technical and economic results of the facilities that would be deployed in each region are shown along this section.

3.1. Process operation

Mass and energy balances are computed for the process through the non-linear model formulated. The model is used to determine the thermal energy and power requirements, as well as the fraction of sawdust devoted to polyol production and heat generation. The results obtained are provided in Table 4.

The process has been designed following the premise of being as environmentally sustainable as possible, but using simple equipment feasible to be deployed and operated by the timber facilities. Therefore, a portion of the sawdust processed is combusted to cover the thermal energy requirements of the process rather than using external fossil fuel supplies. This results in a ratio of sawdust devoted to combustion over the total sawdust processed of 0.72, being the remaining sawdust used for the production of polyol. The heat requirements per kilogram of sawdust processed, including the energy required for sawdust drying and reactor warming, remain almost constant for all processing capacities studied, with values between 2330 and 2371 kJ/kg of sawdust processed. By contrast, the power requirements show a significant influence of the economies of scale due to the need for multiple units and/or units of different sizes and characteristics, being lower for those scenarios in which more sawdust is processed. The values of power required range from $7.88 \cdot 10^{-3}$ to $1.32 \cdot 10^{-2}$ kJ/kg of sawdust processed.

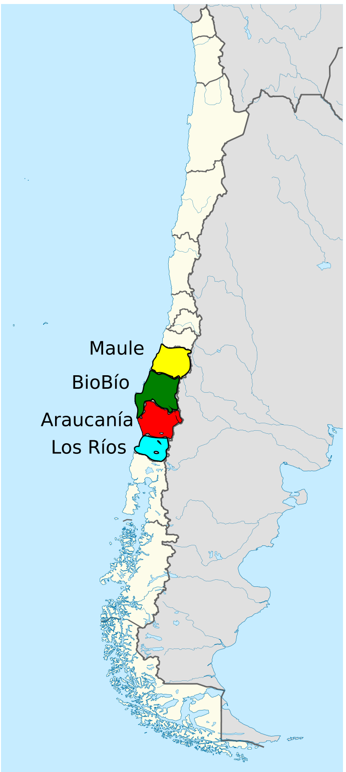


Fig. 3. Chilean regions evaluated for the installation of polyol based biopolymer production plants from sawdust waste. Map adapted from Wikimedia Commons (2011).

3.2. Economic assessment

3.2.1. Investment cost

The investment costs required for the installation of facilities for the production of polyol based biopolymer from sawdust in

Table 3
Characteristics of the forestry sector in Maule, Biobío, Araucanía, and Los Ríos Chilean regions.

	Region			
	Maule	Biobío	Araucanía	Los Ríos
Forestry sector employment (% over regional total, year 2017)[a]	2.97	4.66	3.12	3.59
Forestry sector GDP (% over regional total, year 2016)[b]	5.9	15.8	8.0	15.1
Sawnwood production (m^3, year 2018)[c]	1,996,174	4,290,695	923,918	630,020
Sawdust production (primary) (m^3, year 2018)[d]	707,606	1,726,109	338,096	160,877
Sawdust production (available for productive activities) (m^3, year 2018)[d]	596,468	922,390	256,759	89,681
Sawdust production (available for productive activities) (metric ton, year 2018)[e]	178,940	276,717	77,027	26,904

[a] Instituto Forestal (2018).
[b] Instituto Forestal (2020c).
[c] Instituto Forestal (2020b).
[d] Instituto Forestal (2020a).
[e] Sawdust density: 300 kg/m^3.

Table 4
Optimal operating conditions for the process for the production of polyol based biopolymer from sawdust.

	Region			
	Araucanía	Biobío	Los Ríos	Maule
Sawdust processed (metric ton/year)	95,708	461,154	66,994	191,415
Sawdust to polyol / Total sawdust processed (kg/kg)	0.72	0.72	0.72	0.72
Sawdust to energy / Total sawdust processed (kg/kg)	0.28	0.28	0.28	0.28
Biopolymer produced / Total sawdust processed (kg/kg)	9.38	9.35	9.15	9.21
Reactor temperature (K)	423	423	423	423
Drying energy (kJ/kg sawdust processed)	860	861	860	862
Mixers electricty consuption (kJ/kg sawdust processed)	0.139	0.179	0.138	0.135
Extruders electricty consuption (kJ/kg sawdust processed)	$6.10 \cdot 10^{-3}$	$5.73 \cdot 10^{-3}$	$6.41 \cdot 10^{-3}$	$5.62 \cdot 10^{-3}$
Total power requirements (kJ/kg sawdust processed)	$1.14 \cdot 10^{-2}$	$7.88 \cdot 10^{-3}$	$1.35 \cdot 10^{-2}$	$8.70 \cdot 10^{-3}$
Total heat requirements (kJ/kg sawdust processed)	2,371	2,340	2,340	2,330

the Chilean regions of Araucanía, Biobío, Los Ríos, and Maule are shown in Fig. 4. Analyzing the specific investment, defined as the monetary amount to be invested per kilogram of residue to be treated on a yearly basis, it can be observed that there is a significant effect of the economies of scale. For the region with the lowest amount of sawdust, Los Ríos (26,904 metric ton/year), the specific investment is 0.89 USD per kg of sawdust processed, while for the region where the largest facility is required, the Biobío region (276,717 metric ton/year), the specific investment cost decreases down to 0.57 USD per kg of sawdust processed. It is worth noting that the specific investment is similar for the Maule and the Biobío regions, 0.58 and 0.56 USD per kg of sawdust processed respectively, although the amount of sawdust waste processed is significantly lower in the Maule region (178,940 metric ton/year), than in the Biobío region. This suggests that the reduction of the specific investment cost is not linear with the amount of sawdust processed, and in turn, with the size of the processing facility; as expected based on the economies of scale. The breakdown of results for each equipment is shown in Section EV.1 of the Supplementary Material.

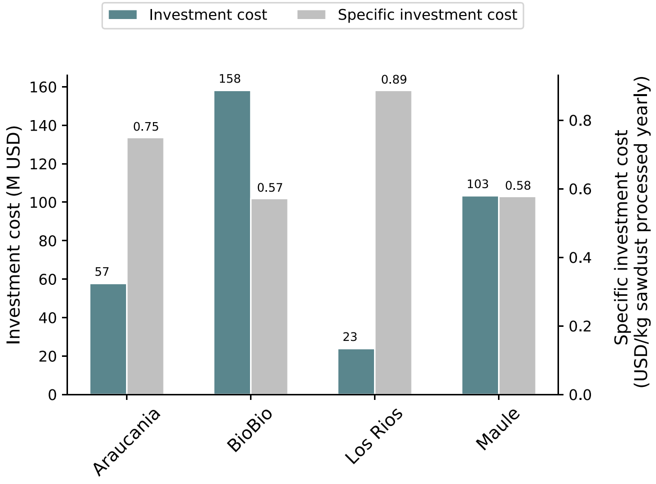


Fig. 4. Investment cost of the facilities for the processing of sawdust waste in Araucanía, Biobío, Los Ríos, and Maule Chilean regions.

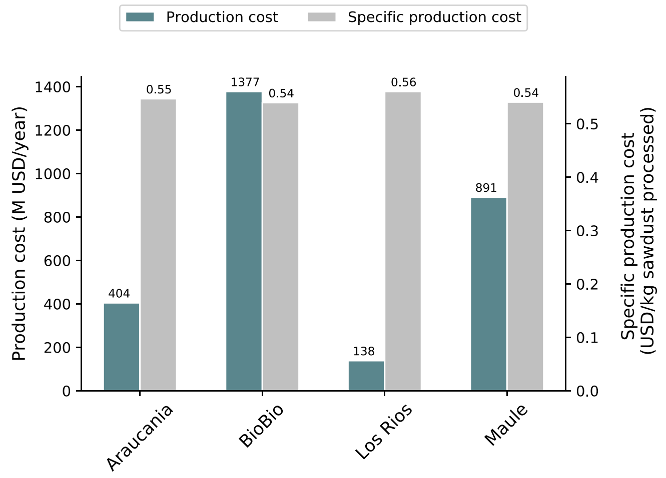


Fig. 5. Production cost of the facilities for the processing of sawdust waste in Araucanía, Biobío, Los Ríos, and Maule Chilean regions.

Table 5
Distribution of production costs.

% Production cost	Region Maule	 Biobóo	 Araucanóa	 Los Róos
Raw materials	93.92	95.23	95.04	91.43
Utilities	0.77	0.53	0.62	1.41
Maintenance	1.84	1.48	1.50	2.22
Labour	0.17	0.05	0.077	0.50
Equipment	0.92	0.74	0.754	1.11
Taxes	0.37	0.30	0.30	0.44
Other	2.00	1.68	1.72	2.90

3.2.2. Production costs

The production costs of the facilities studied are shown in Fig. 5, accounting for materials, labor and energy costs, and the amortization of the investment. The prices of raw materials considered are listed in Table 2. It can be observed the the production costs are considerably larger than the investment costs. This is due to the characteristics of the production process of polyol-based biopolymer from sawdust. On the one hand, this is a process that does not involve complex or highly expensive equipment, resulting in low investment costs. On the other hand, large amounts of raw materials are needed, especially glycerol and starch, which turns into large production costs. In addition, due to the large contribution of the raw materials to the production costs, the specific production costs is slightly affected by the economies of scale. The distribution of production costs is given in Table 5, with values around 0.55 USD/kg of biopolymer produced in all cases. The breakdown of results for each equipment is shown in Section EV.2 of the Supplementary Material.

3.2.3. Scale-up study and sensitivity analysis

A scale-up study to evaluate the effect of the scale in the economy of the process has been carried out. It can be observed that the investment cost is highly affected by the economies of scale, as shown in the study of the Chilean regions, exhibiting important reductions in the investment cost needed per kilogram of sawdust waste processed, as shown in Fig. 6. Correlations to estimate the total and specific investment costs are developed, Eqs. (9) and (10) respectively, where *Capacity* refers to the sawdust processed in kton per year. In addition, correlations to estimate the production costs as a function of the residue processed are shown in Eqs. (11) and (12). In Fig. 7 it can be observed that the production costs increase linearly with the amount of waste processed, as a result of the very large costs in raw material required. A non-linear behavior in the specific production costs can be observed due to the reduction of the equipment cost amortization in the final production cost as the size of the processing facilities increases. However, considering absolute values, the decrease of the costs associated with the amortization of equipment results in a small reduction of production costs.

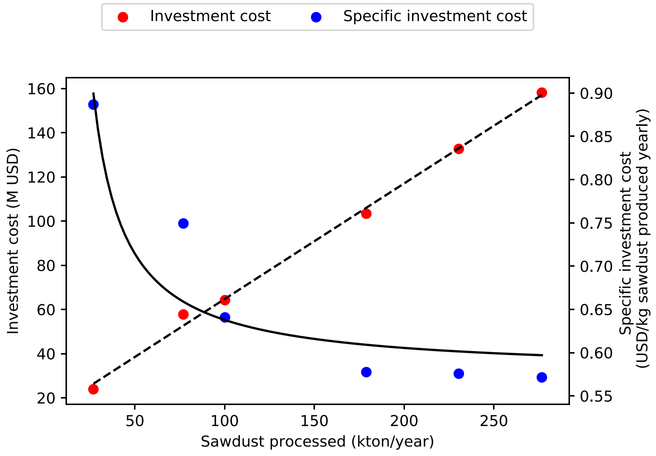


Fig. 6. Scale-up study for investment costs.

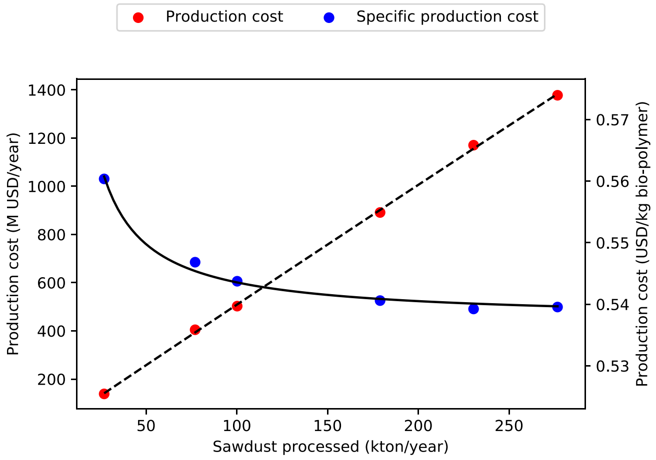


Fig. 7. Scale-up study for production costs.

$$\text{Investment cost (M USD)} = 5.23 \cdot 10^{-1} \cdot Capacity + 12.31 \tag{9}$$

$$\text{Specific investment cost (USD/kg year)} = \frac{5.76 \cdot 10^{-1} \cdot Capacity}{-9.67 \cdot 10^{-1} + Capacity} \tag{10}$$

$$\text{Production cost (M USD/year)} = 4.98 \cdot Capacity + 9.00 \tag{11}$$

$$\text{Specific production cost (USD/kg)} = \frac{5.38 \cdot 10^{-1} \cdot Capacity}{-1.11 + Capacity} \tag{12}$$

As glycerol and starch are the major constituents of the biopolymer produced, the production costs are heavily affected by the raw materials cost. Since market values of chemicals are dynamic, it can be expected that the production costs vary over time as a result of the price of the raw materials. To determine the range of

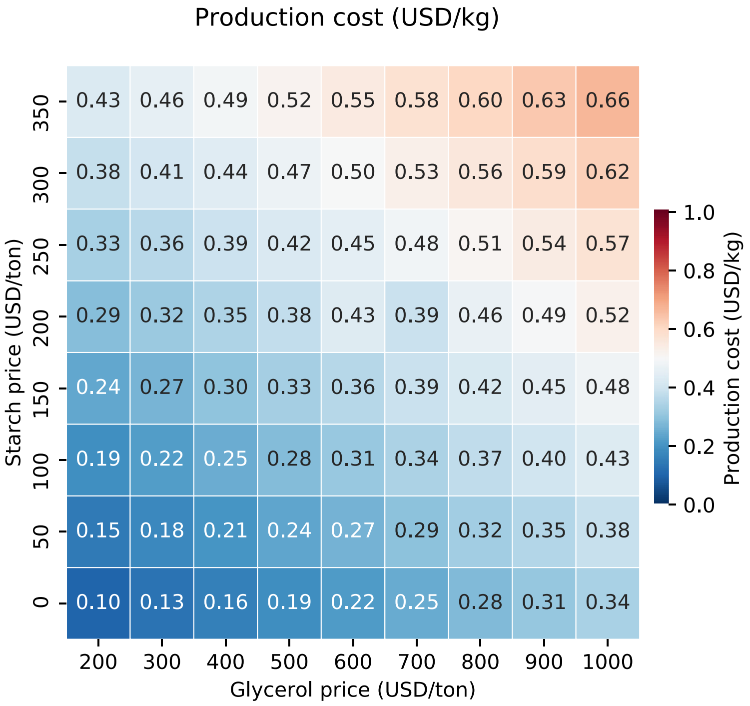


Fig. 8. Sensitivity analysis for the prices of glycerol and starch.

values for production cost that can be expected, as well as the influence of the raw materials price, a sensitivity study considering the prices of glycerol and starch has been carried out. The results obtained are illustrated in Fig. 8. This sensitivity analysis study considers as reference a facility with a processing capacity of 95,700 ton of sawdust per year. However, since the dependency of the production costs with the facility size is almost negligible, as described in Section 3.2.2, the results obtained can be extrapolated to facilities with different capacities. For market prices of starch between 0 (considering residual starch from the agri-food industry) to 350 USD per ton, and from 200 to 1000 USD per ton of glycerol, the production costs ranges from 0.10 to 0.66 USD per kilogram of biopolymer produced. It can also be observed that, although the price of starch is lower than the price of glycerol, it has a larger impact on the price of the final product than the price of glycerol due to the larger portion of starch in the final product.

4. Conclusions

A conceptual design and techno-economic evaluation of a process for the production of polyol based biopolymers from sawdust at full-scale have been carried out in this study. This process has been conceived to be a sustainable alternative for the processing of waste generated by the forestry industry, allowing the development of a circular economy around sawdust residues, obtaining biodegradable polymers than can be re-incorporated into the production cycles as, for instance, agricultural plastics. The process has been designed following the premise of being as environmentally sustainable as possible, but using simple equipment feasible to be deployed and operated by the timber facilities. Therefore, a portion of the sawdust processed is combusted to cover the thermal energy requirements of the process rather than using external fossil fuel supplies. Experimental data are used to evaluate the performance of each of the units.

The results show that it is a process with a low economic entry barrier due to the low investments required. On the other hand, the intensive use of raw materials results in high production costs. Investment costs are largely affected by the economies of scale, allowing a significant reduction of the investment per unit of waste processed as the facilities increase their size. In order to evaluate the effect of the scale in the economy of the process a scale-up study has also been performed. The variation of the production cost shows a linear behavior, since the reduction of the equipment cost item the final production cost due to economies of scale is blurred by the high costs of raw materials. In addition, a sensitivity analysis has been performed to determine the effect of the raw materials price on the production cost. The results show that, for usual market values of glycerol and starch, the production cost ranges from 0.10 to 0.66 USD per kilogram of biopolymer produced.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary material

Supplementary material associated with this article can be found, in the online version, at 10.1016/j.spc.2021.01.015.

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