Modeling and Analysis

Biofpr Biofuels Bioproducts & Biorefining

Techno-economic assessment of carboxylic acids, furfural, and pellet production in a pine sawdust biorefinery

Nicolás M. Clauser, María C. Area, Fernando E. Felissia, and María E. Vallejos, Instituto de Materiales de Misiones (IMAM), Universidad Nacional de Misiones – Consejo Nacional de Investigaciones Científicas y Técnicas (UNaM – CONICET), Posadas, Misiones, Argentina.
Soledad Gutiérrez, Facultad de Ingeniería – Universidad de la República (UDeLaR), Montevideo, Uruguay.

Received January 24, 2018; revised June 03, 2018; accepted June 08, 2018
View online at Wiley Online Library (wileyonlinelibrary.com);
DOI: 10.1002/bbb.1915; *Biofuels, Bioprod. Bioref*. (2018)

Abstract: Pine sawdust is an important lignocellulosic waste from the primary industrialization of wood, and its valorization using the biorefinery concept could add new value chains to the forest industry. Compared with large-scale biorefineries, small-scale ones involve lower capital and logistics costs, lower risk, and can increase the use of labor in rural areas. A scheme was proposed for the use of the hemicelluloses obtained from the spent liquor of a steam explosion pretreatment of pine sawdust. With the proposed scheme, levulinic acid (LA), formic acid (FA), acetic acid and furfural are obtained from the liquid fraction while pellets are produced from the solid fraction. This pine sawdust biorefinery allows about 747 kg of pellets, 57 kg of LA, 23 kg of FA, 18 kg of acetic acid, and 22 kg of furfural per 1000 kg of dry sawdust to be obtained. The energy used for LA production is one of the main production costs. When 95% of the residual solid is used to generate steam, there is an improvement in the internal rate of return (IRR). The heat integration allows a reduction of 10% in the steam consumption for LA, increasing the capacity for pellet production. The results obtained are therefore essential when seeking alternatives for pine sawdust biorefineries, focusing on the improvement of the production processes, satisfaction of energy requirements, and the reduction of the recovery costs. Three alternatives for the valorization of pine sawdust were analyzed and the best of them obtained an IRR of about 17%. © 2018 Society of Chemical Industry and John Wiley & Sons, Ltd

Keywords: biorefinery; pine sawdust; steam explosion; levulinic acid; pellets; techno-economic assessment

Correspondence to: Nicolás M. Clauser, Instituto de Materiales de Misiones (IMAM), Universidad Nacional de Misiones – Consejo Nacional de Investigaciones Científicas y Técnicas (UNaM – CONICET), Posadas, Misiones, Argentina. E-mail: nicolas.clauser@gmail.com

© 2018 Society of Chemical Industry and John Wiley & Sons, Ltd

Introduction

In recent decades, the forest industry and the forest products trade have endured major changes as a consequence of globalization, climate change, high energy prices, and the financial crisis. Finland, Norway, Sweden, Canada, the USA, and some countries in South America have a large forested area available to be harvested and used in industrial processes.[1] The global forest industry is relying increasingly on forests located in South America, Africa, and Asia. International enterprises purchase forest lands or land for plantations in Asian and Latin American countries to supply raw materials for pulp mills and forest products.[2] Latin American countries are emerging producers in the global markets of forest products. In these countries, government policies and incentives for plantation have attracted foreign investments to the wood and pulp and paper industries.[3] Fast-growing species are planted to supply the world's industrial wood. In the southern hemisphere, the production cycle of the fast-growing species is 5–12 years (30–50 m^3 ha^{-1} per year) whereas in the northern hemisphere, it is 20–60 years (5–15 m^3 ha^{-1} per year).[4] Softwoods (pine, fir, spruce, others) are typical native species industrialized in the northern hemisphere, although in the southern hemisphere non-native species are implanted for industrial use. The manufacture of wood products generates a variety of residues as sawdust and bark, with almost no commercial value. In regions with intensive industrial forest activity, large amounts of these residues are produced. The average costs from wood residues at mill were estimated, in a study based on selected countries (Argentina, Brazil, Canada, China, among others; 2017 baseline), to be within a range of USD 18–36 per dry ton.[5] In the case of Brazil, the estimated price of these wastes (forestry processing residues and sawdust) could be even lower (USD 16–23 per dry ton).[6] These wastes can be used in nearby locations because they are already concentrated and do not need to be collected. The projection of the biomass waste associated with current forest activities during the 2017–2027 period in Argentina is around 2 100 000 metric tons (wood waste available: 5 000 000), mainly from pine and eucalyptus.[5,7]

Pine sawdust is an important lignocellulosic waste from the primary industrialization of wood in Argentina, so its valorization using the biorefinery platform could add new value chains to its forest industry and this could serve as a model for other countries. The global forest industry is focused on the development of technologies for waste reuse or valorization. A typical large-scale biorefinery scenario is based on the production of commodities such as the extraction of sugars from biomass to produce cellulosic ethanol, steam, and electricity. However, the production of various wood byproducts is crucial to have competitive production costs.[8,9] Numerous products from each component of the lignocellulosic material (cellulose, hemicelluloses, lignin, and extractives) can be obtained. Pine hemicelluloses are mainly formed by galactoglucomannans, arabinoglucuronoxylan, and arabinogalactan. Their chemical structure allows their use as precursors for a wide range of chemicals such as alcohols, organic acids, and furanic compounds. However, current alternatives for the valorization of hemicelluloses are commercially limited. *Lactobacillus* species and *Saccharomyces cerevisiae* yeasts are conventionally used for lactic acid and bioethanol production, from sucrose or starch (glucose), respectively. However, the use of other sugars such as galactose and mannose (hexoses) or xylose and arabinose (pentoses) could improve productivity and make the fermentation process economically feasible.[10–13]

Bio-based chemicals from hemicelluloses would be an alternative to the products derived from oil. Levulinic acid is a platform molecule that can be converted into derivable high-value-added chemicals. Levulinic acid can be synthesized from petrochemical feedstocks but can also be produced from carbohydrates (starches, cellulose, or hemicelluloses). The petrochemical route involves the conversion of maleic anhydride or the hydrolysis of furfuryl alcohol, which is expensive and polluting. The biobased production of levulinic acid (LA) is a cheaper and more environmentally friendly alternative.[14,15]

The commercial-scale production of LA from lignocellulosic materials requires a cheap feedstock such as forestry wastes (branches, foliage, and roots) or industrialized wood wastes (bark, sawdust, wood chips, and other residues) to compete with the petrochemical route.[16–19] Levulinic acid from carbohydrates is produced by sequential reactions, involving the isomerization of the hexoses, dehydration to hydroxymethylfurfural (HMF), and the rehydration and rearrangement of HMF to LA and formic acid (FA). Levulinic acid can be used in the manufacture of various high-value organic chemicals with numerous potential industrial applications as polymers, resins, perfumery, flavorings, pesticides, and fuel additives.[20] The global market for LA, FA, and furfural are expected to grow at a compound annual growth rate (CAGR) of 5.7%,[21] 4.9%[22] and 11.6%,[23] respectively. Formic acid reacts with alcohols and alkenes to produce formate esters, which may be applied as solvents, chemicals, or fuel additives.[24] It is used principally as a preservative in the food industry. Furfural is used for the production of furfuryl alcohol, tetrahydro furfuryl alcohol, acetyl furane, furoic acid, methyl furane, and tetrahydrofuran (THF). These furfural derivatives can be used for the production of lubricants, adhesives, and polymers.[25,26] Pellets are a clean renewable fuel, mostly produced from highly compressed sawdust, planer shavings, and bark. This fuel has been considered as one of the substitutes for fossil fuels like coal and oil for heating and cogeneration.[27]

One of the alternatives to develop the exploitation of the forest residues is pelletization. The pellets are denser, drier, and easier to handle than the original forest residues and can be used in the production of electricity and heat. Its manufacture is growing mainly in Nordic countries.[28]

The main production of wood pulp and wood-derived products in Argentina is concentered in in the north-eastern region, mainly in Misiones. This highly forested province has an important number of sawmills and other forest-based industries, pine being one of the most important raw materials. In sawmills, about 9% of the initial raw material is converted to sawdust, so its valorization could add new value chains to the forest industry of Argentina and other countries in the region.

Pine sawdust represents an attractive raw material for the production of high-value-added compounds but its fractionation is complex due to its chemical composition, e.g. its high content resin acid content, hemicelluloses, and guaiacyl-type lignin, which is not highly reactive.[29] Steam explosion (SE) has shown to be one of the most successful pretreatments for the removal of hemicelluloses from lignocellulosic materials, including pine[30] and in optimized conditions, SE allows the extraction of the hemicellulosic fraction from pine sawdust with low degradation.[29]

Currently, most processes and technologies for biorefineries are in development at pilot scale and at demonstration plants, so information about commercial plants is not available. The design of these processes and technologies requires economic, technical, and environmental analysis. Techno-economic analysis considers the processes and their mass and energy balances (input–output model). The feasibility of a given processing technology set can be determined on the basis of the available feedstocks and their prices in the region, the existing and emerging technologies that can be used to produce the targeted products, and their mass and energy balance models. This allows capital and operating costs to be estimated. Revenues and profitability are a function of the plant capacity. The internal rate of return (IRR) is a reliable measure for a first profitability estimation.[31] The uncertain economic variables that will probably have a major impact on the economic performance of the project must be identified. For this purpose, a sensitivity analysis is performed by varying economic variables in order to identify the sensitive factors. The probability distribution of an uncertain variable can also be defined and the IRR and its probability can be calculated using the defined distributions.[32]

Many articles and patents propose the production of LA as a single product based on the use of the raw material.[33–35] However, few studies analyze its production in conjunction with other co-products to improve the economy of the process.[36–38]

The present work presents a techno-economic analysis of alternatives for the production of carboxylic acids, such as LA, FA, acetic acid, and furfural, from the hemicelluloses obtained in the liquid fraction of a steam explosion pretreatment of pine sawdust, together with pellet production from the solid fraction and the generation of process steam. The best alternative for pine sawdust biorefinery were determined, focusing on the improvement of the production processes, the satisfaction of the energy requirements, and the reduction of the recovery costs. Some parameters were selected and a sensitivity analysis was performed for the alternative with the highest IRR value, varying one parameter at a time (One-At-a-Time test, OAT). The way in which each parameter would affect the IRR value was also determined.

Methods

The technological scheme In Fig. 1 shows the alternatives for the production of carboxylic acids, furfural, pellets, and the generation of process steam for the pine sawdust biorefinery studied in this work.

The production of LA proposed in this study mainly involves the following stages: (1) hemicellulose extraction by steam explosion, (2) conversion of hemicellulosic sugars to LA, and (3) recovery of LA and byproducts (formic and acetic acids, and furfural). The alternatives of using the residual sawdust from the steam explosion for pellets and/or steam production were also analyzed.

Definition of scenarios

In the present work, LA production from the hexose-rich spent liquor of the steam explosion pretreatment of pine sawdust was analyzed to valorize the hemicellulosic sugars. The following alternatives were also proposed to valorize the residual solid: (1) the use of 100% of the residual solid for pellet production, (2) the use of a fraction of the residual solid to satisfy the demand of process steam and

© 2018 Society of Chemical Industry and John Wiley & Sons, Ltd

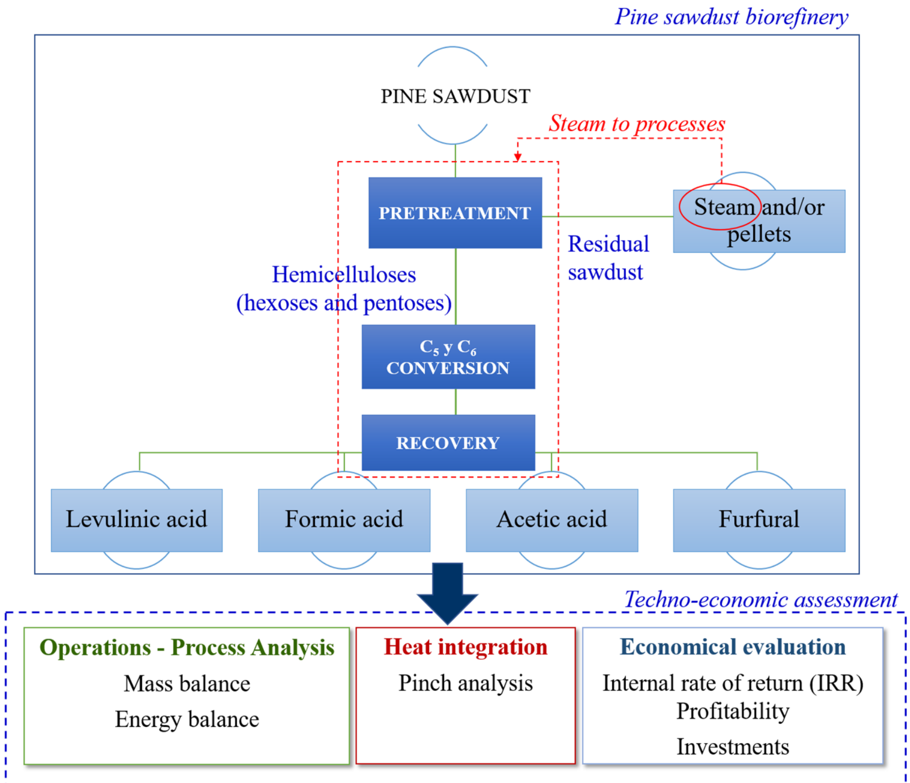

Figure 1. Techno-economic assessment for the proposed biorefinery of pine sawdust.

Table 1. Main parameters of operations and conversion processes.

Stage	Process conditions	Scaling factors (Eq. (2))
Levulinic acid production		
Steam Explosion (Reactor)	190 °C; 7.5 min; 3% of H_2SO_4 w/w and a liquid solid ratio (LSR) of 1:1.[39]	0.78[40]
Evaporation	To reach 200 g L^{-1} of sugars.[41]	0.54[42]
Acid-catalyzed dehydration (Reactor)	140 °C; 2 h; 98 g L^{-1} H_2SO_4 (catalyst)[43]	0.78[40]
Liquid-liquid extractor	25 °C; 1 atm; solvent-aqueous phase ratio of 1.2:1[44]	0.78[40]
Recovery	Two columns at 169 °C (1.21 atm) and 260 °C (1.16 atm), respectively, to separate LA, FA, and furfural.[44]	0.70[45]
Furfural recovery	One column at 90 °C (1 atm) and a settler.[46]	0.70[45]
Pellets production		
Drying	Rotary drum dryer heated with steam to reach 12–17% moisture[47,48]	0.60[48]
Pelletizing	High-pressure pelletizer (~1 t h^{-1}), 8–5% final moisture[47]	0.85[48]
Cooling	Countercurrent air (~20 min)[47]	0.58[48]
Screening	To remove and recover the fine material[47]	0.60[48]

the remaining fraction for pellets production, and (3) the integration of selected streams to improve the energy consumption in alternative 2.

The main parameters of the operations and processes involved are shown in Table 1.

Raw material

Pine sawdust from local sawmills (Misiones, Argentina) was used as raw material. The chemical composition of pine sawdust was reported by Stoffel;[39] it was 39.4% glucans, 6.42% xylans, 1.97% galactans, 1.32% arabans, 10.6

 © 2018 Society of Chemical Industry and John Wiley & Sons, Ltd

mannans, 1.79% acetyl groups, 2.28 extractives, and 30.1% lignin (percentage of oven-dry weight of sawdust, or % o.d.w.).

Levulinic acid production

The selected processes involved the extraction of hemicelluloses by steam explosion, the conversion of the hexoses from spent liquors to LA, and the production of pellets from the residual solid, as shown in Fig. 2.

The temperature and time to maximize the extraction of hexoses by steam explosion were selected from previous studies performed by our research group.[29,39] The conditions of the steam explosion and the composition of the residual liquor were defined by Stoffel.[39] In the steam explosion step, the reactants are fed into a batch reactor and a 69% yield is assumed.[39] The residual solid is washed after the steam explosion to extract the hemicelluloses using 3.5 m^3 of water per ton of pulp obtained after pretreatment.[49] Washing is developed in the vessel used for the steam explosion. The washing stream, rich in hexoses, is concentrated in a falling film evaporator to reach 200 g L^{-1} of sugars. The acetic acid present in this stream is removed in the evaporation step[50] and could be recovered as vinegar for nonfood use (not considered in this study). In evaporators, it was assumed that 3 t of water are evaporated for each ton of consumed steam.[51] The hexoses are dehydrated to HMF by an acid-catalyzed process and subsequently rehydrated to LA and FA. The yield of glucose conversion to LA is 60% (mol mol^{-1}).[43] It is assumed that other hexoses (mannose and galactose) are converted to LA at the same rate.[52] This process generates FA, furfural, and acetic acid as byproducts.[34,44] To simplify the analysis, the concentrations of FA and furfural were considered to be similar and the acetic acid concentration was considered to be negligible.[34,52] Another byproduct that could be formed is humins (formed from hexoses and HMF degradation)[41,43] and its formation in the acid catalysis process depends principally on the temperature.[53] This byproduct could be separated from the product mixture in a filter unit.[41] The formation and treatment of humins will be considered in a later work.

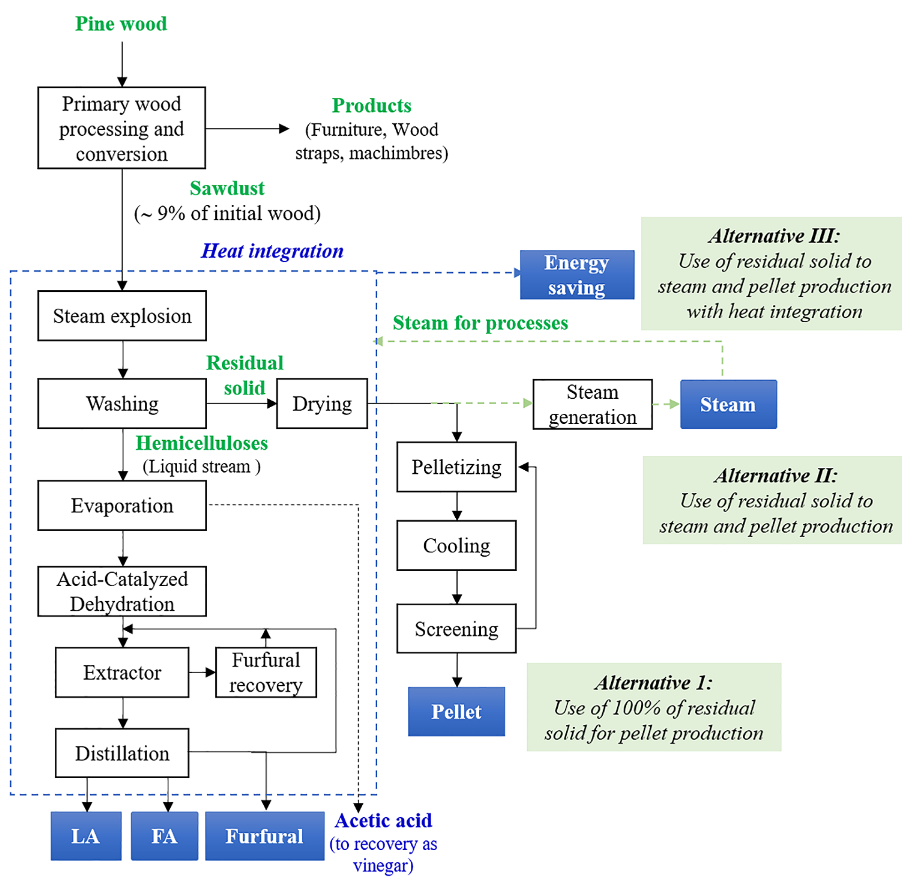

Figure 2. Simplified block flow diagram of the processes for different alternatives (LA: levulinic acid; FA: formic acid).

Levulinic acid, FA, and furfural (5.2%, 2.1%, and 2.1%, respectively) are recovered from the liquid stream coming out from the acid catalysis by liquid-liquid extraction using furfural as a solvent.[44] This liquid stream, together with furfural, is introduced into the extractor to generate an aqueous phase (top stream) and a solvent phase containing mainly LA, FA, and furfural (bottom stream). It is supposed that LA and FA are completely extracted in the solvent phase.[34,44] The solvent phase was simulated with ASPEN Plus using the scheme proposed by Nhien *et al.*,[44] and the operational parameters were determined. The solvent stream is fed to the first distillation column to recover FA at the top (99.9%), whereas the bottom stream is introduced into the second distillation column to recover LA and furfural (both with 99% of yield).[44]

The aqueous phase coming out of the extractor, containing water, furfural (7%), and H_2SO_4[34] is sent to a distillation column to recover the furfural. The liquid stream at the top of the column is sent to a settler to separate the furfural-rich phase and the water-rich phase. The aqueous stream at the bottom of the column, containing mainly water and H_2SO_4, is reused in the acid catalysis process.[46]

Pellet production

The chemical composition of the pretreated sawdust is 49.1% glucans, 1.3% xylans, 1.28% mannans, and 43.3% lignin (percentage on oven-dry weight, % o.d.w.).[39] Three alternatives were assessed to exploit the residual solid from the steam explosion for pellet production.

Alternatives for steam use and energy saving

Alternative I

Based on updated literature,[47,54] a process was selected that involves drying, pelletizing, cooling (to allow solidifying and strengthening of the pellets, which provide strength and durability to granules), and screening through a vibrating sieve to remove fine material and ensure a clean fuel source.

The fine material is recovered by introducing it back into the pelleting process. In conventional production processes, grinding of pellets is usual after drying,[47] but grinding is not necessary in this case because the particle size of the sawdust is within the specified values (< 6 mm).[55]

Alternative II

For the application of this alternative, the amount of residual solid needed to satisfy the process steam for LA production and the remaining solid available for pellet production has to be determined. The calorific value of pine sawdust after the steam explosion treatment is estimated with the higher heating value (HHV) parameter, as shown in Eqn (1):[56]

$$HHV\ (MJ\ kg^{-1}) = 0.1736Ce + 0.2663L + 0.3219 \qquad (1)$$

where Ce, L, and E are the weight percentage on dry biomass basis of polysaccharides (cellulose and hemicelluloses), lignin, and extractives, respectively.

Alternative III

Pinch analysis was used to identify the opportunities for heat integration.[57] To determine the potential of heat recovery, heat integration was performed by synthesizing and optimizing the heat exchanger network (HEN), using a global minimum temperature difference (ΔTmin) of 10 °C.[57]

Mass and energy balances

The mass and energy balance calculation of the global process, equipment sizing, product yields, and economic analysis was carried out using Apache OpenOffice Calc software. Global mass balances were conducted in all the unit operations. The mass balances of the individual components in the steam explosion, washing, and evaporation steps were performed considering sawdust, water, sulfuric acid, glucans, xylans, mannans, galactans, glucose, xylose, mannose, galactose, arabinose, HMF, furfural, and acetic acid. For acid catalysis, the extractor, furfural recovery, and distillation steps were performed considering furfural, water, FA, LA, and sulfuric acid. Mass and energy balances were expressed per ton of dry pretreated sawdust. The main flows involved in each step of the different processes formerly described were considered to accomplish the mass and energy balances. The yields of the different operations and chemical reactions, chemical reagents, supplies, etc., were established on the basis of an updated bibliography.[39,43,44,46–48] The energy balance was developed by calculating the energy consumption of equipment and processes, and the need for heating and cooling of the different streams. Utilities, electricity consumption of the processes and related equipment, and water heating and cooling were estimated as proposed by Stuart and Halwagi.[42] Saturated steam at 8 bar (evaporation, acid catalysis, distillations) and 13 bar (steam explosion) was used for heating. The energy lost during operation time in each equipment were assumed in 10% of total heat energy required.

The heat integration to reduce the energy costs by reusing the heat energy in the process streams was evaluated by pinch analysis. For this purpose, the streams with values of $m \times Cp > 17$ kJ s^{-1} °C were considered, where m is flow (kg s^{-1}) and Cp is the heat capacity of the stream (kJ kg^{-1}°C).

© 2018 Society of Chemical Industry and John Wiley & Sons, Ltd | *Biofuels, Bioprod. Bioref.* (2018); DOI: 10.1002/bbb

Economic analysis

The economic analysis was performed considering the process design and estimating the production costs, labor costs, and capital investment, among other considerations.[42,58,59]

Equation (2) was used to estimate the capital required for the project based on biomass production at different scales:

$$C = C_o \left(\frac{M}{M_o} \right)^n \tag{2}$$

where C is the process equipment cost of a plant with a capacity M, C_o is the reference cost of a plant with a capacity M_o, and n is the scaling factor (smaller than 1). Different scaling factors, cost installations, and other costs were estimated from updated literature.[31,40,42,59]

Labor requirements were calculated based on the type of process (batch process) and the capacity of the facility.[40]

The availability of the raw material was established as 1 28 800 tons per year of dry sawdust. The internal rate of return (IRR) was used as an indicator of the profitability of potential investments in biorefinery projects[42,60] as the higher the IRR, the higher the profitability of potential investments. The straight-line depreciation method was used to calculate the annual depreciation of the investment and the IRR values were determined from the cash flows. Usually, a financial analysis could be developed in a different time horizon, like 10 years,[61] 15 years,[62] and 20 years.[63] In Argentina, due to economic instability, requests for financial support to the National Bank are evaluated with an IRR of 5 years.[64] Other studies state that in financial analysis, a 5-year value is in the range of the standard requirements by the financial market.[65]

A sensitivity analysis was carried out varying each selected input parameter for the alternative with the highest IRR value, to determine how these parameters impact on the IRR values. The method is based on the impact of the main uncertain parameters one at a time, keeping the other parameters fixed. The selected parameters were therefore varied by ±10%, independently, assuming a normal distribution around the mean value.

Results and discussion

Levulinic acid production

The steam explosion extracts 309 kg of materials per ton of dry sawdust. Dissolved solids are recovered from the residual solid by water washing (2422 kg of water per ton of dry sawdust). The composition of the liquid stream is 45 g L^{-1} of sugars (9.2 g L^{-1} of glucose, 5.4 g L^{-1} of galactose, 10.5 g L^{-1} of xylose, 19.9 g L^{-1} of mannose), 2.7 g L^{-1} of HMF, 2.7 g L^{-1} of furfural, and 4.8 g L^{-1} of acetic acid. The energy consumption of the process is 354.7 kWh per ton of dry sawdust.

Before the acid catalysis, the liquor is concentrated up to 200 g L^{-1} of total hexoses in a triple effect falling film evaporator.[66,67] The amount of liquor (water + acetic acid) removed by evaporation is 2712 kg and the energy required is 1898 kWh. It is assumed that all acetic acid formed in the steam explosion process (about of 18 kg) is removed by

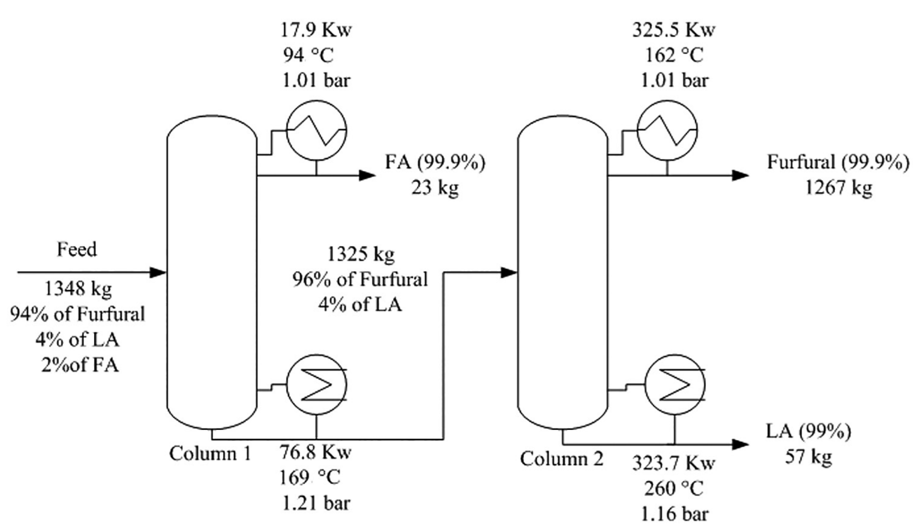

Figure 3. Scheme of LA recovery for a dry sawdust feed of 1 ton (LA: levulinic acid; FA: formic acid).

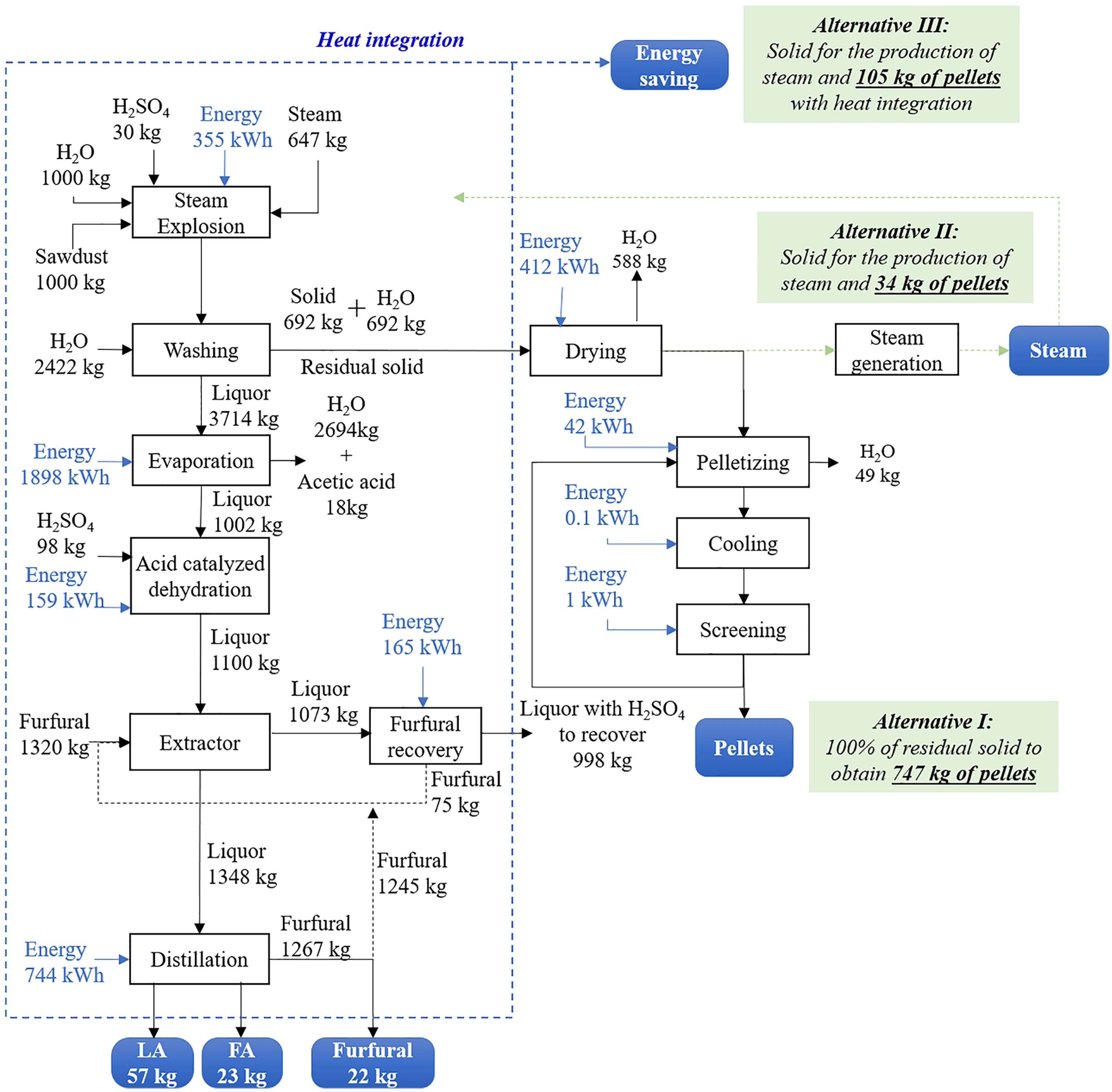

Figure 4. Mass and energy balances for the technological schemes of the different alternatives (LA: levulinic acid; FA: formic acid).

evaporation.[50] The concentrated stream, rich in hexoses (1002 kg), is converted to LA in a jacketed reactor by acid-catalyzed dehydration (159 kWh of energy requirement). The outgoing stream from the reactor contains about 57 kg of LA, and 23 kg of FA, 22 kg of furfural, water, and H_2SO_4. This stream is sent to a liquid-liquid extractor at room temperature using furfural as a solvent. In the extractor, a water-rich phase (84% of water, 7% of furfural, and 9% H_2SO_4)[34] and a furfural-rich phase (LA and FA) are separated (supposing that the furfural-rich phase lacks water). To make the process economically viable, the water-rich phase is sent to a distiller column to recover furfural with a yield of 99.5%, requiring 165 kWh. At the top of this column, 75 kg of furfural are recovered. The stream at the bottom of the column contains the H_2SO_4 that could be reused in the acid catalysis, although its reuse is not considered

© 2018 Society of Chemical Industry and John Wiley & Sons, Ltd

in this work. The furfural-rich phase coming out of the extractor is recovered by two distillation columns. The balances of mass and energy were performed using ASPEN Plus software and these results are presented in Fig. 3.

In the first column, 23 kg of FA are recovered at the top and the stream at the bottom is sent to a second column where 57 kg of LA and 1267 kg of furfural are obtained with an energy demand of 744 kWh. The mass balance for 1 t of dry pretreated sawdust is shown in Fig. 4. The total amounts of products obtained and to be sold are 57 kg of LA (99 wt.%), 23 kg of FA (99 wt.%), and 22 kg of furfural (99.9 wt.%).

Pellet production

Alternative I

Conditions for pellet production were chosen from selected references.[47,54,68] Pellet production is 0.62 m^3 per ton of dry sawdust (or 747 kg per ton of dry sawdust for a pellet density of 1200 kg m^{-3}). In the drying process, the final moisture content has to be about 15%, so 588 kg of water by ton of solids must be removed in this step. Drying consumes a large amount of energy and is a focal point of research as the industry attempts to minimize costs and improve the quality of wood-pellet energy.[47] The rotary drum dryer is the one most commonly used in pellet production plants[69] and could be heated by steam.[70] In pelletizing, 49 kg of water are removed from the material because the mechanical treatment increases the temperature to 100 °C due to friction, leaving 5–8% of moisture content in pellets. Pellets are subsequently air cooled to solidify lignin. This strengthens the pellets. In contrast to the drying process, cooling does not involve any additional energy.[47] Finally, the pellets are screened, and the recovered fines are returned to the pelletizing process to ensure that no raw material is wasted.

The drying process consumes 411 kWh per ton of pretreated sawdust, representing about 90% of the total energy used for pellet production (about 11% of the total energy used for the LA and pellet production). The evaporation stage to concentrate of sugars represents almost 50% of the total energy consumed (Fig. 5).

The production costs are detailed in Fig. 6. The highest production cost of the mill is processing energy, including the energy for LA production (45%) and the energy for pellet production (11%). This cost involves all direct production activities (see Fig. 3).

In the case of LA, energy costs refer to the steam necessary for all direct activities, whereas in the case of pellets, the costs refer to the electrical energy and steam needed for the direct activities. Supplementary activities costs (conveyor belts, suction systems, etc.) are included in the utilities. Different alternatives were proposed for its reduction, improving the profitability of the process.

Alternative II

An alternative to reduce the energy costs is the use of a fraction of pretreated sawdust to generate steam for the production of LA. It was determined that the solid faction needed to supply the demand of steam would be 95% of the total solid available after the steam explosion, and the remaining 5% could be used to produce commercial pellets. Considering this alternative, all the energy required

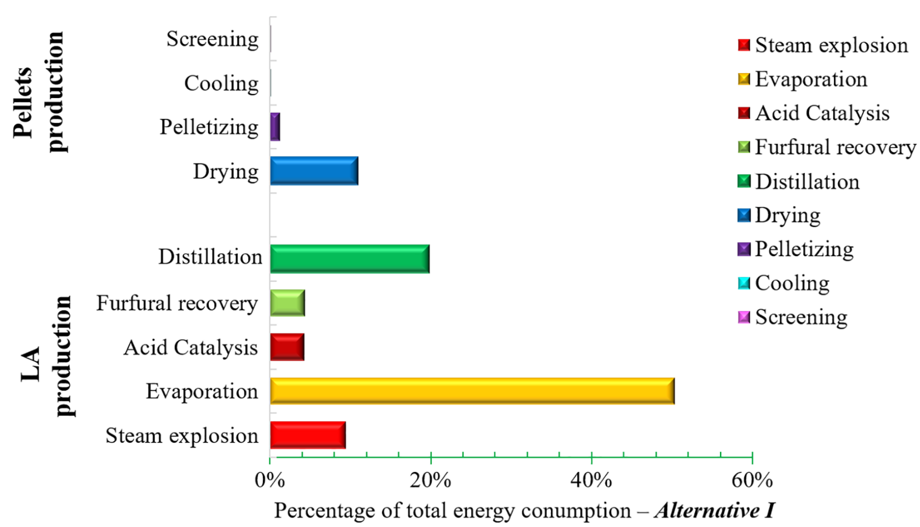

Figure 5. Main energy consumption for levulinic acid and pellets production (Alternative I).

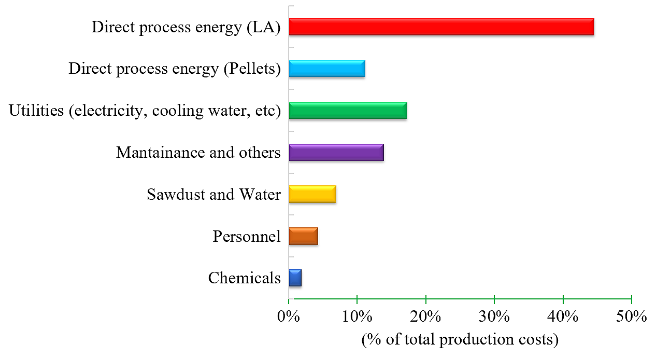

Figure 6. Production costs for levulinic acid and pellets production (Alternative I).

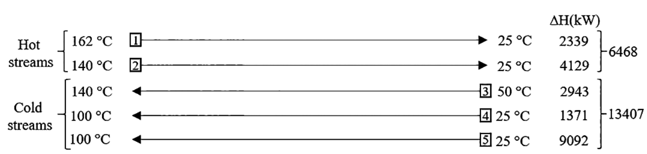

Figure 7. Exchanger network for the selected streams.

for LA production is supplied by the steam produced by the residual solid (steam for the steam explosion, evaporation, acid-catalysis, and distillations columns). This option allows an 80% reduction in total energy costs. In this scenario, 34 kg of pellets per ton of pretreated sawdust are produced. The production and the other costs of LA, FA, and furfural are similar to those in the first alternative.

Due to the low amount of solid available for pellet production, two options were analyzed: (1) its use as biomass fuel to satisfy the energy requirements of LA production, using the solid remnants for pellet production (as was studied previously), and (2) its use as biomass fuel as it is, without any pellet production (in this case the drying process was taken into account).

Alternative III

A pinch analysis was performed to reduce the energy consumption. The following streams were taken into account in the analysis: (1) outcoming furfural from distillation unit; (2) incoming liquor to the extraction unit; (3) incoming liquor of the hydrolysis unit; (4) incoming liquor of the distillation unit, and (5) incoming liquor of the evaporation unit (stream details are presented in Fig. 7). Streams inside the distillers were not taken into account because the adopted processes were already optimized.[44,46]

The analysis determines that the minimum requirement for cooling duty is 750 kW and the minimum requirement for heating duty is 8033 kW. The potential heat recovery is

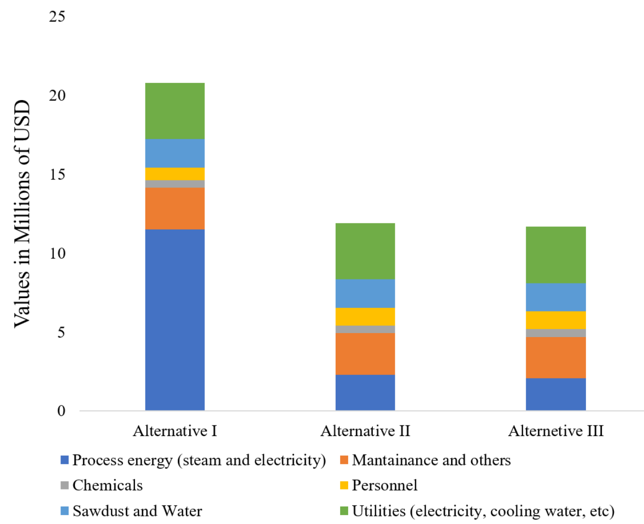

Figure 8. Annual production costs of LA of the proposed alternatives.

5701 kW, which means that the consumption of residual solids to generate steam for LA production could be reduced from 95% to 86%, thus increasing the capacity for pellet production (105 kg of pellets per ton of dry sawdust in this alternative).

The annual production costs of LA (including energy, utilities, raw materials, chemicals, and maintenance) in the different alternatives are summarized in Fig. 8. Production costs of LA were reduced by 42.8% in alternative II in comparison with alternative I, and when integrating the selected streams (alternative III), annual production costs of LA were reduced by 43.9% in comparison with alternative I.

Alternative III allows a reduction of 10% in the steam consumption for LA production in comparison with alternative II, increasing the capacity for pellet production.

Economic evaluation

This study assumes that the facility will have a life cycle of 10 years and the project is considered to be economically viable when the IRR exceeds 15%. The parameters taken into account for the analysis are shown in Table 2. It was considered that the plant would operate at 50% of its nominal capacity in the first year, and at full capacity in the rest of its lifetime (10 years).

The methods to estimate the total costs investment (TCI) are summarized in Table 3. TCI is 3.5 times greater than the purchased equipment costs using the modified NREL method.

The IRR of each scenario was calculated taking into account the conversion of the hexoses from the residual

© 2018 Society of Chemical Industry and John Wiley & Sons, Ltd | *Biofuels, Bioprod. Bioref.* (2018); DOI: 10.1002/bbb

Table 2. Unit prices of pine sawdust, chemicals, products, energy, labor, and maintenance.

Unit prices at mill gate	
Pine sawdust (USD t^{-1})[a]	7.02
Water (USD m^{-3})[b]	0.585
Electricity (USD MWh^{-1})[c]	85
Labor (USD h^{-1})[d]	3.09–4.41*
Steam (USD t^{-1})	25
Maintenance and taxes	8% (of revenue)
Tax rate	35%
Days operation (days $year^{-1}$)	261
Operational hours (hours day^{-1})	16
Chemicals for production	
H_2SO_4 (USD kg^{-1})[e]	0.04
Products (assumptions)	
Formic acid (USD kg^{-1})[f]	0.7
Levulinic acid (USD kg^{-1})[g]	3.8
Pellets (USD t^{-1})	125.7*
Furfural (USD kg^{-1})[h]	1

[a]Price estimated from the Instituto Nacional de Tecnología Agroindustrial (INTA).[71]
[b]Average price in Argentina.
[c]Energy cost in Misiones, Argentina.
[d]Value depends on the worker position.
[e]Average international price.[72]
[f]Average international price.[74]
[g]International price.[73]
[h]International price.[73]
*Assumptions.

hemicellulosic liquor to LA, FA, and furfural, and alternatives for the valorization of the residual solid. The production costs in the different alternatives include feedstocks, chemicals, utilities (electricity and steam), depreciation, labor, and maintenance. It is assumed that the feedstock costs (sawdust and water) of each alternative are taken into account in the production costs of LA and are excluded from the production costs of the pellets. Internal rates of return for these alternatives are summarized in Table 4.

The first alternative (all residual solid is used to produce commercial pellets) presents the lowest IRR, due to the high energy production costs of the LA. To reduce LA production costs, alternative II-*a* (the use of a fraction of the pretreated sawdust for steam production) presents an

Table 4. Comparative results of the economic analysis obtained for the three studied biorefinery scenarios.

Alternative	Option	IRR (%)	Investment (MUSD[a])	Production costs	
				Pellets (USD/ton)	LA (USD/kg)[b]
I		13.4	75.0	62.42	3.71
II	(*a*)	16.5	70.5	132.04	2.57
	(*b*)	16.6	70.1	—	2.57
III		17.0	71.7	76.14	2.54

[a]Millions of USD.
[b]The production costs of LA include the production costs of FA and furfural.

Table 3. Total costs investment (TCI) for all scenarios.

Cost Items	Factor	Scenario costs (MUSD[a]) for 1 28 800 ton sawdust $year^{-1}$		
		Alternative I	Alternative II	Alternative III
Total direct costs				
Purchased equipment	1.000	21.3	20.0	20.4
Installation[b]	0.700	14.9	14.0	14.3
Warehouse	0.025	0.53	0.50	0.51
Site development	0.153	3.26	3.07	3.12
Total Indirect Costs				
Prorateable Costs	0.188	4.01	3.77	3.83
Fixed Expenses	0.188	4.01	3.77	3.83
Office and construction	0.470	10.0	9.42	9.57
Contingency	0.282	6.01	5.65	5.74
Other	0.188	4.01	3.77	3.83
Fixed capital investment (FCI)	3.194	68.0	64.0	65.1
Working capital investment (WCI = 10% of FCI)	0.319	6.80	6.40	6.50
Total Costs Investment (TCI)	**~3.520**	75.0	70.5	71.7

[a] Millions of USD.
[b]This factor varies for each type of equipment. Calculation of TCI is based on an average value of installation cost of 0.7.

economic improvement with a lower investment cost due to a decrease in the pellet production scale. This alternative presents pellet production costs that are higher than the other alternatives due to the small fraction of sawdust used and the economy of scale.[48] Alternative II-*b* presents similar results to alternative II-*a*, due to the small influence of the pellets in the global scheme and the higher production costs of pellets. To be profitable it would be necessary to increase the selling price of the pellets over the production cost.

Finally, the energy integration of some streams involved in the production process in alternative II generates the economic improvement in alternative III, due to the increased availability of residual solids to produce pellets.

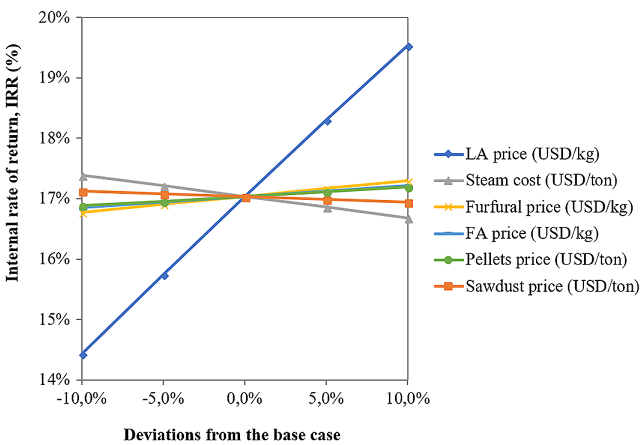

Figure 9. The result of the sensitivity analysis (one at a time test) on IRR values of alternative III.

A sensitivity analysis was carried out on the IRR of alternative III. For this analysis the following input parameters were selected: sawdust price, LA price, steam cost, furfural price, FA price, and pellet price. These parameters were varied ±10%. The results are shown in Fig. 9.

The LA price is the factor that most affected the IRR (due to its high market value), followed by the steam cost and furfural price. The factor that least affects the IRR is the price of sawdust and pellets. The LA price adopted in the present work (3.8 USD ton^{-1}) is lower than the current market price (5 and 8 USD ton^{-1}) because it is expected that the LA market price will decrease in the short or medium term as a result of the improvements that are being made in the process conditions and technology,[75] thus giving a more conservative result for the economic analysis. The range of the IRR values obtained, based on alternative III for the current market prices, is about 25% to 41%. These IRR values are very attractive when the current market price of LA is adopted.

Most technical-economic studies of pellet production have been based on the full use of feedstock to obtain a single product (pellets) – see Table 5. However, the production of pellets from pretreated biomass (using processes such as autohydrolysis or steam) allows the extraction of one or more components of lignocellulosic

Table 5. Recent economic studies on the production of pellet and LA.

Product	Feedstock	Capacity (ton year^{-1}) ×1000	Production costs (USD ton^{-1})	Country	References
Pellets	Agricultural residues	70 150	170 122	Canada	48
	Pine sawdust	22 44	56 42[a]	Argentina	27
	Steam treated hardwood	150	215	Canada	76
	Wood	64 80	114 106[a]	Finland	77
	Pretreated sugarcane bagasse[b]	13.2 44 61	88 67 64	Argentina	78
	Pretreated pine sawdust[b]	4.4 13.5 96	132 76 62	Argentina	Present Study
LA	Sugarcane fiber (Cellulose fraction)	200	2000	Australia	79
	Eucalyptus and olive pruning (Cellulose fraction)	395	N.d.	Southern Europe	38
	Pine sawdust (Hemicellulose fraction)	128.8	3.710–2.540	Argentina	Present Study

[a]Values converted using a factor of 1.2 to convert euros to dollars.
[b]Biomass pretreated with autohydrolysis or steam explosion before pelletizing.
Not determined.

 © 2018 Society of Chemical Industry and John Wiley & Sons, Ltd

material (extractives, hemicelluloses or lignin), which can be converted into various products. This alternative is potentially advantageous in comparison with conventional pellet production. Pelletization of the pretreated material resulted in denser pellets and greater mechanical strength. Technical characteristics of the production process are also improved, such as the minimization of the energy required for densification in comparison with conventional pellets,[80] and the cost of electricity production from these pellets is less than from conventional pellets.[76] In the present study, it was proposed to produce pellets with pretreated sawdust with steam explosion; one of the advantages of using sawdust is that it is not necessary to use the grinding process (which is necessary in the case of bagasse and other waste). Another strong point of the proposed scheme is that is possible to obtain a product with a production cost within the values obtained by other authors on a small scale (< 4500 ton/year), which means a real alternative for the recovery of waste for small forest industries. International prices depend on each country. North American conventional pellet prices have been estimated to range from 140 to 210 USD ton^{-1},[76,81] in Canada about 137 USD ton^{-1},[81] and in Argentina, the market price is in the range of 200 and 300 USD ton^{-1}.[82]

In the case of LA, few technical-economic studies are based on the use of a cellulose fraction as feedstock on a large scale with high production yields. The production costs of LA reported in Table 5 are lower than the cost obtained in the present work, perhaps due to the difference in scale and the fraction used for LA production (a hemicellulose fraction in this study). In the present work, an innovative scheme for LA production was analyzed to valorize the hemicellulosic fraction of pine sawdust (which is rich in hexoses). The production costs obtained are below the market prices (LA market value ranges between 5 and 8 USD kg^{-1}).[21]

The results obtained show that small-scales pine sawdust biorefineries are feasible and can be integrated into a bioenergy plant, farm heat plant, heat and power plant, or electricity generating plant by using solid residuals as feedstock.

Conclusions

The present study analyzed the production of LA from the hexoses available in the liquid fraction from the steam explosion of pine sawdust integrated with alternatives for the use of the solid fraction.

Levulinic acid production from the liquid fraction and pellets production from the solid fraction was analyzed initially (alternative I). It was determined that the energy used for LA production was one of the main production costs, so two other alternatives (II *a* and *b*) were proposed with the objective of reducing energy costs. When 95% of the residual solid was used to generate steam for the production of LA, there was an improvement in the IRR with respect to alternative I. However, when integrating some selected streams (alternative III), a decrease in steam consumption for LA production and an increase of the residual solid available for pellet production was obtained. Three alternatives for the valorization of pine sawdust were analyzed and the best of them obtained an IRR of about 17%.

The integration of this production scheme with conventional chains could contribute significantly to the total revenues of sawmills, valorizing the wood waste through the manufacture of multiple products and generating, at the same time, a modern industrial core with qualified manpower requirements benefiting the region socioeconomically.

References

1. Ojala J, Voutilainen M and Lamberg J-A, *The Evolution of Global Paper Industry 1800–2050*, Vol. 17. Springer, Dordrecht, Netherlands (2012).
2. Toppinen A and Zhang Y, *Forests and Society – Responding to Global Drivers of Change.* International Union of Forest Research Organizations (IUFRO), Springer, Vantaa, Finland, pp. 135–156 (2010).
3. Laaksonen-Craig S, The determinants of foreign direct investments in Latin American forestry and forest industry. *J Sustainable For* **27**:172–188 (2008).
4. Pöyry. *Pöyry Point of View. Reinventing Plantation Forestry.* Poyry, Vantaa, Finland (2014).
5. Kline KL, Oladosu GA, Perlack RD, Dale VH and McMahon M, *Biofuel Feedstock Assessment for Selected Countries: To Support the DOE Study of Worldwide Potential to Produce Biofuels with a Focus on U.S. Imports.* U.S. Department of Energy, Oak Ridge, Tennessee, United States (2008).
6. Eisentraut A, *Sustainable Production of Second-Generation Biofuels – Potential and Perspectives in Major Economies and Developing Countries.* International Energy Agency (IEA), Paris, France (2010).
7. Vallejos ME, Kruyeniski J and Area MC, Second-generation bioethanol from industrial wood waste of South American species. *Biofuel Res J* **15**:654–667 (2017).
8. Ragauskas AJ, Williams CK, Davison BH, Britovsek G, Cairney J, Eckert CA *et al.,* The path forward for biofuels and biomaterials. *Science* **311**:484–489 (2006).
9. Zhang Y-HP, Reviving the carbohydrate economy via multi-product lignocellulose biorefineries. *J Ind Microbiol Biotechnol* **35**:367–375 (2008).
10. Ahring BK, Traverso JJ, Murali N and Srinivas K, Continuous fermentation of clarified corn stover hydrolysate for the production of lactic acid at high yield and productivity. *Biochem Eng J* **109**:162–169 (2016).
11. Duangwang S, Ruengpeerakul T, Cheirsilp B and Yamsaengsung R, Pilot-scale steam explosion for xylose production from oil palm empty fruit bunches and the use of xylose for ethanol production. *Bioresour Technol* **203**:252–258 (2016).

© 2018 Society of Chemical Industry and John Wiley & Sons, Ltd

12. Lin T, Guo G, Hwang W and Huang S, The addition of hydrolyzed rice straw in xylose fermentation by *Pichia stipitis* to increase bioethanol production at the pilot-scale. *Biomass Bioenergy* **91**:204–209 (2016).
13. Madhavan A, Srivastava A, Kondo A and Bisaria VS, Bioconversion of lignocellulose-derived sugars to ethanol by engineered *Saccharomyces cerevisiae*. *Crit Rev Biotechnol* **32**:22–48 (2012).
14. Rackemann DW and Doherty WOS, Review: the conversions of lignocellulosics to levulinic acid. *Biofuels Bioprod Biorefin* **5**:198–214 (2011).
15. Morone A, Apte M and Pandey RA, Levulinic acid production from renewable waste resources: bottlenecks, potential remedies, advancements and applications. *Renewable Sustainable Energy Rev* **51**:548–565 (2015).
16. Dumesic JA, Alonso DM, Gürbüz EI and Wettstein SG, Production of levulinic acid, furfural, and gamma valerolactone from C5 and C6 carbohydrates in mono- and biphasic systems using gamma- valerolactone as a solvent, US 8399688 B2 (2012).
17. Fitzpatrick SW, Production of levulinic acid from carbohydrate-containing materials. US Patent 5,608,105, pp. 1–2 (1997).
18. Klingler FD and Ebertz W, Oxocarboxylic acids, in *Ullmann's Encyclopedia of Industrial Chemistry*, Vol. 25. Wiley-VCH, Weinheim, Germany (2012). DOI: 10.1002/14356007.a18
19. Tanskanen J, Rousu E, Anttila J and Rousu P, Preparation of levulinic acid. FI Patent 20125274A (2013).
20. Peng L, Lin L, Zhang J, Zhuang J, Zhang B, Gong Y, Catalytic conversion of cellulose to levulinic acid by metal chlorides. *Molecules* **15**:5258–5272 (2010).
21. Datta D, Marti ME, Pal D and Kumar S, Equilibrium study on the extraction of levulinic acid from aqueous solution with Aliquat 336 dissolved in different diluents: solvent's polarity effect and column design. *J Chem Eng Data* **62**:3–10 (2016). DOI: 10.1021/acs.jced.6b00164
22. Markets and Markets, *Formic Acid Market*. [Online]. (2017). Available: https://www.marketsandmarkets.com. [10 October 2017].
23. Allied Market Research, *Furfural Market Report*. [Online] (2017). Available: https://www.alliedmarketresearch.com. [11 October 2017].
24. Bond JQ, Alonso DM and Dumesic JA, in Catalytic strategies for converting lignocellulosic carbohydrates to fuels and chemicals, *Aqueous Pretreatment of Plant Biomass for Biological and Chemical Conversion to Fuels and Chemicals,* ed. by Charles EW. John Wiley & Sons, Ltd, Chichester, UK, pp. 61–102 (2013). DOI: 10.1002/9780470975831.ch5
25. Win DT, Furfural – gold from garbage. *Aust J Technol* **8**:185–190 (2005).
26. Mamman A., Lee JM, Kim YC, Hwang IT, Park NJ, Hwang YK *et al.,* Furfural: hemicellulose/xylose derived biochemical. *Biofuels Bioprod Biorefin* **2**:438–454 (2008).
27. Uasuf A and Becker G, Wood pellets production costs and energy consumption under different framework conditions in northeast Argentina. *Biomass Bioenergy* **35**:1357–1366 (2011).
28. Moreno-Lopez M, Alarcón-Herrera MT and Martin-Dominguez IR, Feasibility of pelletizing forest residues in Northern Mexico. *Waste Biomass Valor* **8**:923–932 (2017).
29. Stoffel RB, Neves PV, Felissia FE, Ramos LP, Gassa LM and Area MC, Hemicellulose extraction from slash pine sawdust by steam explosion with sulfuric acid. *Biomass Bioenergy* **107**:93–101 (2017).
30. Ramos LP, The chemistry involved in the steam treatment of lignocellulosic materials. *Quim Nova* **26**:863–871 (2003).
31. Sadhukhan J, Ng KS and Martinez E, *Biorefineries and Chemical Processes*. John Wiley & Sons, Ltd, Chichester, United Kingdom (2014). DOI: 10.1002/9781118698129
32. Mansoornejad B, Sanaei S, Gilani B, Batsy DR, Benali M, Stuart PR, Designing integrated biorefineries using process systems engineering tools, in *Biorefineries*. *Targeting Energy, High Value Products and Waste Valorisation*, ed. by Rabaçal M, Ferreira AF, Silva CAM and Costa M. Springer International Publishing, Basel, Switzerland, pp. 201–226 (2017). DOI: 10.1007/978-3-319-48288-0_8
33. Bozell, JJ, Moens L, Elliott DC, Wang Y, Neuenscwander GG, Fitzpatrick SW *et al*., Production of levulinic acid and use as a platform chemical for derived products. *Resour Conserv Recycl* **28**:227–239 (2000).
34. Reunanen J, Oinas P and Nissinen T, Process for recovery of formic acid. US Patent 8530695 (2013).
35. Hayes DJ, Ross J, Hayes MHB and Fitzpatrick S, The biofine process: production of levulinic acid, furfural and formic acid from lignocellulosic feedstocks. *Biorefineries-Industrial Process and Products*, Vol. 1. WILEY-VCH, Weinheim, Germany (2005).
36. Farzad S, Mandegari MA, Guo M, Haigh KF, Shah N, Görgens JF, Multi-product biorefineries from lignocelluloses: a pathway to revitalisation of the sugar industry? *Biotechnol Biofuels* **10**:87 (2017).
37. Mountraki A, Tsakalova M, Panteli A, Papoutsi A and Kokossis AC, Integrated waste management in multi-product biorefineries: systems optimization and analysis of a real-life industrial plant. *Ind Eng Chem Res* **55**:3478–3492 (2016)
38. Giuliano A, Poletto M and Barletta D, Process optimization of a multi-product biorefinery: the effect of biomass seasonality. *Chem Eng Res Des* **107**:236–252 (2016). DOI: 10.1016/j.cherd.2015.12.011
39. Stoffel RB, Fraccionamiento de aserrín de pino destinado a una biorrefinería forestal. [Online]. Doctoral dissertation. Universidad Nacional de La Plata, Facultad de Ingeniería (2016). Available: http://sedici.unlp.edu.ar/handle/10915/52523 [2 July 2017].
40. Seider WD, Seader JD and Lewin DR, *Product and Process Design Principles - Synthesis, Analysis, and Evaluation*. pp. 505–556 (2003).
41. Girisuta B, *Levulinic Acid from Lignocellulosic Biomass*. University of Groningen, Netherland, 148 p. (2007).
42. Stuart PR and El-Halwagi MM, *Integrated Biorefineries, Design, Analysis and Optimization*. CRC Press, Boca Raton, FL, US (2013).
43. Girisuta B, Janssen LPBM and Heeres HJ, A kinetic study on the conversion of glucose to levulinic acid. *Chem Eng Res Des* **84**:339–349 (2006). DOI: 10.1205/cherd05038
44. Nhien LC, Long NVD and Lee M, Design and optimization of the levulinic acid recovery process from lignocellulosic biomass. *Chem Eng Res Des* **107**:126–136 (2016).
45. Sadhukhan J, Ng KS and Martinez E, *Biorefineries and Chemical Processes: Design, Inntegration and Sustainability Analysis*. Wiley, Chichester, UK (2014).
46. Vila C, Santos V and Parajó JC, Recovery of lignin and furfural from acetic acid-water-HCl pulping liquors. *Bioresour Technol* **90**:339–344 (2003).
47. Peksa-Blanchard M, Dolzan P, Grassi A, Heinimö J, Junginger M, Ranta T *et al.*, *Global Wood Pellets Markets and Industry: Policy Drivers, Market Status and Raw Material Potential*. Utrecht University, Utrecht (2007).

 © 2018 Society of Chemical Industry and John Wiley & Sons, Ltd

48. Sultana A, Kumar A and Harfield D, Development of agri-pellet production cost and optimum size. *Bioresour Technol* **101**:5609–5621 (2010).
49. TAPPI, *Kraft Pulping Short Course Notes*, Vol. 466. Tappi Press, Atlanta, Georgia, US (1997).
50. Mussatto SI and Roberto IC, Alternatives for detoxification of diluted-acid lignocellulosic hydrolyzates for use in fermentative processes : a review. *Bioresour Technol* **93**:1–10 (2004).
51. Geankoplis CJ, *Procesos de transporte y operaciones unitarias*. Prentice Hall, Englewood, New Jersey, US (1993).
52. Girisuta B, Danon B, Manurung R, Janssen LPBM and Heeres HJ, Experimental and kinetic modelling studies on the acid-catalysed hydrolysis of the water hyacinth plant to levulinic acid. *Bioresour Technol* **99**:8367–8375 (2008).
53. Girisuta B, Janssen LPBM and Heeres HJ, Kinetic study on the acid-catalyzed hydrolysis of cellulose to levulinic acid. *Ind Eng Chem Res* **46**:1696–1708 (2007).
54. Brizuela JG, Pellets para combustión a partir de residuos foresto-industriales. Degree thesis. Universidad Nacional de Misiones, Posadas, Misiones, Argentina (2015).
55. Serret-Guasch N, Giralt-Ortega G and Quintero-Ríos M, Caracterización de aserrín de diferentes maderas. *Tecnol Química* **36**:395–405 (2016).
56. Shafizadeh F, Sarkanen K and Tillman D, *Thermal Uses and Properties of Carbohydrates and Lignins*. *Thermal Uses and Properties of Carbohydrates and Lignins*. Academic Press, New York, US (1976). DOI: 10.1016/B978-0-12-637750-7.50011-X
57. Kemp I, *Pinch Analysis and Process Integration: A User Guide on Process Integration for the Efficient Use of Energy*. Elsevier Ltd, Oxford, UK (2007).
58. Sadhukhan J, Ng KS and Martinez E, in *Biorefneries and Chemical Processes: Design, Integration and Sustainability Analysis*, ed. by Sadhukhan J, Ng KS and Martinez E. John Wiley & Sons, Ltd., Chichester, UK, pp. 425–473 (2014). DOI: 10.1002/9781118698129
59. Harmsen J, *Industrial Process Scale-up: A Practical Innovation Guide from Idea to Commercial Implementation*. Elsevier, Oxford, UK (2013). DOI: 10.1016/B978-0-12-416584-7.00001-7
60. da Silva SS and Chandel AK. *Biofuels in Brazil, Fundamental Aspects, Recent Developments, and Future Perspectives*. Springer International Publishing, Basel, Switzerland (2014). DOI: 10.1007/978-3-319-05020-1
61. Kazi FK, Fortman J and Anex R, *Techno-Economic Analysis of Biochemical Scenarios for Production of Cellulosic Ethanol*. U.S. Department of Energy, Golden, Colorado (2010).
62. O'Keeffe S, Schulte RPO, Sanders JPM and Struik PC, II. Economic assessment for first generation green biorefinery (GBR): scenarios for an Irish GBR blueprint. *Biomass Bioenergy* **41**:1–13 (2012).
63. Towler G and Sinnott R, Economic evaluation of projects, in *Chemical Engineering Design*, ed. by Towler G and Sinnott R. Elsevier Ltd., Oxford, UK, pp. 389–429 (2013).
64. BNA, *Banco de la Nación Argentina. Guía para empresarios PyMEs para elaborar un Plan de Negocios*. Talleres Gráficos del Banco de la Nación Argentina, Buenos Aires, Argentina (2002).
65. Franceschin G, Sudiro M, Ingram T, Smirnova I, Brunner G and Bertucco A, Conversion of rye straw into fuel and xylitol: a technical and economical assessment based on experimental data. *Chem Eng Res Des* **89**:631–640 (2011).
66. Couper JR, Penney RW, Fair JR and Walas SM, *Chemical Process Equipment*. Elsevier, Burlington, US (2005).
67. Matches. *Matches engeneering to chemical energy manufacturing metallurgical industries*. [Online]. (2017). Available: http://www.matche.com. [10 August 2017].
68. Sultana A and Kumar A, Ranking of biomass pellets by integration of economic, environmental and technical factors. *Biomass Bioenergy* **39**:344–355 (2012).
69. Campbell K, *A Feasibility Study Guide for an Agricultural Biomass Pellet Company Request for Comments*. Agricultural Utilization Research Institute, Minnesota, US (2007).
70. DVA Holland-Merten GmbH. *Drum dryers, coolers/ Vacuum drum dryer*. [Online]. (2018). Available: http://www.dva-gmbh.de/en/products/drum-dryers-coolers-vacuum-drum-dryer/. [1 October 2018].
71. INTA, *Planilla de Precios Forestales*. [Online]. (2013). Available: http://inta.gob.ar/. [1 February 2016].
72. Hörhammer HS, Treasure TH, Gonzalez RW and Van Heiningen ARP. Larch biorefinery: technical and economic evaluation. *Ind Eng Chem Res* **53**:1206–1213 (2014).
73. E4tech, *From the Sugar Platform to biofuels and biochemicals. Final report for the European Commission Directorate-General Energy* (2015).
74. Alibaba, *International Prices*. [Online]. (2017). Available: http://www.alibaba.com [3 April 2017].
75. Mukherjee A, Dumont MJ and Raghavan V, Review: sustainable production of hydroxymethylfurfural and levulinic acid: challenges and opportunities. *Biomass Bioenergy* **72**:143–183 (2015).
76. Mckechnie J, Saville B and Maclean HL, Steam-treated wood pellets : Environmental and financial implications relative to fossil fuels and conventional pellets for electricity generation. *Appl Energy* **180**:637–649 (2016).
77. Agar DA, A comparative economic analysis of torre fi ed pellet production based on state-of-the-art pellets. *Biomass Bioenergy* **97**:155–161 (2017).
78. Clauser NM, Gutiérrez S, Area MC, Felissia FE and Vallejos ME, Alternatives of small-scale biorefineries for the integrated production of xylitol from sugarcane bagasse. *J Renew Mater* **6**(2):139–151 (2018).
79. Rackemann DW, *Production of Levulinic Acid and Other Chemicals From Sugarcane Fibre*. Queensland University of Technology (2014). Available: https://eprints.qut.edu.au/72741/1/Darryn_Rackemann_Thesis.pdf [25 October 2017].
80. Tooyserkani Z, Kumar L, Sokhansanj S, Saddler J, Bi XT, Lim CJ *et al*., SO2-catalyzed steam pretreatment enhances the strength and stability of softwood pellets. *Bioresour Technol* **130**:59–68 (2013).
81. Argus. *Argus Biomass Markets*. Argus Media groupCity, London, UK (2018). Available: https://www.argusmedia.com/
82. Mercado Libre 2015. *International Prices*. [Online]. (2017). Available: http://www.mercadolibre.com. [12 November 2017].

Nicolás M. Clauser
Nicolás Martín Clauser is currently a doctorate student in applied science in the Institute of Materials of Misiones (Argentina). He is also assistant professor at the National University of Misiones. His work concerns process modeling, process simulation, and technoeconomic evaluation of biorefineries.

Soledad Gutierréz
Dr Soledad Gutiérrez is an associate professor in the Chemical Engineering Institute, University of the Republic of Uruguay. She obtained a PhD from University of the Republic of Uruguay that included modelling of biochemical processes in wastewater treatment. Her fields of expertise consist of modeling, simulation, and optimization in chemical processes. She addressed modeling and optimization problems in biorefineries since 2010. She founded the chemical processes system engineering research group in 2011.

María Cristina Area
María Cristina Area is a senior researcher and principal of the pulp and paper program of the Institute of Materials of Misiones (Argentina). She is also a professor at the National University of Misiones. She has published books, book chapters, and over 90 research papers in specialized journals. Her areas of interest are: biorefinery; fibrous materials; and clean technologies of pulping and bleaching.

Fernando E. Felissia
Fernando Esteban Felissia graduated in industrial chemistry and chemical engineering, and is a doctor in technical sciences. He is a professor at the National University of Misiones and senior researcher in the pulp and paper program of the Institute of Materials of Misiones (Argentina). His areas of interest are chemical and technological aspects of biorefineries, pulping, and bleaching processes.

María Evangelina Vallejos
María Vallejos is adjunct researcher of the National Scientific and Technical Research Council (CONICET) at the Materials Institute of Misiones (Argentina) and she is also Head of Practical Assignments at the National University of Misiones. She works as a researcher on bioproducts and biomaterials from the biorefinery of agro industrial and forest industrial waste. Her main fields of research are fractionation of lignocellulosic materials; biorefinery; bioproducts, lignocellulosic fiber, and biocomposite materials.

© 2018 Society of Chemical Industry and John Wiley & Sons, Ltd | *Biofuels, Bioprod. Bioref.* (2018); DOI: 10.1002/bbb