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Soybean Biorefinery: Process Simulation and Analysis

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In recent years, climate changes and fossil resources depletion prompted efforts on R&D of technologies associated with the production of biodiesel, among other biofuels. However, expensive refined vegetable oils and supply shortages of waste cooking oils are still major factors hindering biodiesel market growth to substitute petroleum diesel, due to lack of economic competitiveness and sustainability issues.

We address in this paper the production of biodiesel coupled with soybean processing to study possible synergies leading to economic and sustainability gains. Simulations in Aspen Plus® were carried employing detailed thermodynamic and kinetic models from previous works; these were obtained from experimental and industrial data, to describe more rigorously the various unit operations. The simulation framework under analysis includes the soybeans preparation and extraction areas, the miscella distillation and physical soybean oil refining, the production of sodium methoxide and biodiesel using the homogeneous alkaline transesterification technology. A base case with a process structure and operating conditions similar to the ones reported in the literature is adopted, and several integration opportunities in the global process are identified.

Results show that biodiesel production costs can be significantly reduced from 795 $/t to 584 $/t, by incorporating in the chemical supply chain soy meal, lecithins and soy deodorization distillate (SODD) products that have high commercial value. Moreover, the integration of these processes helps to further reduce the biodiesel production costs by 2.6 % and the amount of wastewater generated by almost 10 %.

1. Introduction

Environmental and sustainability concerns associated with fossil fuels consumption have motivated worldwide research and development efforts on the production of biofuels from various biomass sources. Biodiesel is currently the main alternative to petroleum diesel, and is obtained from glycerides transesterification and fatty acids esterification. Although extensive literature has been devoted to the technological and economic issues of biodiesel production from various lipid sources including reactive distillation-based alternatives (Karacan and Karacan, 2014), studies addressing the integration of the production of biodiesel with other processes, particularly in oilseed processing facilities, are much scarcer. The identification of potential synergies among these processes is important, since single biofuel-oriented manufacturing plants are hardly sustainable and economically competitive, due to their high dependency on energy prices, feedstocks availability and manufacturing costs. One alternative to overcome these difficulties is to seek the integration of the biodiesel production within a biorefining system with a more extensive chemical supply-chain, broadening the products' portfolio, and achieving lower production costs while making the overall process more sustainable.

This contribution reports part of an ongoing work towards a systematic study of the production of biodiesel from soybeans, in which the crushing and extraction processes are also included and analyzed together. The soybean crop is an excellent feedstock since it contains balanced amounts of proteins, lipids, cellulose, hemicellulose, lignin, starch and soluble carbohydrates. This chemical diversity allows the production of a wide range of products from high-value/low-volume to commodity/high-volume for food or industrial applications. Figure 1 depicts the overall processing framework under analysis.

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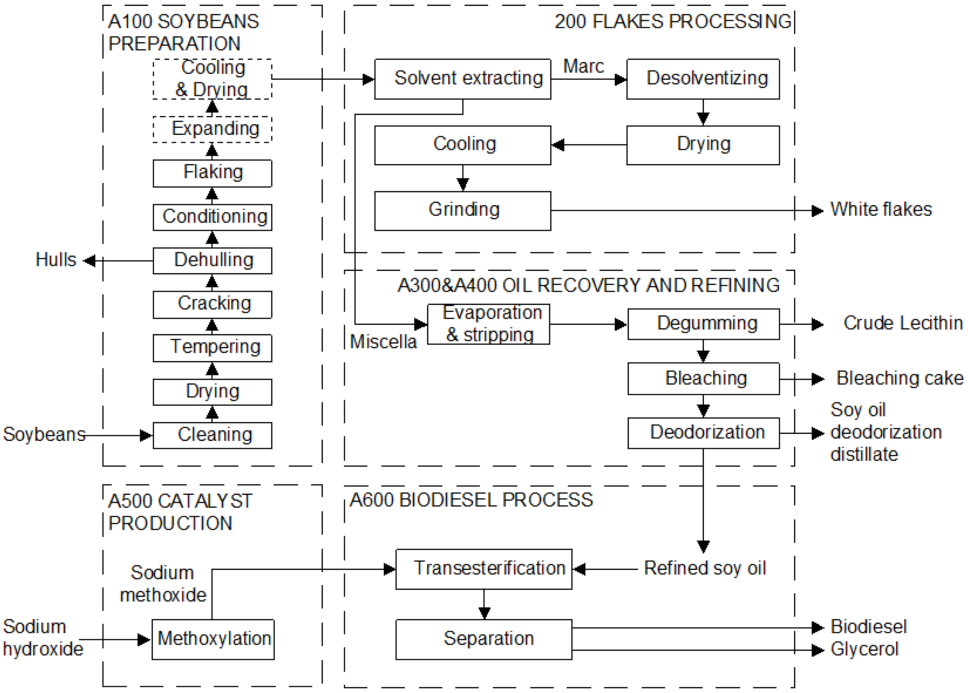

Figure 1: Soybean biorefinery block diagram

Our approach differs from previous life-cycle-analysis (e.g., Sheehan et al., 1998) in a way that not only resources needs, the production of products and waste are quantified, but also process improvements are pursued with the support of mathematical models. State-of-the-art numerical techniques developed earlier for optimal model identification (Duarte et al., 2008) and the regression of equilibrium data to thermodynamic models using consistency metrics and phase stability (Granjo et al., 2014) were applied, respectively, to build kinetic models of the transesterification reactions and the modelling of vapour-liquid and liquid-liquid equilibrium of mixtures. All the information gathered at this stage was included in the simulations. For validation each processing area was simulated separately in typical conditions, and then they were all connected, forming the case base which is presented in Section 2. Subsequently, opportunities for process, mass and heat integration were identified in order to reduce energy needs and waste production. Section 3 briefly highlights some of our findings.

2. Process simulation

Figure 2 presents the interconnections of the simulation blocks in the overall process. In the beans preparation processing area (A100) soybeans are first cleaned to remove the foreign matter, adjust the moisture, cook and crack the cell structure (Figure 3). The oil becomes more readily available to be removed from the flakes by solvent extraction in A200, originating the miscella (soy oil + solvent) and the marc (defatted flakes + solvent). The wet flakes are desolventized to recover the solvent and grinded, forming white flakes that may or not be toasted (Figure 4). The miscella distillation area (A300), represented in Figure 5, is where the solvent is evaporated and stripped out from the oil. This is followed by its refining in A400 where the oil is degummed, bleached and deodorized to eliminate remaining impurities (Figure 6). Finally, the biodiesel and glycerol are produced from refined oil in A600 (Figure 8), using 30 % sodium methoxide in methanol as catalyst which is prepared in processing area A500 (Figure 7). The mass rate of soybean seeds entering the plant was set to about 92 t/h, corresponding to a production capacity of biodiesel close to 150 kt/y. Raw materials market prices and specific soybeans processing equipment costs, such as the dehulling and grinding machines, extractor and desolventizing-toaster were retrieved from Alibaba Group Holding Limited (1998). The remaining equipment costs were calculated using the bare module cost technique and the extensive list of cost functions tabulated in Turton et al. (2012). All the information obtained from the simulations (e.g., mass and energy balances, components composition, and equipment sizes) was incorporated in the economic analysis carried out with CapCost, a freely available software that accompanies the textbook. Our modelling framework main limitations are on the mathematical description of the operations in A100, since the dehulling, griding or flaking units have very specific designs and geometric parameters in order to be rigorously modelled, which are not easily found in the open literature. For these we used the industrial data in Sheehan et al. (1998) to estimate mass split fractions and utility costs. For the remaining processing areas, unit models were validated against data reported in the open literature and a good agreement with existing data is observed and therefore we consider that our models are reliable and robust so that can be used in further studies.

Considering first the biodiesel production process individually (A600), both 30 % sodium methoxide (NaOCH3), 890 $/t, and crude degummed soy oil (650 $/t) as used as raw materials. We estimate the production costs to be 795 $/t of biodiesel, including glycerol credits and equipment depreciation costs. This value is in agreement with the one reported in Haas et al. (2006), which is 792 $/t, after adjusting the raw materials prices and capital costs to current values. Moreover, the estimated mass rate of wastewater produced is 25 kg/t of products. When the production of NaOCH3 (A500) is coupled with A600 and excess catalyst production is marketed at production cost (875 $/t), the biodiesel production costs drops 2 % to 779 $/t. However, the amount of wastewater increases to 62 kg/t of products due to water resulting from caustic soda used in the methoxylation process.

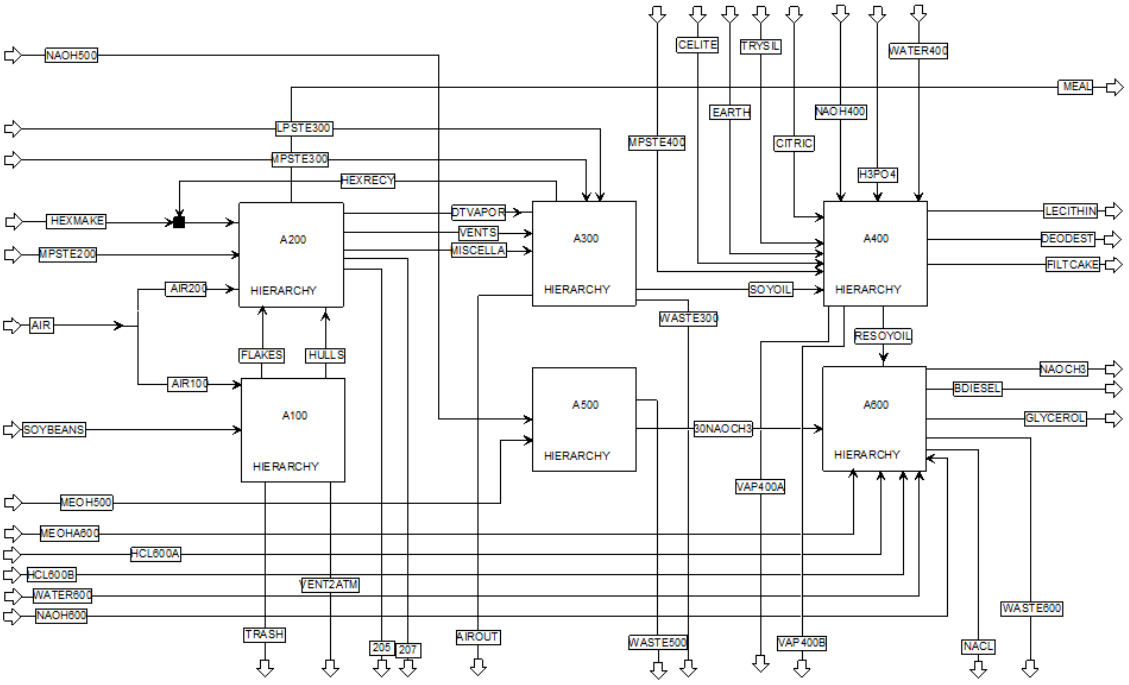

Figure 2: Structure of the simulation blocks in Aspen Plus®

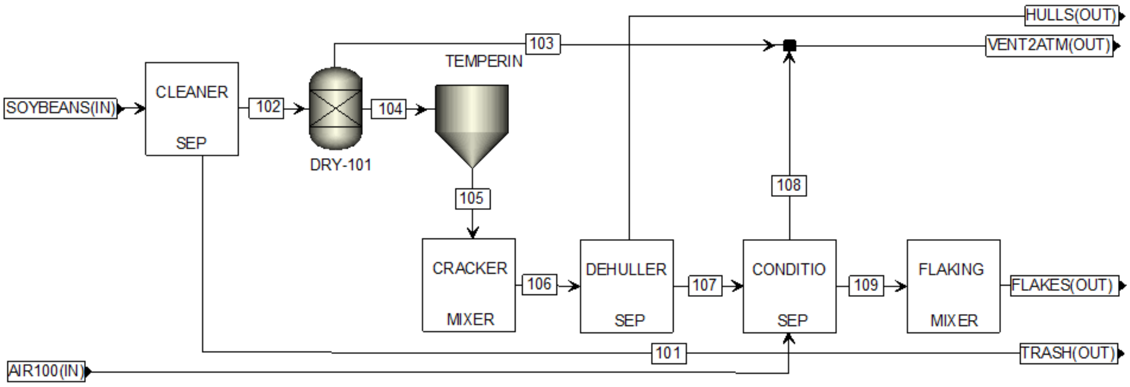

Figure 3: Process flowsheet diagram of soybeans preparation area (A100)

With the incorporation of biodiesel production in soybeans crushing facilities (A100-A400), biodiesel nominal costs decrease significantly to 584 $/t. This reduction is primarily explained by the improvement of the chemical supply value due to the incorporation of soy meal, lecithins and soy deodorization distillate (SODD) products that are of great commercial value. Conversely, the integration of biodiesel and sodium methoxide processes also reduces costs with soybean oil production, which is estimated to be 606 $/t. Partial process indicators (Table 1) reveal that areas A100 and A200 are the main consumers of hot utilities (56 %) and electricity (84 %), due to operations of beans drying, soy meats conditioning, flaking and meals desolventizing-toasting that are both energy and mechanically intensive.

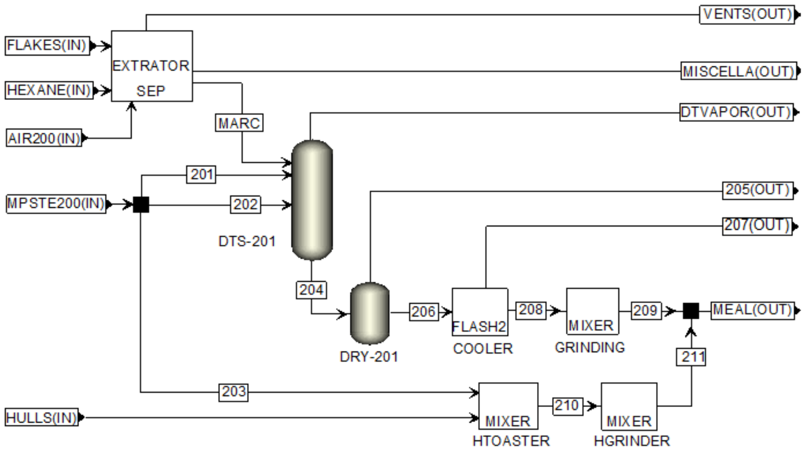

Figure 4: Process flowsheet diagram of extraction area (A200)

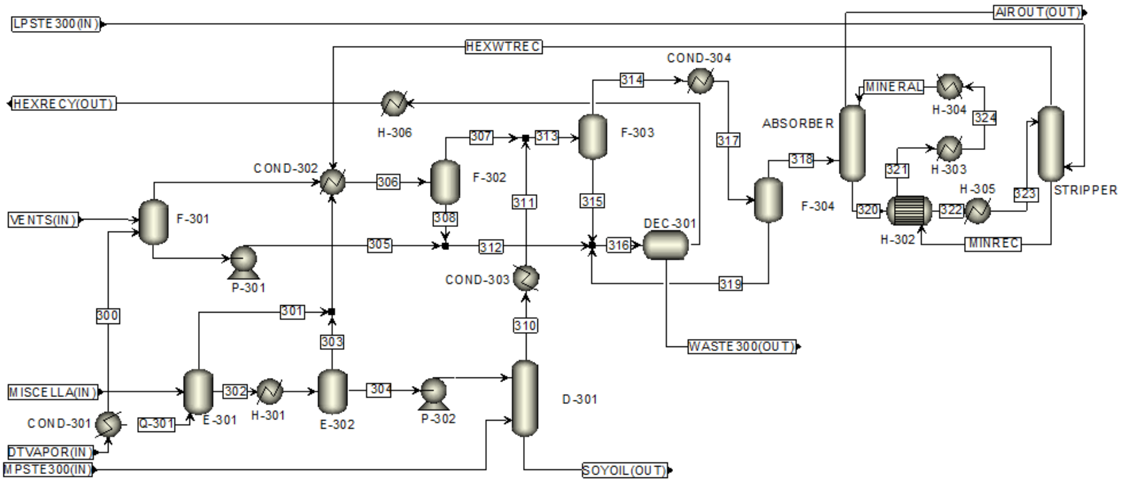

Figure 5: Process flowsheet diagram of miscella distillation area (A300)

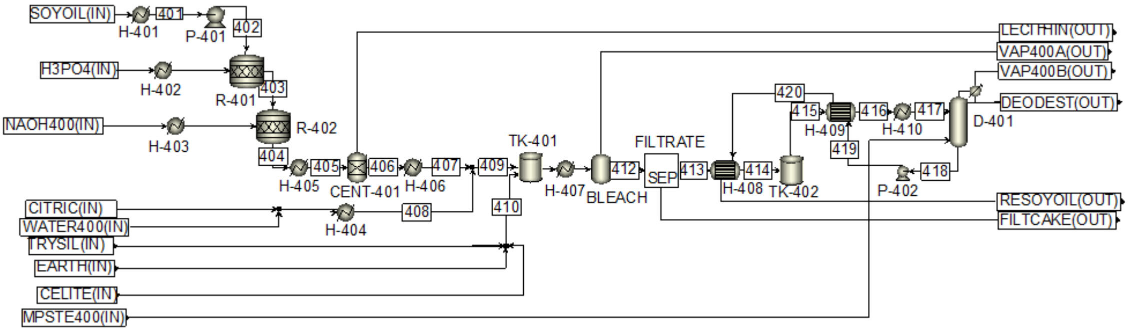

Figure 6: Soy oil refining processing area (A400)

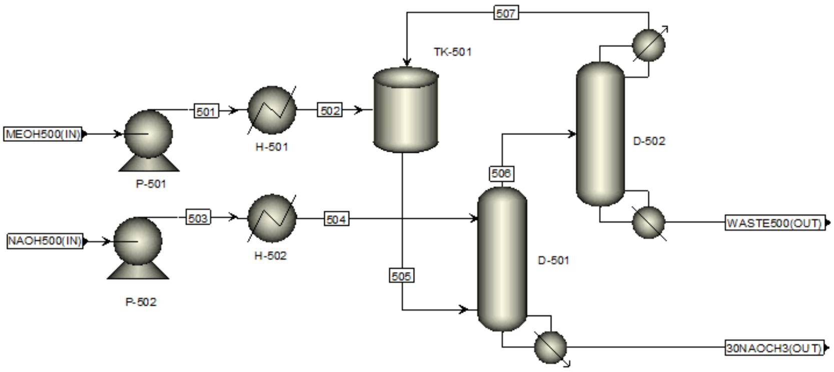

Figure 7: Sodium methoxide production area (A500)

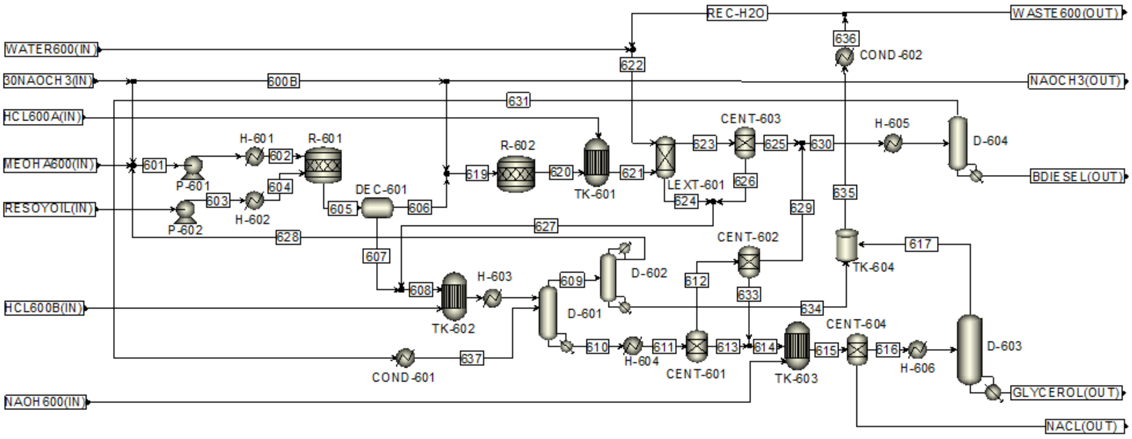

Figure 8: Biodiesel production area (A600)

Table 1: Raw materials and energy consumptions, products and wastewater mass rates

	A100	A200	A300	A400	A500	A600		A200	A300	A400	A500	A600
Raw materials[a]							Products[a]					
Soybeans[b]	1,000						Soy meal	733				
Hexane (×10)		8.00					Biodiesel					178
Live steam		89.2	10.3	5.37			92 % Glycerol					19.8
Air	2.16	1.19					Lecithins			6.95		
Filtration M.				1.07			SODD (x10)			9.57		
50 % NaOH (×10)				1.30	113	1.97	30 % $NaOCH_3$				15.3	
H3PO4 (×10)				3.71			Filtration cake			1.39		
50 % Citric acid (×10^2)				5.56			Wastewater[d]		36.8		8.78	5.25
Water (×10)				39.2		8.73						
Methanol					23.3	9.54						
36 % HCl						7.89						
Utilities[c]												
Electricity	148	84.8	1.36	24.9		18.5						
Steam	173	152	95.3	35.8	338	148						
Natural gas	448											
Cooling water			226	19.1	220	136						
Refrigeration			15.1									
Products[a]												
Soy meal		733										
Biodiesel						178						
92 % Glycerol						19.8						
Lecithins				6.95								

[a] kg/t of soybeans. [b] Mass rate: 91,746 kg/h. [c] MJ/t of soybeans. [d] kg/t of total products

3. Integration opportunities

In the previous section, we observed that a significant decrease of the nominal costs can be achieved through the incorporation of value in the chemical supply chain of this process. However, further heat and mass integrations are still possible. Methanol recycling is responsible for the major consumption of steam in A600 and distillations columns D-601 and D-602 are needed to recover it for R-601 free of water. By redirecting the recycling stream to D-502 of A500, D-602 is suppressed and the overall steam and cooling water consumptions are further reduced. Biodiesel stream exits D-603 at 146 ºC and is employed to heat the D-603 and D-604 feeding streams and the hexane recycling stream at A300, obviating the need for low pressure steam. Vapours of evaporator E-302 and oil stripping column (D-301) are used to heat the miscella and the mineral oil in the air scrubbing system. Crude degummed soybean oil leaving A300 at 114 ºC furnishes heat to water solutions in A400 and the soybean oil leaving A400 after the deodorization column (D-401) is redirected to A500 to heat caustic soda to the boiling point and evaporate methanol in A400. Mass integration was also performed, by redirecting part of the wastewater leaving the hexane/water decantation (DEC-301) to A400 and all the wastewater of A500 to the biodiesel washing column in A600. With these modifications, the overall consumption of utilities is reduced by 8.4 %, the wastewater generated is reduced by 9.7 % to 46 kg/t of products, and the biodiesel production costs decrease 2.6 % to 569 $/t.

4. Conclusions

This contribution summarizes some of the major findings of an ongoing work to systematically integrate the production of biofuels with soybean processing facilities. A more integrated supply chain with a wider product portfolio, generates various integration opportunities, which can be used to greatly reduce the energy and water consumptions, making the overall process more competitive and sustainable, as demonstrated in this paper. Future studies will address the application of systematic methodologies for heat and mass integration, making use of this more detailed modelling framework and the base case simulation results obtained at this stage. Mathematical formulations for the synthesis of alternative configurations for biodiesel production integrated with this more holistic structure can also be made, as well as the exploration of products chemical transformation pathways in order to assist the decision-making regarding portfolio management and production planning at an enterprise-wide level.

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