A NEURAL FUZZY MODEL APPLIED TO HYDROGEN PEROXIDE BLEACHING OF NON-WOOD SODA PULPS

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A neural fuzzy model was used to examine the influence of pulp bleaching variables of empty fruit bunches from oil palm (EFB) and *Hesperaloe funifera*, such as soda concentration (0.5-3%), hydrogen peroxide concentration (1-10%) and processing time (1-3 h), on Kappa number, brightness and viscosity. The experimental results are reproduced with errors below 10% and 15% for EFB and *H. funifera*, respectively.
Bleaching pulp simulation permits to obtain optimal values of the operating variables, so that the properties of bleached pulps will only slightly differ from their best values, while the lower values of the operating variables will save chemical reagents, energy and plant size. Thus, if applying 0.5% soda and 3% peroxide for 3 h, it is possible to get a pulp with a brightness of 74.9% and a viscosity of 716 mL/g, for EFB pulp, and of 63.3% and 584 mL/g, respectively, for *H. funifera* pulp.

Keywords: non-wood material, pulp, bleaching, hydrogen peroxide, neural fuzzy model

INTRODUCTION

The pulp bleaching plant, which is the most contaminated sector of the paper manufacturing process, has gone through a number of changes intended to alleviate its adverse impact. The need to reduce or eliminate the formation of highly toxic organochlorinated compounds, during bleaching processes, led to the emergence of new products on the market, such as ECF (Elemental Chlorine Free) and TCF (Totally Chlorine Free) pulps.[1] TCF pulping processes avoid the formation of highly toxic organochlorine compounds (AOX) during bleaching, by sequences including oxygen-, hydrogen peroxide- and ozone-based stages.[2-8] Recently, the enzyme stages involving xylanases or laccase-mediator systems provided very promising results in pulp bleaching sequences.[9-12]

Several authors have studied the influence of the operating variables – during pulping of different materials – on the characteristics of pulps obtained by polynomial and neural fuzzy models.

The use of polynomial models has also been successfully employed in the study of the operating variables involved in pulp bleaching,[2,5,9,10,12-15] but never in the case in which neural fuzzy models were used.

On the other hand, in recent decades, in some countries, the increasing production of pulp for paper and other uses raised the problem of the supply of classical raw materials (mainly hardwoods and softwoods). That is why, a growing emphasis was put on the use of alternative raw materials, mainly non-wood wastes, such as agricultural and food industry residues, forest residues and fast-growing plants other than conventional wood.[16] Alternative raw materials may be the empty fruit bunches from oil palm (EFB) and *Hesperaloe funifera*.

In the present study, EFB from Malaysia, a country producing 51% of the world production of oil,[17-19] was used. Each hectare of oil palm produces an average of 10 tons of fruits per year, which give about 3000 kg of oil (as the main product).[20] EFB is a lignocellulosic material residue from the palm oil industry. Oil palm fibre is a non-hazardous, biodegradable material, extracted from oil palm empty fruit bunches (EFB) through decortication. The fibres can be processed into various dimensional grades to suit specific applications, such as ceramic and brick manufacturing, thermoplastic filler, erosion control, soil stabilization, horticulture, paper production, livestock care and compost.

EFB is an interesting raw material, as confirmed by several studies. Numerous authors have studied the Kraft process applied to these residues, the recent results presented by Ibrahim[21] being the most relevant ones. He compared the composition of EFB pulp obtained by Kraft, Kraft-anthraquinone, soda and soda-anthraquinone processes; the pulp obtained by the soda process had the highest content of lignin, holocellulose and α-cellulose, and higher viscosity, compared to pulps obtained by other processes. Law and Jiang[22] studied the soda process for producing fibres with higher wall thickness and rigidity, higher solubilities in hot water and 1% soda and higher ash content. These pulps were bleached with hydrogen peroxide more easily than those of aspen; the paper sheets made from such pulps had lower tensile index, but higher stretch and tear index than those of aspen. Moreover, Daud *et al*.[23] pulped EFB by soda, sodium carbonate and sodium sulfite processes, the first one appearing as the most efficient. With a central composite experimental design, Wanrosli *et al.*[24] studied the influence of the operating conditions (temperature, time and alkali concentration) on the properties of EFB pulps (yield, Kappa number and tensile and tear index), obtaining pulp yields in the 30-45% range. The values of 160 °C, 60-120 min and 20-30% alkali were considered sufficient for a proper pulping. Jiménez *et al*.[25] also studied EFB pulping with soda-anthraquinone, considering the influence of the pulping variables and of subsequent beating. Semi-chemical pulping for board by soda-anthraquinone processes was also investigated.[26] Thermomechanical pulp was studied by several researchers, the results of Ghazali *et al.*[27] being worth mentioning. Organosolv processes have also been studied: ethanol,[28] by modified IDE process[29] and high-boiling point organic solvents.[30] Finally, biopulping has been investigated[31] using a white fungus – K14.

Hesperaloe funifera is a plant of the *Agavaceae* family, up to 80 cm tall and 1.0-1.2 m wide, with long leaves, up to 5 cm wide and 2-3 cm thick. All species of its genus originated in Mexico and its neighbouring USA regions, where they have mainly ornamental purposes. *H. funifera* has very modest irrigation requirements, as it uses the acid metabolism of *Crassulaceans* (CAM) for photosynthesis. Its plants fix carbon dioxide and transpire water more intensely at night than during the day; also, because their coefficient of transpiration is lower at night, they use water in a highly efficient manner. Based on these properties, *H. funifera* might be an effective cellulose raw material in arid zones.[32] In several regions of Spain, the cultivation of this species could be particularly interesting. High-density plantations (27000 per hectare) can yield approximately 20 tons of dry biomass per hectare.[33] These crop yields can be increased by a careful control of plant flowering and by the use of higher planting densities.[32]

Although the fibre morphology of *H. funifera* plants is especially suitable for making cellulose pulp,[34] little research in this direction appears to have been conducted. In the few investigations made, the material was subjected to alkaline sulphite–anthraquinone or mechanical pulping,[32,35] the resulting paper sheets having very high tensile, burst and tear indices, which makes them highly suitable for making special paper. More recently, *H. funifera* has been pulped by different processes: soda-anthraquinone,[36] ethanolamine, ethylenglycol and diethylenglycol[37] and diethanolamine.[38,39] Rodríguez *et al*.[40] compared simulations of diethanolamine pulping using polynomial and neural fuzzy models. Similarly, *H. funifera* has been used to advantage hemicelluloses, by authohydrolysis, and lignin, by acidification separation of the pulping waste liquor.[41] So far, no studies dealing with bleaching of *H. funifera* pulp have been reported in the literature of the field.

The aim of this work has been to obtain bleached pulps from EFB and *H. funifera* with the best application conditions of the Po stage. A pressurized hydrogen peroxide stage (Po) was performed after a W_AOq sequence (W_A – acid washing; O – oxygen delignification; q – chelating stage). For this reason, this Po stage was optimized following a sequential statistical plan of three variables (soda concentration, hydrogen peroxide concentration and processing time). The results obtained were analyzed according to the neural fuzzy model.

EXPERIMENTAL

Characterization of raw materials

The chemical properties of EFB were determined according to the respective Tappi standards, for different components, namely, T-222 for lignin, T-203

0S-61 for α-cellulose, T-9m-54 for holocellulose, T-204 for ethanol-benzene extractives and T-211 for ash, the following results being obtained: 24.5% lignin, 41.9% α-cellulose, 67.0% holocellulose, 1.2% extractives and 3.2% ash. The average fibre length of EFB, determined on a Visopan projection microscope, was of 0.53 mm.

The samples of *H. funifera*, for educational and research purposes, were kindly supplied by the Hesperaloe Project research team at the University of Arizona. The contents of holocellulose, lignin, α-cellulose, ethanol–benzene extractives, and ash of the raw material were the following: 76.5%, 7.3%, 40.9%, 4.0%, and 5.9%, respectively, and fibre length was of 4.19 mm.

Pulping

The pulps were obtained in an electrically heated 15 L batch cylindrical reactor, coupled to a control unit through a rotary axle, to ensure proper agitation, including a motor actuating the reactor and the required instruments for measurement and control of both pressure and temperature.

The EFB were cooked in the reactor, using 15% soda, 170 °C, a liquid/solid ratio of 10 and a processing time of 30 min, at a pulp yield of 48.0%. When operating with 15% soda, at 170 °C, a liquid/solid ratio of 8, for 40 min, *H. funifera* provides a yield of 41.5%. The operating conditions were selected from the results of other authors.[22,23,25] Further on, the cooked material was fiberized in a wet desintegrator at 1200 rpm for 30 min and the screenings were separated by sieving through a 0.14 mm mesh screen. The pulp obtained was beaten in a Sprout-Bauer refiner.

Bleaching

The initial pulp properties of EFB were 38.4% ISO brightness and 9.7 Kappa number for EFB, and 31.2% and 13.6, respectively, for the pulp of *H. funifera*. Before applying the hydrogen peroxide stage (Po), the pulps were washed in an acidic medium (W_A), and an oxygen delignification stage (O) was performed, followed by a chelating stage (q) (W_AOq sequence).

The pressurized peroxide bleaching stage (Po) was carried out with 25 g o.d.p. (oven-dried pulp) in a 5 L reactor, at 0.6 MPa O_2, with 0.5% o.d.p. of Na_2SiO_3, 0.2% o.d.p. of $MgSO_4$, and 5% consistency, at 105 ºC and 60 rpm. The operating sequence was selected on the basis of previous experimental results.[2-8,42] Soda concentration, hydrogen peroxide concentration and processing time were the three variables of the experimental design, varying over the following ranges: 0.5-3% o.d.p. for soda concentration, 1-6% o.d.p. for hydrogen peroxide and 1-5 h processing time for the EFB pulp, and 0.5-3%, 1-10% and 1-5 h, respectively, for the *H. funifera* pulp. After the Po stage, the liquors were recovered for pH measurement and the pulp was efficiently washed for characterization.

Pulp properties

The treated pulp samples were characterized in terms of Kappa number, brightness and viscosity, according to ISO 302, ISO 3688 and ISO-5351-1, respectively. Kappa number was measured twice and brightness – four times, in order to calculate standard deviation, which was found to be ≤0.1% for both properties.

Experimental design

The factorial design used[43] consisted of a central experiment (in the centre of a cube) and several additional experiments (additional points lying at cube vertices and side centres). With the three operating variables considered (soda concentration – S, hydrogen peroxide concentration – P, and bleaching time – T), the total number of experiments was 15.

The integration of fuzzy systems and neural networks combines the advantages of the two systems and provides an especially powerful modeling tool, *viz.* the neural fuzzy system, which uses neural networks as tools in fuzzy systems.[44]

The variation of pulp properties as a function of the operational variables of the bleaching process can be predicted by the following expression:[44]

$$Y_e = \frac{\sum_{l=1}^{8} c_l R_l}{\sum_{l=1}^{8} R_l} \qquad (1)$$

where Ye is the estimated value of the property to be modeled (dependent variable), c_l – a constant parameter and R_l – a fuzzy rule.

With the three independent variables, one can establish the following eight fuzzy rules, according to the extreme (high and low) values of such variables (x_{1i} – low, and x_{2i} – high):

R_1: low S, low P and low T: $R_1 = x_{1S} . x_{1P} . x_{1T}$

R_2: low S, low P and high T: $R_2 = x_{1S} . x_{1P} . x_{2T}$

………………………

R_7: low S, high P and high T: $R_7 = x_{1S} . x_{2P} . x_{2T}$

R_8: high S, high P and high T: $R_8 = x_{2S} . x_{2P} . x_{2T}$

The low (x_{1i}) and high (x_{2i}) values are obtained with the following equations (linear membership function):

$$x_{1i} = 1 - \frac{(x_i - x_{lowi})}{x_{highi} - x_{lowi}} \qquad (2)$$

$$x_{2i} = \frac{(x_i - x_{lowi})}{x_{highi} - x_{lowi}} \qquad (3)$$

where x_{highi} and x_{lowi} denote the extreme values of the operational variable and x_i – the absolute value of S, P or T.

With three levels (low, medium and high) for one of the variables and a linear membership function with two levels (low and high) for the other two, Eq. [1] would include 12 terms in the numerator and 12 in the denominator. Values x_{ij} (low – x_{1i}, medium – x_{2i}, and high – x_{3i} of the operational variables S, P and T) are obtained with the following equation (Gaussian membership function):

$$x_{ji} = \exp\left[-0.5((x_i - x_{ci}/L_i))^2\right] \quad (4)$$

where x_i denotes the absolute value of the variable concerned; x_{ci} is its minimum, central or maximum value; and L_i – the width of its Gaussian distribution.

The constant parameters of Eq. [1] were estimated with the ANFIS (Adaptative Neural Fuzzy Inference System) Edit tool in the Matlab© 6.5 software suite.

RESULTS AND DISCUSSION

Based on the results of other researchers on pulps obtained from different materials,[2,5,14] and after previous tentative experiments, the ranges reported in the experimental part were applied for the operational variables during hydrogen peroxide bleaching of EFB and *Hesperaloe funifera* pulps.

Table 1 shows the experimental values of the bleached pulps properties of EFB and *Hesperaloe funifera*. During the hydrogen peroxide stage, brightness increased, while Kappa number and viscosity decreased, as depending on the application conditions. In fact, the bleaching effect of hydrogen peroxide has been attributed to its ability to react with various coloured carbonyl-containing structures in lignin.[1]

Bleaching of EFB pulp

Table 2 lists the values of the constant in the neural fuzzy models, c_i, obtained from the brightness and viscosity values listed in Table 1, obtained by a Gaussian membership function, for the time processing variable, and with a linear membership function for the other two (soda concentration and hydrogen peroxide concentration). Also, Table 2 shows the values of the constants in the neural fuzzy models, obtained from the Kappa number values given in Table 1, realized with a Gaussian membership function for the soda concentration variable, and with a linear membership function for the other two (peroxide concentration and processing time).

Table 1
Normalized values of operational variables and experimental values of bleached pulp properties

		EFB			*Hesperaloe funifera*		
Exp.	Soda; peroxide; time*	Brightness, %	Viscosity, mL/g	Kappa Number	Brightness, %	Viscosity, mL/g	Kappa Number
1	-1; -1;-1	63.7	814	4.86	51.4	619	5.74
2	-1; +1; -1	72.7	678	3.27	60.9	502	4.93
3	+1; +1; -1	77.0	637	3.15	61.7	460	7.79
4	+1; -1; -1	71.4	771	3.42	53.9	620	6.14
5	-1; -1; +1	71.5	774	3.57	60.0	623	5.25
6	+1; -1; +1	75.3	695	3.13	57.9	582	5.66
7	-1; +1; +1	80.1	580	1.14	68.8	451	1.54
8	0; 0; 0	77.7	671	3.00	62.4	543	5.20
9	+1; +1; +1	78.9	573	2.95	66.6	456	4.26
10	+1; 0; 0	78.2	641	2.74	62.9	645	5.54
11	0; 0; +1	79.3	670	2.70	63.4	556	4.34
12	-1; 0; 0	76.0	731	3.05	65.4	532	4.05
13	0; -1; 0	74.0	765	3.23	56.0	669	5.41
14	0; 0; -1	74.4	703	3.60	61.2	596	6.52
15	0; +1; 0	81.5	637	2.81	66.4	548	3.99
16	-0.5;-0.5;-0.5	72.7	745	3.83	60.8	620	5.15
17	+0.5;+0.5;+0.5	79.5	626	2.97	66.0	540	4.63

*The values of the operational variables were normalized to values from -1 to +1 by using the following equation: $X_n = \frac{2(X-\bar{X})}{X_{max}-X_{min}}$
where X_n is the normalized value of S, P and T; X is the actual experimental value of the variable concerned, and the mean of X_{max} and X_{min}; X_{max} and X_{min} are the maximum and minimum value, respectively, of such a variable

The predictions obtained with the previous models reproduced the experimental results for the dependent variables with errors below 3% for brightness, 5% for viscosity and 10% for Kappa number, respectively, in 93% of cases (always below 15%) (Table 3).

The proposed models were validated in two pulping experiments (entries 16 and 17 in Table

1). The errors made in predicting pulp properties by means of neural fuzzy models were quite small (Table 3), which testifies for their accuracy. Therefore, the neural fuzzy system is suitable for simulating the process of EFB pulp bleaching. Similar matches in the application of neural fuzzy models were proposed in pulping of various materials by different processes: vine shoots with ethanolamine,[45] paulownia with ethanol,[46] and *Leucaena leucocephala*, *Chamecytisus proliferus*, vine shoots and cotton stalks with ethylene glycol.[47]

López *et al.*,[2,14] who applied an experimental design of peroxide bleaching to kraft pulp from olive prunings, by using polynomial models, found out that the minimum Kappa number values of the bleached pulp and the maximum brightness and viscosity values are achieved when operating at 5% peroxide, for 210 min. Moreover, Pedrola *et al.*[5] used an experimental design and polynomial models to describe the P stage of the OXZP sequence (where O stands for the oxygen stage, X – for the enzymatic treatment, Z – for the ozone stage, and P – for the hydrogen peroxide stage) applied to eucalyptus kraft pulp, with 4 independent variables: hydrogen peroxide concentration, soda concentration, processing time and temperature. The models obtained in the cited research predict brightness and viscosity values ranging from 84.6 to 90.5% and from 890 to 919 mL/g, respectively, the best results being attained when processing time and peroxide concentration were the highest and temperature and soda concentration recorded mean values, peroxide concentration being found as the most influential variable. The reported results coincide only partially with those obtained in this work, which may be due to the different nature of the treated materials (olive prunings and eucalyptus wood being compared with a non-wood – EFB) and to the different pulping procedures performed (kraft pulping *versus* soda pulping).

Figure 1 shows how Kappa number varies with the concentrations of soda and peroxide over short, medium and long time intervals. It is observed that the minimum value of Kappa number corresponds to the pulp bleached at high levels of peroxide concentration and processing time variables, and at a low value of soda concentration.

Table 2
Values of the constants in the neural fuzzy model for bleached pulp properties

		EFB			*Hesperaloe funifera*		
Rule	Soda; peroxide; time*	Brightness, %	Viscosity, mL/g	Kappa Number	Brightness, %	Viscosity, mL/g	Kappa Number
1	-1; -1;-1	62.9	827	5.11	49.9	605	5.60
2	-1; -1; +1	71.4	780	3.76	59.4	626	5.14
3	-1; +1; -1	73.1	680	3.34	60.4	477	3.18
4	+1; -1; -1	70.8	786	3.54	52.5	614	6.04
5	-1; +1; +1	81.2	571	1.11	69.1	435	1.63
6	+1; -1; +1	75.1	702	3.25	57.1	587	5.59
7	+1; +1; -1	77.3	641	3.17	61.2	437	8.23
8	+1; +1; +1	79.4	569	2.99	66.7	449	4.54
9	0; -1; -1	-	-	2.85	-	685	-
10	0; -1; +1	-	-	2.41	-	565	-
11	0; +1; -1	-	-	4.00	-	644	-
12	0; +1; +1	-	-	3.51	-	523	-
9	-1; 0; -1	-	-	-	-	-	4.96
10	-1; 0; +1	-	-	-	-	-	4.02
11	+1; 0; -1	-	-	-	-	-	4.69
12	+1;0;+1	-	-	-	-	-	3.73
9	-1;-1;0	77.1	678	-	64.7	-	-
10	-1;+1;0	72.4	766	-	61.8	-	-
11	+1;-1;0	83.2	575	-	65.9	-	-
12	+1;+1;0	77.9	666	-	66.7	-	-
R^2	-	0.92	0.96	0.95	0.80	0.88	0.85

*Normalized values of the operational variables

Table 3
Values of the dependent variables as estimated with neural fuzzy models, and deviations (in %) from their experimental counterparts (in brackets)

	EFB			*Hesperaloe funifera*		
Exp	Brightness, %	Viscosity, mL/g	Kappa Number	Brightness, %	Viscosity, mL/g	Kappa Number
1	64.0(0.47)	820(0.74)	4.97(2.26)	50.9(0.97)	614(0.81)	5.56(3.14)
2	73.1(0.55)	684(0.88)	3.38(3.36)	56.3(7.55)	549(9.36)	5.16(4.67)
3	77.4(0.52)	642(0.78)	3.22(2.22)	57.8(6.32)	533(15.87)	8.02(2.95)
4	71.8(0.56)	776(0.65)	3.49(2.05)	53.5(0.74)	622(0.32)	5.96(2.93)
5	71.9(0.56)	775(0.13)	3.68(3.08)	59.8(0.33)	618(0.80)	5.07(3.43)
6	75.7(0.53)	696(0.14)	3.20(2.24)	57.7(0.35)	584(0.34)	5.48(3.18)
7	80.5(0.50)	580(0.00)	1.25(9.65)	64.7(5.96)	522(15.74)	1.77(14.94)
8	77.3(0.51)	674(0.45)	3.20(6.67)	63.8(2.24)	610(12.34)	4.45(14.42)
9	79.3(0.51)	574(0.17)	3.02(2.37)	62.5(6.16)	514(12.72)	4.49(5.40)
10	79.2(1.28)	643(0.31)	2.77(1.09)	64.3(2.23)	624(3.26)	5.52(0.36)
11	76.8(3.15)	656(2.09)	2.94(8.89)	61.2(3.47)	554(0.36)	3.92(9.68)
12	74.6(1.84)	722(1.23)	3.32(8.85)	63.3(3.21)	576(8.27)	4.48(10.62)
13	71.5(3.38)	730(4.58)	3.47(7.43)	54.6(2.50)	666(0.49)	4.98(7.95)
14	75.4(1.34)	706(0.43)	3.63(0.83)	63.3(3.43)	596(0.00)	4.86(25.46)
15	80.1(1.72)	627(1.57)	3.23(14.95)	63.4(3.16)	563(2.74)	4.42(10.78)
16	72.6(0.14)	729(2.15)	3.76(4.70)	58.9(3.13)	615(0.81)	4.76(9.40)
17	78.1(1.76)	638(1.92)	3.23(8.75)	64.1(2.88)	530(1.85)	4.73(2.16)

Figure 2 shows that viscosity was maximum when bleaching was performed at low values of the operating variables. Finally, Figure 3 shows that brightness was the highest when operating at high peroxide concentration and low soda concentration, over long time intervals.

According to Figure 1 (illustrating the variations of Kappa number with soda concentration and time, and also with peroxide concentration and time, at low, medium and high values of the other independent variables), the most influential operational variables on the Kappa number of bleached pulps were hydrogen peroxide concentration and time, which coincides with the results obtained for the bleaching of Kraft olive pruning pulp[2,14] and Kraft eucalyptus,[5] while soda concentration was the least influential variable, which coincides with the results of Pedrola *et al*.[5] Kappa number (Fig. 1) strongly decreased when increasing peroxide and processing time at low soda concentration. However, this effect was less notable at medium and high soda concentration values. Generally, the increase in soda concentration had a detrimental effect on Kappa number.

Similarly, as shown in Figure 2, there follows that, in the case of viscosity, hydrogen peroxide concentration is again the most influential variable, the least influential ones being processing time and soda concentration; these results are consistent with those of López *et al.*[2,14] and Pedrola *et al*.[5] Pulp viscosity (Fig. 2) was negatively affected by all variables, the strongest effect being produced by hydrogen peroxide concentration. The decrease in viscosity occurred because cellulose may undergo depolymerization by the reaction with hydroxyl radicals.[45]

Another observation is that, for brightness (Fig. 3), the most influential operational variable is hydrogen peroxide concentration, while the least influential one is soda concentration. These results are consistent with those obtained by Pedrola *et al*.[5] for bleaching of eucalyptus Kraft pulp, but not with those obtained for Kraft pulp from olive prunings,[2,14] where the most influential variable was found to be processing time. Generally, the increase of soda concentration from 0.5 to 3% increases brightness, as well (Fig. 3). However, the effect of soda concentration on pulp brightness was affected by peroxide concentration and processing time, since, at low values of these variables, the effect was more noticeable. At high processing time and high soda concentration, pulp brightness decreased (Fig. 3). According to Dence and Reeve,[48] for each peroxide concentration, there exists an optimum soda concentration. At soda concentrations above the optimum, the effectiveness of hydrogen peroxide is reduced and brightness reversion is observed. On the other hand, hydrogen peroxide concentration and processing time increased brightness, their effect being more visible at low soda concentration.

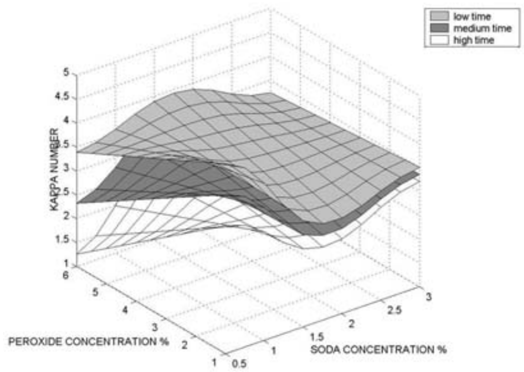

Figure 1: Variation of Kappa number of EFB bleached pulps with soda concentration and hydrogen peroxide, for short, medium and long processing times

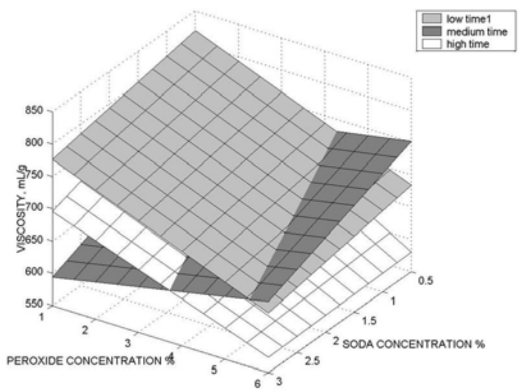

Figure 2: Variation of viscosity of EFB bleached pulps with soda concentration and hydrogen peroxide, for short, medium and long processing times

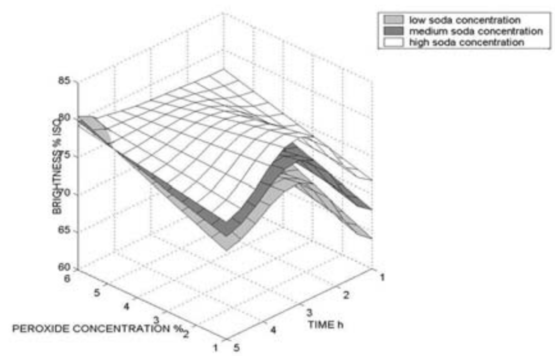

Figure 3: Variation of brightness of EFB bleached pulps with hydrogen concentration and processing time, for low, medium and high soda concentrations

A comparison between the maximum values of the results for brightness (80.5%), and viscosity (820 mL/g) and the minimum value of Kappa number (1.25) with those obtained by Jimenez *et al.*[49] for EFB pulps, obtained by soda-anthraquinone and diethanolamine processes, bleached by the A_1OpA_2ZRP sequence (A is an acid treatment, Op – an oxygen and peroxide stage, Z – an ozone stage, R – a reductive treatment, and P – a peroxide stage), permits the observation that, in both cases, Kappa number is higher (2.8 and 5.5), brightness is lower (77.5% and 71.3%), and viscosity is also lower (653 mL/g and 783 mL/g); these discrepancies can be explained by the more severe treatment applied to the pulps in the compared sequence, and also by the different nature of the unbleached pulps (pulping with diethanolamine).

Bleaching of *Hesperaloe funifera* pulp

Table 2 lists the values of constant c_i in neural fuzzy models. For the Kappa number, a Gaussian membership function was used for hydrogen peroxide concentration, and a linear membership function for the other two (soda concentration and processing time) while, for viscosity, a Gaussian membership function has been used for the soda concentration variable and, for brightness – a Gaussian membership function for the processing time variable.

The predictions obtained with the previous models reproduced the experimental results for the dependent variables with errors below 8% for brightness, 15% for viscosity and 15%, respectively, for Kappa number (in more than 90% of the cases) (Table 3).

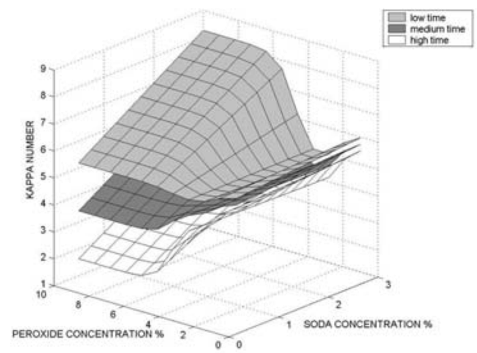

Figure 4: Variation of Kappa number of *H. funifera* bleached pulp with soda concentration and hydrogen peroxide, for short, medium and long processing times

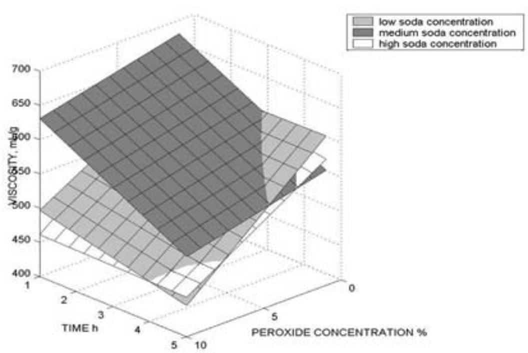

Figure 5: Variation of viscosity of *H. funifera* bleached pulp with hydrogen concentration and processing time, for low, medium and high soda concentrations

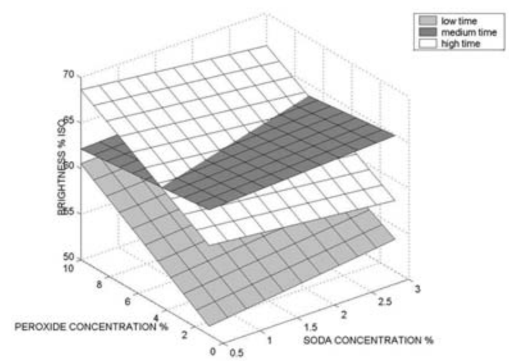

Figure 6: Variation of brightness of *H. funifera* bleached pulp with soda concentration and hydrogen peroxide, for short, medium and long processing times

As in the case of EFB pulp, experiments 16 and 17 (Table 1) permit to validate the neural fuzzy model. By the utilization of the neural fuzzy model, the errors possibly occurring in the prediction of the results of experiments 16 and 17 are reduced (Table 3).

The analysis of Figures 4 to 6 permits similar conclusions as in the case of EFB pulp bleaching. Thus, Figure 4 shows that the minimum value of Kappa number corresponds to the *H. funifera* paste bleached at high peroxide concentration, long processing time and low value of soda concentration. Figure 5 shows that viscosity is maximum during bleaching performed at low values of peroxide concentration and processing time, and at the mean value of soda concentration. Finally, Figure 6 shows that brightness is the highest when operating at high levels of peroxide concentration and time and at low soda concentration. Of the dependent variables considered (Kappa number, viscosity and brightness), the most influential variable is peroxide concentration, and the least – soda concentration.

The maximum values for brightness (68.6%) and viscosity (680 mL/g) and the minimum value for Kappa number (1.63) are lower than those found for EFB pulp: brightness – 80.5%, viscosity – 820 mL/g and Kappa number – 1.25.

Optimum operating conditions

EFB

According to the experimental design carried out, soda concentration has to be diminished, since it has a detrimental effect upon all properties. In addition, the hydrogen peroxide concentration should not be high, because of its negative effect on pulp viscosity.

Thus, by applying fuzzy models to various combinations of values of the operational variables, one can identify those providing acceptable bleached pulp properties (*viz.* values close to the optimum ones: brightness – 80.5%, viscosity – 820 mL/g and Kappa number – 1.25) while saving chemical reagents, energy and the industrial resources for capital investments in facilities, by using lower concentrations of soda and peroxide and shorter processing times than those required to obtain optimum bleached pulp properties. One such combination uses a soda concentration of 0.5% and a hydrogen peroxide concentration of 3%, for a time of 3 h. Under such conditions, a brightness value of 74.9% (7.0% below the maximum) and a viscosity value of 716 mL/g (12.7% less than the maximum value) were attained. This value of brightness (74.9%) is higher than that found by Law and Jiang,[22] namely 64.1% for bleaching EFB soda pulp with 5% hydrogen peroxide, 4.5% soda, at 70 °C, for 1 h. The difference found may be due to the different operating conditions considered in these cases. A comparison between the brightness and viscosity values obtained in the present work and those reported by Jiménez *et al.*[49] for bleaching EFB soda pulp and diethanolamine pulp (653 mL/g and 783 mL/g, 77.5% and 71.3%, respectively) shows that the obtained values are intermediary ones. This can be explained by the different pulping and bleaching processes used.

Hesperaloe funifera

As in the case of EFB, by applying fuzzy models for *H. funifera* pulp to various combinations of values of the operational variables, one can identify those providing acceptable properties for bleached pulps (*viz.*, values close to the optimum ones: brightness – 68.6%, viscosity – 680 mL/g and Kappa number – 1.63), while saving chemical reagents, energy and the industrial resources for capital investments in facilities, by the application of lower soda and peroxide concentrations and shorter processing times than those required to obtain optimum properties of the bleached pulps. One of these combinations uses a soda concentration of 0.5%, and a hydrogen peroxide concentration of 3%, for 3 h. Under these conditions – similar to those used for EFB pulp – a brightness of 63.3% (7.7% below the maximum) and a viscosity of 584 mL/g (14.1% less than the maximum value) could be attained.

CONCLUSIONS

The neural fuzzy models applied for bleaching pulps from EFB and *H. funifera* are suitable to predict the brightness and viscosity values of bleached pulps, the possible errors recorded being, in the worst case, below 10% for EFB pulp and 15% for *H. funifera* pulp.

By simulating the bleaching of EFB and *H. funifera* pulps by the neural fuzzy models, the optimal values for the operating variables may be established, so that the properties of bleached pulps will differ only slightly from their best values; besides, chemical reagents, energy and plant size will be saved, once operating at lower values of the operating variables. Thus, operating at a soda concentration of 0.5%, a hydrogen peroxide concentration of 3%, for 3 h, a pulp with a brightness of 74.9% (7.0% below the maximum) and a viscosity of 716 mL/g (12.7% less than the maximum value) may be obtained, for the EFB pulp, and of 63.3% (7.7% below the maximum) and of 584 mL/g (14.1% less than the maximum value) respectively, for the *H. funifera* pulp.

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