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Simulation of bleaching of soda pulp from *Hesperaloe funifera* by polynomial and neural fuzzy models

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Influence of variables [soda, (0.5 to 3.0%), hydrogen peroxide (1.0 to 10.0%) and time (1 to 5 h)] in the bleaching of soda pulp of *Hesperaloe funifera*, on the properties of bleached pulps, was studied. Polynomial and neural fuzzy models had reproduced the results of Kappa number, brightness and viscosity of the pulps with errors less than 10 and 15%, respectively. By simulating the bleaching process of pulp *H. funifera*, with the polynomial and neural fuzzy models, the optimal values of operating variables can be found, so that the properties of bleached pulps differ little from their best values and instead will save chemical reagents, energy and plant size, operating with lower values of operating variables. Thus, by application of polynomial models, it was found that operating with a soda concentration of 0.5%, a hydrogen peroxide concentration of 5.5% and for a processing time of 3 h, it was possible to get a pulp with a brightness of 65.9% and a viscosity of 587 ml/g.

Key words: Pulp bleaching, *Hesperaloe funifera*, hydrogen peroxide, neural fuzzy model, polynomial model.

INTRODUCTION

In the industry of cellulosic pulp and paper two main problems today are the reduction of environmental pollution and shortage of raw materials. Regarding the environment, the pulp bleaching plants are the most contaminating section in the pulp and paper manufacturing process, so you have to take numerous changes intended to alleviate its adverse impact. The need to reduce or eliminate the formation of organo-chlorinated compounds of high toxicity, during the bleaching processes has led to the emergence of new products in the market, such as elemental chlorine free (ECF) and totally chlorine free (TCF) pulps (Ramos et al., 2008). TCF pulping processes avoid the formation of highly toxic organochlorine compounds adsorbable

organic halogen (AOX) during bleaching. Usually, TCF sequences include oxygen, hydrogen peroxide and ozone based stages (Freire et al., 2006; López et al., 2003; Pedrola et al., 2004; Shatalov and Pereira, 2005; Villaverde et al., 2009).

Recently, enzyme stages involving xylanases or the laccase-mediator system have so far provided very promising results in pulp bleaching sequences (Valls et al., 2009).

The use of polynomial models and neural fuzzy models has been used successfully for the study of operating variables in the bleaching of pulps (Jiménez et al., 2008; López et al., 2001, 2002, 2003; Pedrola et al., 2004; Valls et al., 2009) and both models have been successfully applied in the pulping of different raw materials, for several authors that have studied the influence of operating variables on the characteristics of the pulps obtained and the resulting paper sheets (Caparrós et al., 2008; Jiménez et al., 2007; Rodríguez et al., 2008, 2010).

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The problem of shortage of raw materials has intensified in recent decades mainly due to the significant increase in the production of pulp, paper and other products. The solution is the use of new raw materials such as agricultural waste, residues from food industry, forest residues and plant fast-growing non-wood, as well as use of all components of these alternative raw materials (Kelley, 2007; Towers et al., 2007).

A promising non-wood raw material is *Hesperaloe funifera*. It is a plant of the family Agavaceae up to 80 cm tall and 1.0 to 1.2 m wide with long leaves up to 5 cm wide and 2 to 3 cm thick. All species in its genus originated in Mexico and its neighbouring USA regions, where it is used mainly for ornamental purposes. *H. funifera* has very modest irrigation requirements by effect of its using the Crassulaceans acid metabolism (CAM) for photosynthesis. Its plants fix carbon dioxide and transpire water more strongly at night than during the day; also, because their coefficient of transpiration is lower at night, they use water highly efficiently. Based on these properties, *H. funifera* might be an effective cellulose raw material in arid zones (McLaughlin, 2000); in several regions of Spain could be particularly interesting the cultivation of this species. High-density plantations (27,000 per hectare) can yield approximately 20 tons of dry biomass per hectare (Wong et al., 2000). These crop yields can be increased by careful control of plant flowering and the use of higher planting densities (McLaughlin, 2000). Although the fibre morphology of *H. funifera* plants is especially suitable for making cellulose pulp (McLaughlin, 2003), little research in this direction appears to have been conducted. In the few exceptions, the material was subjected to alkaline sulphite–anthraquinone or mechanical pulping (Fairbank and Detrick, 2000; McLaughlin, 2000) and the resulting paper sheets found to have very high tensile, burst and tear indices Äand hence to be highly suitable for making special paper. More recently *H. funifera* has been pulped by different processes: soda-anthraquinonone, ethanolamine, ethylenglycol and diethylenglycol diethanalamine (Sánchez et al., 2010). Rodriguez et al. (2010) compare the simulation of diethanolamine pulping using the polynomial and neural fuzzy models. Similarly, *H. funifera* has been used to advantage hemicelluloses by authohydrolysis and lignin by acidification separation of pulping waste liquor (Sánchez et al., 2011). So far, no studies dealing with the bleaching of pulp H. funifera have been found.

The aim of this paper is TCF bleaching of soda pulp *H. funifera* using hydrogen peroxide and oxygen (Po) as a stage in the sequence WAOqPo (WA is an acid washing stage, O an oxygen delignification stage, q a chelating stage, and Po a peroxide and oxygen stage). We studied the influence of operating variables in the stage Po (soda concentration, hydrogen peroxide concentration and processing time) on the properties of the resulting pulp (kappa number, brightness and viscosity) using polynomial and neural fuzzy models, with the idea find the optimal conditions for bleaching.

MATERIALS AND METHODS

Raw materials

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 in holocellulose, lignin, α-cellulose, ethanol–benzene extractives, and ash of the raw material (determined in accordance with the following Tappi standards: T-9, T-222, T-203 0S-61, T-204, and T-211) are: 76.5, 7.3, 40.9, 4.0, and 5.9%, respectively. The fiber length of *H. funifera* was determined by using a projection microscope Visopan, proved to be of 4.19 mm.

Pulping

Pulp was obtained by using a 15 L batch cylindrical reactor that was heated by means of an electrical wire and linked through a rotary axle Äto ensure proper agitationÄ to a control unit including a motor actuating the reactor and the required instruments for measurement and control of the pressure and temperature.

The raw material was cooked in the reactor, using a 15% soda, 170°C, a 8 liquid/solid ratio and a processing time of 40 min, obtaining of pulp yield of 41.5%. These operating conditions were selected based on the results of others authors (Sánchez et al., 2010). Next, the cooked material was fiberized in a wet desintegrator at 1200 rpm for 30 min and the screenings were separated by sieving through a screen of 0.14 mm mesh size. The pulp obtained was beated in a Sprout-Bauer refiner.

Bleaching

The initial pulp properties of *H. funifera* were 31.2% ISO brightness and 13.6 of Kappa number. Before applying the hydrogen peroxide stage (Po) the pulp was washed in 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 odp (oven-dried pulp) in a 5 L reactor at 0.6 MPa O_2, with 0.5% odp of Na_2SiO_3, 0.2% odp of $MgSO_4$, at 5% consistency, at 105°C and 60 rpm. The soda concentration, hydrogen peroxide concentration and processing time were the three variables of the experimental design and they varied over the following ranges: 0.5 to3% odp for soda concentration, 1-10% odp for hydrogen peroxide and 1 to 5 h for processing time. After the Po stage the pulp was efficiently washed for characterization.

Pulp properties

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

Table 1. Normalized values of operational variables and experimental values of the properties of bleached pulp of *Hesperaloe funifera.*

Experiment	Normalized values			Kappa number	Brightness (%)	Viscosity (ml/g)
	Soda	Peroxide	Processing time			
1	-1	-1	-1	5.74	51.4	619
2	-1	+1	-1	4.93	60.9	502
3	+1	+1	-1	7.79	61.7	460
4	+1	-1	-1	6.14	53.9	620
5	-1	-1	+1	5.25	60.0	623
6	+1	-1	+1	5.66	57.9	582
7	-1	+1	+1	1.54	68.8	451
8	0	0	0	5.20	62.4	543
9	+1	+1	+1	4.26	66.6	456
10	+1	0	0	5.54	62.9	645
11	0	0	+1	4.34	63.4	556
12	-1	0	0	4.05	65.4	532
13	0	-1	0	5.41	56.0	669
14	0	0	-1	6.52	61.2	596
15	0	+1	0	3.99	66.4	548
16	-0.5	-0.5	-0.5	5.15	60.8	620
17	+0.5	+0.5	+0.5	4.63	66.0	540

Experimental design

The experimental design used consisted of a series of points or tests (located in the centers of the faces and the vertices of a cube), and a central point or test (located in the center of the cube), that were used to estimate the terms of mathematical models. The design met the general requirement, that is, it allowed all parameters in mathematical models to be estimated with a relatively small number of tests (Montgomery, 1991).

The total number of tests required for the three independent variables studied [namely: soda concentration (S), hydrogen peroxide concentration (P) and processing time (T)] was found to be 15.

Polynomial modelling

To fit the experimental data to a polynomial model, the independent variables were normalized to values from -1 to +1 using Equation 1 in order to facilitate direct comparison of the coefficients of the resulting polynomial equation and an understanding of the effects of the individual independent variables on the dependent variables considered (namely: the kappa number, brightness and viscosity of the bleached pulps of *H. funifera*):

$$X_n = 2\frac{X - \bar{X}}{X_{max} - X_{min}} \tag{1}$$

Where X_n is the normalized value of a operational variable (S, P or T);

X is the absolute experimental value of the variable concerned; $\bar{X}$ is the mean of the extreme values of X; and X_{max} and X_{min} are its maximum and minimum values, respectively.

Experimental data were fitted to the second-order polynomial equation:

$$Z = a_o + \sum_{i=1}^{3} b_i X_{ni} + \sum_{i=1}^{3} c_i X_{ni}^2 + \sum_{i=1;j=1}^{3} d_{ij} X_{ni} X_{nj} \quad (i<j) \tag{2}$$

Where Z is the response or dependent variable [*viz.* Kappa number (KN), brightness (BR) and viscosity (VI)]; X_n is the normalized value of the independent variable concerned; and a_0, b_i, c_i and d_{ij} are unknown characteristic constants estimated from the experimental data.

Table 1 shows the normalized values obtained for the independent variables in the 15 tests required to construct the model.

Neural fuzzy modelling

The integration of fuzzy systems and neural networks combines the advantages of the two systems and provides an especially powerful modeling tool, namely the neural fuzzy system, which uses neural networks as tools in fuzzy systems. The generic equation from Jang et al. (1997) was adapted to the variation of bleached pulp properties as a function of the operational variables of the bleaching process, by using the following expression for three operational variables:

$$Ye = \frac{\sum_{i=1}^{8} c_i * R}{\sum_{i=1}^{8} R_i} \tag{3}$$

Where Ye is the estimate value of output variable (dependent variables), R_i, the fuzzy rules, and c_i, constant term (singleton defuzzifier). The eight fuzzy rules are:

R_1: low S, low P and low T; $R_1 = S_1 * P_1 * T_1$.

R_2: low S, low P and high T; $R_2 = S_1 * P_1 * T_2$.

R_7: low S, high P and high T; $R_7 = S_1 * P_2 * T_2$.

R_8: high S, high P and high T; $R_8 = S_2 * P_2 * T_2$.

Where S_1 and S_2, P_1 and P_2, and T_1 and T_2 are the values low and high of the linear membership function soda concentration, hydrogen peroxide concentration and processing time, respectively.

These linear membership functions have the form:

$$X_1 = 1 - \frac{1}{(xhigh - xlow)}(x - xlow)$$

$$X_2 = \frac{1}{(xhigh - xlow)}(x - xlow)$$

(4)

Where x is the absolute value of the soda concentration, hydrogen peroxide concentration and processing time; x_1 the value of S_1, P_1 or T_1; x_2 the value of S_2, P_2 or T_2; and x_{high} and x_{low} the extreme values of the variable concerned.

When the neural fuzzy models obtained by using linear membership functions for the three operational variables fail to acceptably predict the experimental results for the dependent variables, a Gaussian membership function at three levels (low, medium and high) can be employed for one of the variables and a linear membership function at two levels (low and high) for the other two. The resulting Equation 3 thus comprises 12 terms in the numerator and 12 in the denominator. The Gaussian membership function will be of the form:

$$X_i = \exp(-0.5\left(\frac{X - X_c}{L}\right)^2)$$

(5)

Where x is the absolute value of the variable concerned; x_c its minimum, medium or maximum value; and L the width of its Gaussian distribution.

The constants in the Equation 3 were estimated by using the ANFIS (Adaptative Neural Fuzzy Inference System) Edit tool in the Matlab 6.5 software suite (The Mathworks, Inc., Natict, MA).

RESULTS

Based on the results of other researchers for pulps from other materials (López et al., 2002, 2003; Pedrola et al., 2004) and after tentative previous experiments have used the ranges reported in the experimental part, for the operational variables during the hydrogen peroxide bleaching of pulp from *Hesperaloe funifera*.

Table 1 shows the experimental values of the bleached pulps properties of the *H. funifera*. During the hydrogen peroxide stage, brightness increased while Kappa number and viscosity decreased 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 (Ramos et al., 2008).

DISCUSSION

Polynomial modelling

Using experimental data from Table 1 in the polynomial model (Equation 2), by the BMDP computer program, the following equations are obtained:

$(R^2 = 0.99;$ t-Student $> 2.57;$ $p < 0.04;$ F-Snedecor $> 6.6)$
$BR = 63.1 + 4.5 X_P + 2.8 X_T - 1,0 X_S X_T - 2.7 X_P^2$ 6

$BR = 63.1 + 4.5 X_P + 2.8 X_T - 1,0 X_S X_T - 2.7 X_P^2$ $(R^2 = 0.95;$
t-Student $> 2.02;$ $p < 0.07;$ F-Snedecor $> 4.1)$ 7

$(R^2 = 0.78;$ t-Student $> 2.10;$ $p < 0.06;$ F-Snedecor $> 4.4)$ 8

Where KN is the Kappa number, BR is the brightness and VI is the viscosity of the bleached pulps, and X_S, X_P, and X_T is the normalized values of operating variables (soda concentration, S, hydrogen peroxide, P, and processing time, T).

The predictions obtained with the previous equations reproduced the experimental results for the dependent variables with errors less than 5% for kappa number, 4% for brightness and 10% for viscosity (Table 2).

The proposed models were validated by conducting two bleaching experiments (Entries 16 and 17 in Table 1). The errors made in predicting bleached pulp properties by using the polynomial models were quite small (Table 2). This testifies to the accuracy of such models.

The values of the operational variables providing the best bleached pulp properties (kappa number, brightness and viscosity) were identified by using multiple non-linear programming. Table 3 shows the optimum values of the dependent variables and those of the operational variables required to obtain them. In all the cases, low soda concentrations are required. In contrast, the hydrogen peroxide concentration should be high if you want to good values of kappa number and brightness, and low if it requires a high viscosity. The same is true with respect to processing time, but it must be a mean to achieve a high viscosity.

López et al. (2002, 2003) applied to Kraft pulp from olive prunings an experimental design of peroxide bleaching, finding that the values minimum of Kappa number of the bleached pulp and the values maximum of the brightness and the viscosity is achieved when operating at 5% peroxide and 210 min.

Moreover, Pedrola et al. (2004) used an experimental design to the P stage of the sequence OXZP (O is an oxygen stage, X a enzymatic treatment, Z an ozone stage and P a hydrogen peroxide stage) applied to eucalyptus Kraft pulp, with 4 independent variables: hydrogen peroxide concentration, soda concentration, processing time and temperature; the obtained models predict values for brightness and viscosity ranging from 84.6% to 90.5% and 890 to 919 ml/g, respectively, with the best results

Table 2. Values of the dependent variables as estimated with polynomial and neural fuzzy models, and deviations (in %) from their experimental counterparts (in brackets).

Experiment	Polynomial model			Normalized values		
	Kappa number	Brightness (%)	Viscosity (ml/g)	Kappa number	Brightness (%)	Viscosity (ml/g)
1	5.81 (1.21)	52.1(1.36)	616 (0.48)	5.56 (3.14)	50.9 (0.97)	614 (0.81)
2	4.96 (0.60)	61.2 (0.49)	477 (4.98)	5.16 (4.67)	56.3 (7.55)	549 (9.36)
3	7.73 (0.77)	63.1 (2.27)	477 (3.70)	8.02 (2.95)	57.8 (6.32)	533(15.87)
4	6.19 (0.81)	54.0 (0.19)	616 (0.64)	5.96 (2.93)	53.5 (0.74)	622 (0.32)
5	5.28 (0.57)	59.6 (0.67)	616 (1.12)	5.07 (3.43)	59.8 (0.33)	618 (0.80)
6	5.66 (0.00)	57.7 (0.35)	616 (5.84)	5.48 (3.18)	57.7 (0.35)	584 (0.34)
7	1.46 (5.19)	68.6 (0.29)	477 (5.76)	1.77 (14.94)	64.7 (5.96)	522(15.74)
8	4.94 (5.00)	63.1 (1.12)	587 (8.10)	4.45 (14.42)	63.8 (2.24)	610(12.34)
9	4.23 (0.70)	66.7 (0.15)	477 (4.61)	4.49 (5.40)	62.5 (6.16)	514(12.72)
10	5.73 (3.43)	63.1 (0.32)	587(8.99)	5.52 (0.36)	64.3 (2.23)	624 (3.26)
11	4.41 (1.61)	65.8 (3.79)	547(1.62)	3.92 (9.68)	61.2 (3.47)	554 (0.36)
12	4.15 (2.47)	63.1 (3.52)	587(10.34)	4.48 (10.62)	63.3 (3.21)	576 (8.27)
13	5.26 (2.77)	55.8 (0.36)	657 (1.79)	4.98 (7.95)	54.6 (2.50)	666 (0.49)
14	6.42 (1.53)	60.3 (1.47)	547 (8.22)	4.86 (25.46)	63.3 (3.43)	596 (0.00)
15	4.12 (3.26)	64.9 (2.26)	518 (5.47)	4.42 (10.78)	64.3 (3.16)	563 (2.74)
16	5.36 (4.08)	62.2 (2.30)	612 (1.29)	4.76 (9.40)	58.9 (3.13)	615 (0.81)
17	4.57 (1.30)	67.7 (2.58)	542 (0.37)	4.73 (2.16)	64.1 (2.88)	530 (1.85)

Table 3. Optimal properties in bleached pulp of *Hesperaloe funifera.*

Dependent variable	Optimum (maximum or minimum*) value of the dependent variable	Variation with the operational variables required to obtain the optimum values of the dependent variables		
		X_s	X_p	X_t
Kappa number	1.46	-1	+1	+1
Brightness (%)	69.8	-1	+0.84	+1
Viscosity (ml/g)	657	-	-1	0

when processing time and peroxide concentration was highest and temperature and soda concentration was mean values, being the most influential variable the peroxide concentration. Reported results only partially coincided with those obtained in this work, which may be due to the different nature of the treated materials (pruning of olive and eucalyptus wood against a non-wood: *H. funifera*) and they have different pulping undergone (Kraft pulping paraded in front of the soda pulping).

The polynomial equations (Equations 6, 7 and 8) allowed one to identify the operational variables most markedly influencing the bleached pulp properties. The maximum variations in the dependent variables with changes in the operational variables over the studied range were obtained by altering one independent variable at a time while keeping all others constant; the results are shown in Table 4 together with the maximum percent differences in the dependent variables from

their optimum values over the studied variation ranges.

As shown in Table 4 and Figures 1 and 2, for the kappa number, the most influential operational variable is the hydrogen peroxide concentration, coinciding with the results obtained for the bleaching of kraft olive pruning pulp (López et al., 2002, 2003); on the other hand, the less influential variables is the soda concentration, coinciding with the results of Pedrola et al. (2004) for the bleaching of eucalyptus kraft pulp. Kappa number (Figure 3) was strongly decreased by peroxide and processing time at low soda concentration. However, this effect was less appreciated at middle and high soda concentration. In general, the increase of soda concentration had a detrimental effect on Kappa number.

Similarly, the Table 4 and Figures 4 and 5, revealed that the brightness has a behavior similar to kappa number: the most influential variable are the peroxide concentration and less soda concentration. These results are consistent with those obtained by Pedrola et al. (2004) for the case of

Table 4. Maximum changes in the dependent variables with the changes in one operational variable on constancy of the others (the percent differences from the changes are give in brackets).

Dependent variable	Variation with the operational variable		
	Soda (0.5 to 3.0%)	Peroxide (1.0 to 10.0%)	Time (1 to 5 h)
Kappa number	2.78 (190.41%)	3.82 (261.34%)	3.50 (239.73%)
Brightness (%)	2.0 (2.87%)	9.1 (13.04%)	4.0 (5.73%)
Viscosity (ml/g)	-	140 (21.31%)	41 (6.24%)
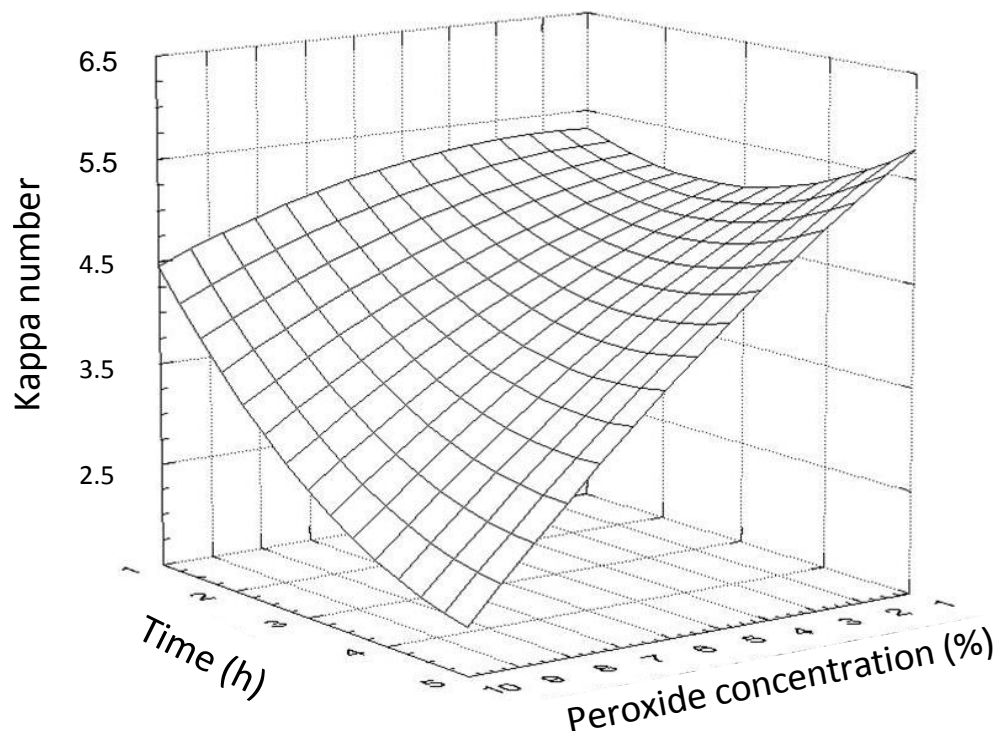
Figure 1. Variation of Kappa number of bleached pulps of *Hesperaloe funifera* with hydrogen concentration and time processing, for a soda concentration of 0.5%, by using polynomial model.

bleaching of eucalyptus Kraft pulp, but not with those obtained for Kraft pulp from olive pruning (López et al., 2002, 2003), where the most influential variable is processing time. Figure 6 shows that the increase of soda concentration made brightness increase for low peroxide concentration. However, at long processing time and high peroxide concentration the increase of soda concentration decrease the pulp brightness. According to Dence and Reeve (1996), for each peroxide concentration, there exists an optimum soda concentration. At soda concentration above the optimum, the effectiveness of hydrogen peroxide is reduced and brightness reversion is observed. On the other hand, the hydrogen peroxide and the processing time increased brightness being their effect more visible at low soda concentration. As in the case of kappa number, the increased soda concentration has a negative effect on the brightness of the bleached pulp.

Finally, Table 4 and Equation 8, shows that the most influential operational variable on the viscosity is the hydrogen peroxide concentration and the less is the processing time, no influencing the soda concentration; these results are consistent with those of López et al. (2002, 2003) and those of Pedrola et al. (2004). The pulp viscosity (Equation 8) was always negatively affected by hydrogen peroxide concentration, while the processing time only makes for extreme values, being the maximum viscosity for intermediate values of processing time. In contrast than with kappa number and brightness, no interactions between variables were found.

The decrease of viscosity was produced because cellulose may undergo depolymerization by reaction
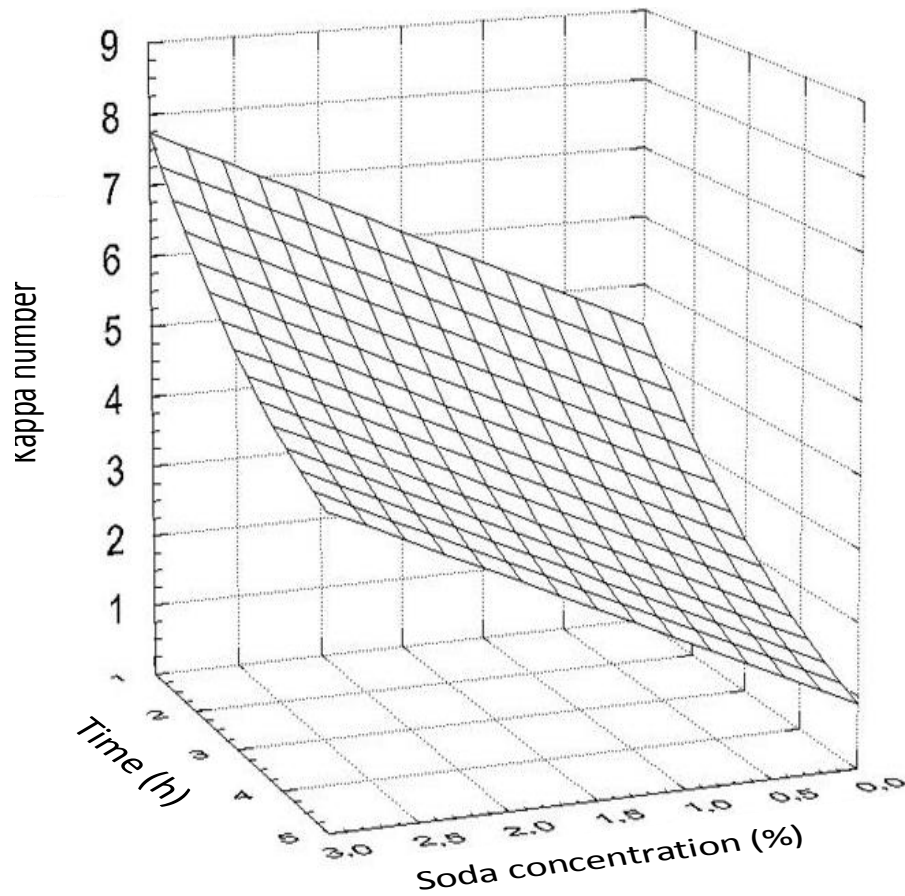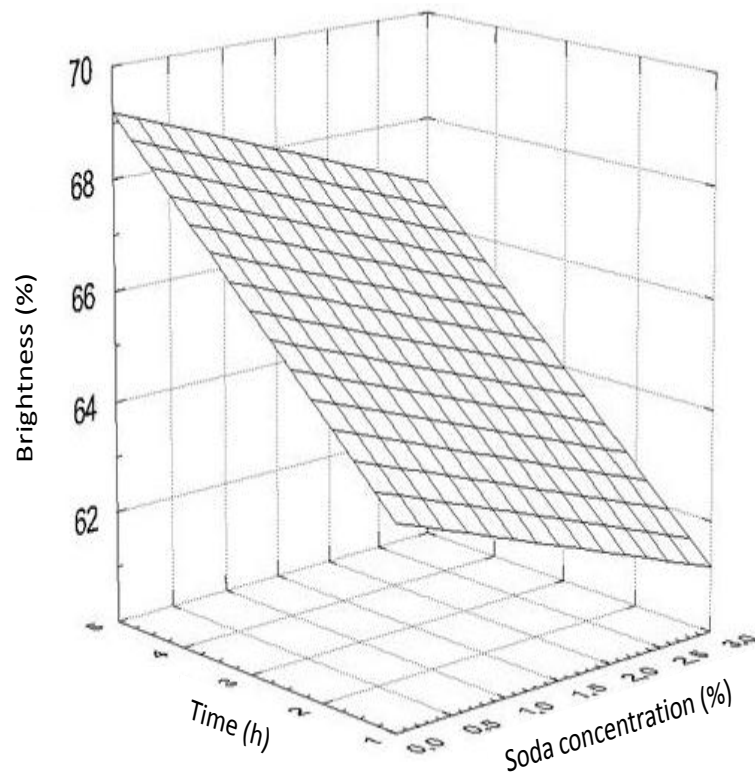
Figure 2. Variation of Kappa number of bleached pulps of *Hesperaloe funifera* with soda concentration and processing time, for a peroxide concentration of 10%, by using polynomial model.
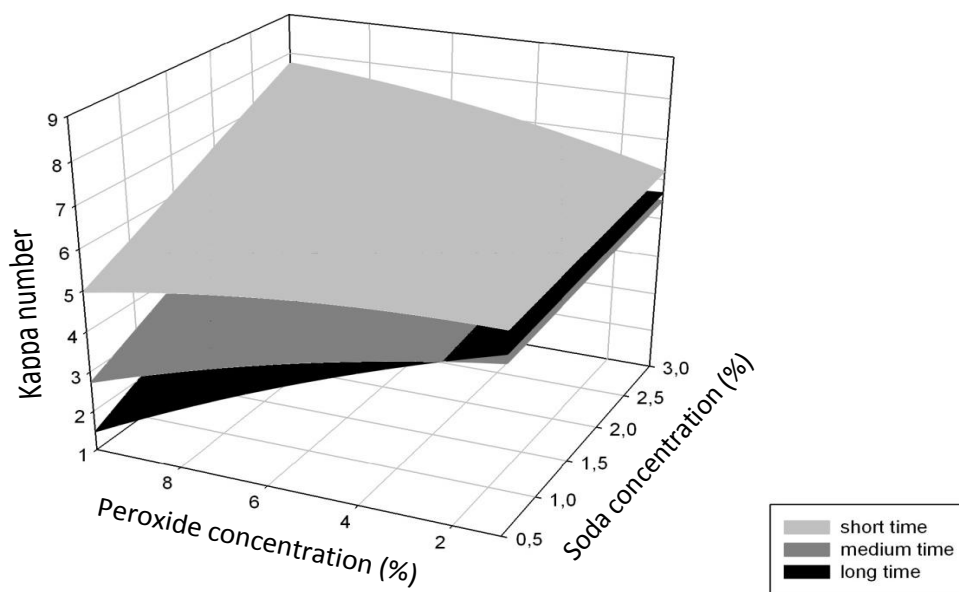
Figure 3. Variation of Kappa number of bleached pulps of *Hesperaloe funifera* with hydrogen peroxide concentration and soda concentration for short, medium and long processing time, by using polynomial model.
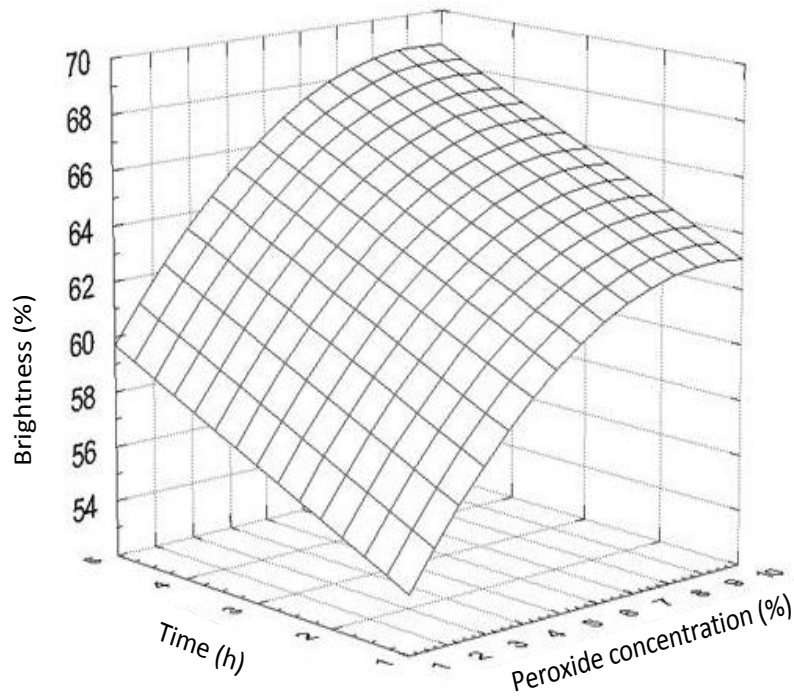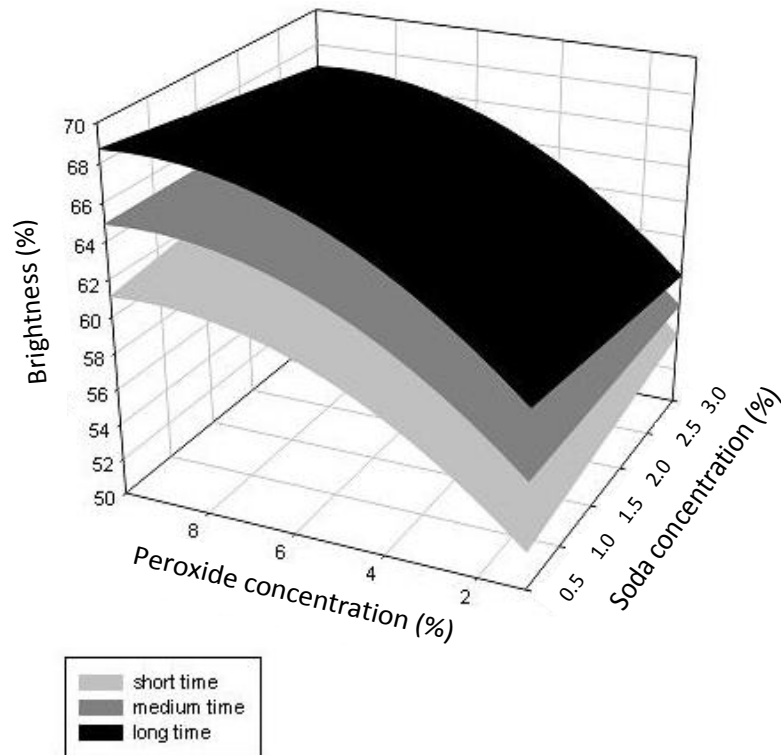
Figure 4. Variation of brightness of bleached pulps of *Hesperaloe funifera* with peroxide concentration and processing time, for a soda concentration of 0.5%, by using polynomial model.

Figure 5. Variation of brightness of bleached pulps of *Hesperaloe funifera* with soda concentration and processing time, for a peroxide concentration of 9.3%, by using polynomial model.

Figure 6. Variation of brightness of bleached pulps of *Hesperaloe funifera* with hydrogen peroxide concentration and soda concentration for short, medium and long processing time, by using polynomial model.

with hydroxyl radicals (Dence and Reeve, 1996).

Neural fuzzy modelling

Table 5 shows the values of the constants in the neural fuzzy models, c_i, as obtained by using the kappa number values of Table 1 was that constructed with a Gaussian membership function for the variable hydrogen peroxide concentration and a linear membership function for the other two (soda concentration and processing time).

Table 5 shows the values of the constants in the neural fuzzy models, as obtained by using the brightness and viscosity values of Table 1, which was that constructed with a Gaussian membership function for the variables processing time and soda concentration, respectively, and a linear membership function for the other two (hydrogen peroxide and soda concentrations, and hydrogen peroxide concentration and processing time, respectively for the brightness and viscosity).

The predictions obtained with the previous models reproduced the experimental results for the dependent variables with errors less than 15% for the Kappa number (in more of the 90% of the cases), 8% for the

brightness and 15% for the viscosity (Table 2). As in the case of polynomial model, by using the Experiments 16 and 17 can be validated the neural fuzzy model. It is found that by using the fuzzy neural model, the errors in the prediction of the results of the Experiments 16 and 17 are small, which confirms the model tested.

Figure 7 shows the variations of the kappa number of the bleached pulps in terms of peroxide concentration and soda concentration, by using fuzzy neural model, for three values of the processing time: short, medium and long. This figure are shows the same conclusions as those obtained in Figure 3, corresponding to the polynomial model, as can be seen that both models advocated in the same direction. Similar to the above figures are for the brightness and the viscosity of the bleached pulps.

Comparison of models and simulation of experimental results

By comparing the errors in the estimates of the properties of bleached pulps *H. funifera*, by applying polynomial and neural fuzzy models, is verified that are lower in the case of polynomial models, so these would be best to simulate the optimum operating conditions in the hydrogen peroxide bleaching process of the pulp of *H. funifera*. These results

Table 5. Values of the constants ci in the neural fuzzy model for the bleached pulp properties.

Rule	Values			Kappa number	Brightness (%)	Viscosity (ml/g)
	Soda	Peroxide	Time			
1	Low	Low	Low	5.60	49.9	605
2	Low	Low	High	5.14	59.4	626
3	Low	High	Low	3.18	60.4	477
4	High	Low	Low	6.04	52.5	614
5	Low	High	High	1.63	69.1	435
6	High	Low	High	5.59	57.1	587
7	High	High	Low	8.23	61.2	437
8	High	High	High	4.54	66.7	449
9	Medium	Low	Low	-	-	685
10	Medium	Low	High	-	-	565
11	Medium	High	Low	-	-	644
12	Medium	High	High	-	-	523
9	Low	Medium	Low	4.96	-	-
10	Low	Medium	High	4.02	-	-
11	High	Medium	Low	4.69	-	-
12	High	Medium	High	3.73	-	-
9	Low	Low	Medium	-	64.7	-
10	Low	High	Medium	-	61.8	-
11	High	Low	Medium	-	65.9	-
12	High	High	Medium	-	66.7	-
R^2				0.85	0.88	0.80
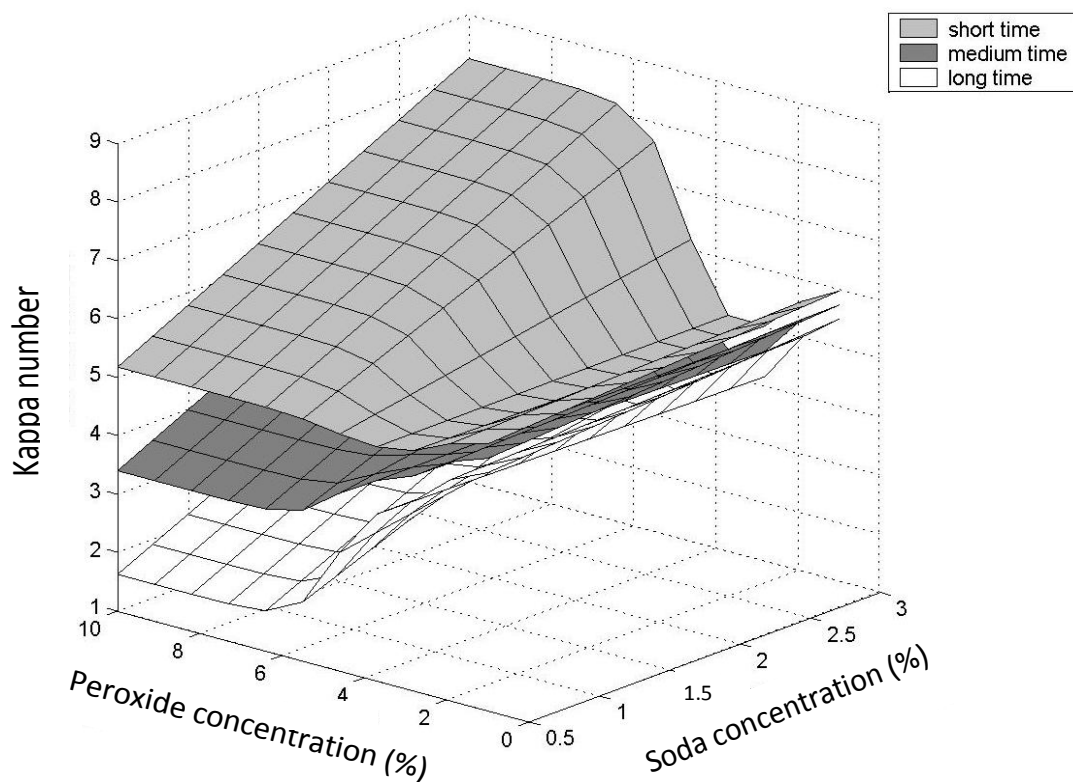
Figure 7. Variation of Kappa number of bleached pulps of *Hesperaloe funifera* with hydrogen peroxide and soda concentration, at short, medium and long processing time, by using neural fuzzy model.

do not completely coincide with those obtained by other authors for the pulping of different materials (vine shoots with ethanolamine (Jiménez et al., 2007), paulownia with ethanol (Caparrós et al., 2008) and *Leucaena leucocephala, Chamecytisus proliferus*, vine shoots and cotton stalks with ethylene glycol (Rodríguez et al., 2008) and *H funifera* with diethanolamine (Rodríguez et al., 2010), which concluded that both models (polynomial and neural fuzzy) are equally good or even better the neural fuzzy model.

To simulate the experimental results, bleached pulps properties, can be applied on polynomial and neural fuzzy models. Thus, by applying the polynomial 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 of Table 3) while saving chemical reagents, energy and industrial Immobilized on Capital Investments facilities, through the use of lower concentrations of soda and peroxide and shorter processing times than those required to obtain the optimum bleached pulp properties. One such combination uses a low soda concentration of 0.5%, a medium hydrogen peroxide concentration of 5.5% for a medium processing time of 3 h.

Under these conditions, we obtained a brightness of 65.9% (5.59% below the maximum) and a viscosity of 587 ml/g (10.65% less than the maximum value).

Conclusions

The polynomial model reproduces the experimental results of the properties of bleached pulp, in hydrogen peroxide bleaching of pulp of *H. funifera*, with errors less than 4-10%, while the fuzzy neural model reproduces with minor errors 8 to 15%.

By simulating the bleaching process of pulp *H. funifera*, with the polynomial and neural fuzzy models, the optimal values of operating variables can be found, so that the properties of bleached pulps differ little from their best values and instead will save chemical reagents, energy and plant size, operating with lower values of operating variables. Thus, by the application of the polynomial models, it is found that operating with a soda concentration of 0.5%, a hydrogen peroxide concentration of 5.5%, for a processing time of 3 h, you get a pulp with a brightness of 65.9% and a viscosity of 587 ml/g.

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