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Manufacture of Fermentable Sugar Solutions from Sugar Cane Bagasse Hydrolyzed with Phosphoric Acid at Atmospheric Pressure

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Sugar cane bagasse, a renewable and cheap bioresource, was hydrolyzed at 100 °C using phosphoric acid at different concentrations (2, 4, or 6%) and reaction times (0−300 min) to obtain fermentable sugar solutions, which have a high concentration of sugars (carbon source for microorganism growth) and a low concentration of growth inhibitors (acetic acid and furfural). Xylose, glucose, arabinose, acetic acid, and furfural were determined following the hydrolysis. Kinetic parameters of mathematical models for predicting these compounds in the hydrolysates were obtained. Derived parameters such as efficiency of hydrolysis or purity of hydrolysates were considered to select as optimal conditions 6% phosphoric acid at 100 °C for 300 min. Using these conditions, 21.4 g of sugars L^{-1} and <4 g of inhibitors L^{-1} were obtained from the hydrolysis with a water/solid ratio of 8 g of water g^{-1} of sugar cane bagasse on a dry basis.

KEYWORDS: Sugar cane; bagasse; xylose; glucose; arabinose; phosphoric acid; kinetic modeling; acid hydrolysis

INTRODUCTION

Sugar cane bagasse is a residual lignocellulosic material of the sugar extraction process. It is an abundant and low-cost waste mainly used in the production of energy by combustion (*1*, *2*). Approximately 25% of the sugar cane bagasse is hemicelluloses, mainly xylan. An added-value use could be the application of sugar cane bagasse as a raw material for the production of fermentative media if sugar solutions can be obtained by the solubilization of hemicelluloses. An alternative is prehydrolysis with dilute acids. Sulfuric, hydrochloric, or acetic acids are usually applied using concentrations in the range of 1−5% and at temperatures in the range of 100−180 °C. The acid medium attacks the polysaccharides, especially hemicelluloses, which are easier to hydrolyze than cellulose. Therefore, the cellulose and lignin fractions remain almost unaltered in the solid phase and can be further processed.

The liquid phase after hydrolysis is constituted by sugars such as xylose, glucose, and arabinose at different concentrations that depend on the selected operational conditions. Other products from the decomposition of hemicelluloses are also present such as acetic acid, furfural, and hydroxymethylfurfural. These products are growth inhibitors of microorganisms. Therefore, the hydrolysates can be used as fermentation media if the concentration of inhibitors remains low in them.

The cellulose and lignin of the solid residue after the hydrolysis of the hemicellulose fraction can be processed for the biotechnological production of ethanol (*3*, *4*) or for pulp paper production (*5*).

The hydrolysis of sugar cane bagasse with sulfuric acid (*6*), hydrochloric acid (*7*), or nitric acid (*8*) has been previously studied. No studies using phosphoric acid have been reported. It should be considered that the main idea in these processes is the use of the hydrolysates of sucar cane bagasse as fermentation media for the production of food additives using microorganisms. All of the hydrolysates have an acid pH and need a neutralization step to be used as fermentation media. The neutralization step produces several salts as a function of the acid used (for example, calcium sulfate from sulfuric acid) that need to be removed, usually by filtration. The novelty in the use of phosphoric acid is that in the neutralization is formed sodium phosphate, a salt that can remain in the fermentation media. Several microorganisms use this salt as a nutrient. In this case, the cost of nutrients can be reduced. A step in the global process is also eliminated: the filtration to remove the salt formed in the neutralization with other acids.

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Xylose is the main sugar obtained in the hydrolysates and is the carbon source of several fermentation processes. The main application of xylose is its bioconversion to xylitol, a functional sweetener with important technological properties such as anticariogenicity, low caloric value, and negative heat of dissolution (*9*). It can also be used for treatment of diabetics (*10*). The economic interest in xylitol production can be enhanced if the needed xylose solutions can be obtained from the hydrolysis of a low-cost lignocellulosic waste such as sugar cane bagasse.

This work deals with the hydrolysis of sugar cane bagasse with phosphoric acid to obtain fermentable media with high concentration of sugars and low concentration of growth inhibitors. Kinetic models were developed to explain the time course of xylose, glucose, arabinose, acetic acid, and furfural generation.

MATERIALS AND METHODS

Raw Material. The raw material used in experiments was sugar cane bagasse collected at a local industry (Ingenio Azucarero de Mante, Tamaulipas, Mexico). The sugar cane bagasse was air-dried, milled, screened to select the fraction of particles with a size of <0.5 mm, homogenized in a single lot, and stored until needed. Aliquots of the homogenized lot were analyzed for moisture determination (drying at 105 °C to constant weight). Analyses of the main fractions (cellulose, hemicelluloses, and Klason lignin) were carried out using a quantitative acid hydrolysis under standard conditions (*11*).

Acid Hydrolysis of Samples. Treatments were performed at 100 °C in media containing 2, 4, or 6 g of H_3PO_4·100 g^{-1} of medium. These values were selected according to the literature for similar acids (*6*, *12*). All experiments were performed using a water/solid ratio (WSR) of 8 g of water g^{-1} of sugar cane bagasse on a dry basis. Samples were taken from the reaction media at given reaction times in the range of 0−300 min and centrifuged. The pellets were washed twice with sterile water, and the supernatant was diluted with water and analyzed by HPLC for glucose, xylose, arabinose, and acetic acid. The HPLC analyses were carried out using a Transgenomic ION-300 column, an oven temperature of 45 °C, an isocratic elution (flow rate = 0.4 mL/min; mobile phase, 0.005 N H_2SO_4), and a refraction index detector. Furfural was determined by spectrophotometry (*8*). The pellets were used for determining the solubilized fraction (SF) by the difference from the original weight, drying at 105 °C to constant weight. The SF was calculated as grams of solubilized solids recovered after acid hydrolysis per 100 g of raw material, on a dry basis.

Statistical Analysis. All experimental data were determined in triplicate, and averages are given. Nonlinear regression analyses of experimental data were performed with a commercial optimization routine dealing with Newton's method (Solver, Microsoft Excel 2000, Microsoft Corp., Redmond, WA) by minimizing the sum of the squares of deviations between experimental and calculated data as previously described (*13*).

RESULTS AND DISCUSSION

Raw Material Composition. The composition obtained for the sugar cane bagasse was (weight percent on a dry basis) as follows: glucan, 38.9%; xylan, 20.6%; araban, 5.56%; Klason lignin, 23.9%; others, 11.0% (average values of three replicates, error <1% for all compounds). These values are in the ranges found for these kinds of materials (*2*, *14*).

Knowing the water/solid ratio (WSR) and the raw composition, the potential concentration of each sugar was calculated by assuming a total conversion of polysaccharides to sugars without degradation as described

$$S_p = F \times \frac{CPn_0}{WSR} \times 10 \qquad (1)$$

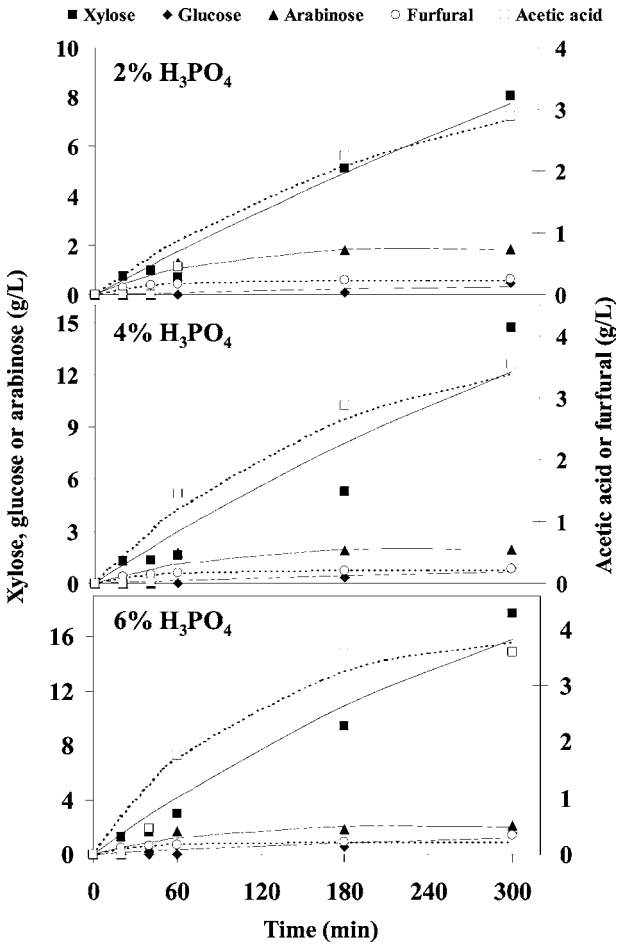

Figure 1. Comparison of experimental data (points) and calculated values fitting the models (lines) of concentration of xylose, glucose, arabinose, acetic acid, and furfural with time at different phosphoric acid concentrations and at 100 °C.

where S_p (g L^{-1}) is the maximum concentration possible of each sugar *S*, *F* is the factor of hydration, which appears during the hydrolysis ($F_{pentoses}$ = 150/132 and $F_{hexoses}$ = 180/162), CPn_0 is the composition of the raw material in the polysaccharide Pn, and WSR is 8 g g^{-1}. Applying eq 1, it was obtained that the potential composition of hydrolysates was 54.0 g of glucose L^{-1}, 29.3 g of xylose L^{-1}, and 7.90 g of arabinose L^{-1}.

Composition of Hydrolysates. Figure 1 shows the composition of hydrolysates (xylose, arabinose, glucose, acetic acid, and furfural concentrations) for each time of reaction and phosphoric acid concentration. The highest xylose concentration was 17.7 g L^{-1} in the experiment carried out at 6% H_3PO_4 for 300 min. The xylose concentration grew with time and phosphoric acid concentration. Final decrease in xylose concentration was not detected, suggesting that degradation reactions toward hydroxymethylfurfural, a byproduct able to inhibit the growth of microorganisms more than furfural, did not occur (*15*, *16*). The use of phosphoric acid has the advantage of its being less aggressive than other acids, which gives solutions with higher concentrations of growth inhibitors of microorganisms, such as furfural or acetic acid.

The glucose concentration was very low and was not detected during the first hour of reaction and then grew up to 1.60 g of glucose L^{-1} in the experiment carried out at 6% H_3PO_4 for 300 min. Nevertheless, the low concentration of glucose (<3% of the potential concentration) confirmed that the fraction of glucan was not altered during the acid hydrolysis; thus, the glucose obtained probably came from the hemicellulosic polymers.

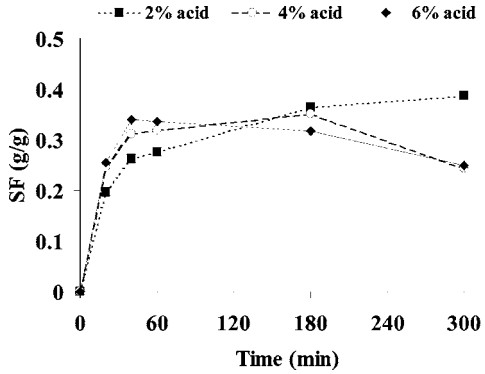

Figure 2. Dependence of solubilized fraction (SF) on time using different phosphoric acid concentrations and at 100 °C.

Arabinose was presented as furanose; thus, it was hydrolyzed more quickly than the pyranoses glucose and xylose (*17*) as can be observed in **Figure 1**. Arabinose concentration showed a slow increase at the start of hydrolysis and then increased quickly after 1 h up to 2.1 g L^{-1} at 5 h. The highest value was obtained in the experiment carried out at 6% H_3PO_4. The occurrence of two steps in the generation of arabinose suggests the presence of degradation reactions, probably to furfural, a compound with an inhibitor effect on fermentations (*16*). It seems that after 1 h the rate of arabinose release is a little higher than the rate of degradation.

The concentration of acetic acid, which is generated from the hydrolysis of the acetyl groups of the hemicelluloses (*18*), showed a fast increase with time and acid concentration, and no degradation of acetic acid to other products took place. The highest value was 3.61 g of acetic acid L^{-1} in the experiment carried out at 6% H_3PO_4 for 300 min. Acetic acid can be an inhibitor of microbial growth when present from 4 to 10 g L^{-1} (*19*, *20*) because it enters the cell membrane and decreases intracellular pH, thus affecting the metabolism of the microorganism (*21*, *22*). In our study, the maximum acetic acid concentrations were lower than the low limit of the toxic effect.

Furfural presents a pattern similar to that shown by arabinose and acetic acid. In the first hour it grew quickly and then slowed. The highest value was 0.35 g of furfural L^{-1} in the experiment carried out at 6% H_3PO_4 for 300 min.

Purity of Hydrolysates. Figure 2 shows the variation of the solubilized fraction (SF) with time and phosphoric acid concentration. It was observed that the SF increased quickly for 40 min to ~0.30 g g^{-1}. Using 2% H_3PO_4, SF increased slowly to 0.386 g g^{-1}, whereas using 4% it reached a maximum of 0.35 g g^{-1} and then decreased with reaction time. Using 6%, the maximum was 0.34 g g^{-1} for 40 min, and the final concentration was 0.25 g g^{-1} for 300 min. The highest value obtained (0.386 g g^{-1}) is according to the sum of xylan, glucan, araban, and others (susceptible fractions of solubilization in the acid hydrolysis), which are 0.388 g g^{-1}.

The main fraction affected by acid hydrolysis is the hemicellulose, but other fractions are partially solubilized, such as lignin, which is in the raw material. To take efficiently economical advantage, it is interesting to obtain a liquid phase with the lower concentration of other compounds different from sugars.

A pretreatment of detoxification to remove growth inhibitors (acetic acid and furfural) and treatments after fermentation for product recovery and depuration of residual waters are needed if hydrolysates are to be used as fermentable sugar solutions. It is obvious that if the concentration of these compounds is low in the hydrolysates, the overall process will be more favorable.

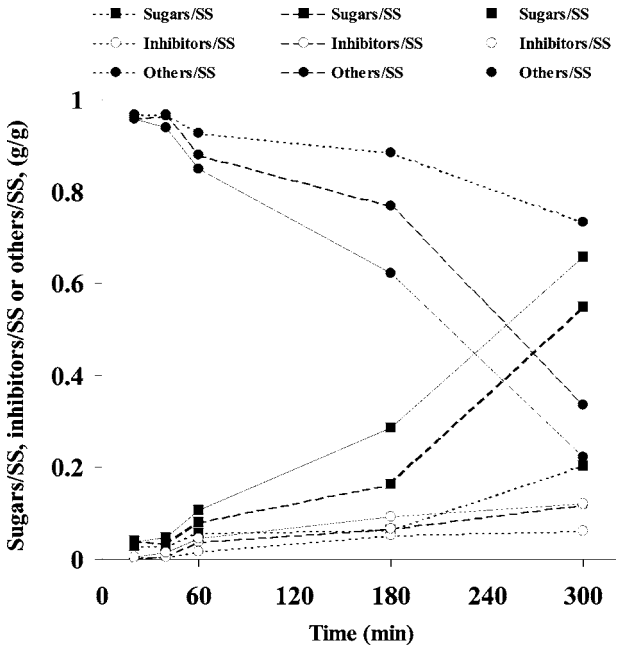

Figure 3. Dependence of the composition of the hydrolysates (sugars, inhibitors, and others) on time using different phosphoric acid concentrations 2% (continuous lines), 4% (large dot lines), and 6% (small dot lines) at 100 °C.

Processing SF data, the concentration of solids solubilized (SS) in the liquid phase can be determined by

$$SS = (SF/WSR) \times 10 \quad (2)$$

where SS is expressed as g of solubilized solids L^{-1} and SF and WSR were previously defined. The volumetric concentration of sugars is the sum of the concentrations of xylose, glucose, and arabinose. In the same way, the volumetric concentration of inhibitors is the sum of concentrations of furfural and acetic acid. The ratios of sugars/SS, inhibitors/SS, and others/SS can be compared to determine the purity of the hydrolysates. **Figure 3** shows the variation with time of the three ratios. It can be observed that the ratios sugars/SS and inhibitors/SS increase with time and phosphoric acid concentration until values of 0.66 g of sugars g^{-1} and 0.12 g of inhibitors g^{-1}, respectively, for 300 min and 6% acid. However, the ratio others/SS increases with time of reaction and decreases with phosphoric acid concentration, the minimum value (0.22 g/g) being reached at 300 min and 6% H_3PO_4. This is interesting because the inhibitors can be removed by a step of vacuum concentration of hydrolysates, but the fraction "others" may not removed. Therefore, additional steps of detoxification should be needed. Thus, the operational conditions leading to maximum value of sugars/SS also gives minimum concentration of others/SS, making the process more economical when using these conditions.

Kinetic Models. The hydrolysis reactions in dilute-acid medium are very complex, mainly because the substrate is in a solid phase and the catalyst in a liquid phase. The mechanism of this hydrolysis reaction has been reported (*12*). Although factors that can interfere in the analytical determinations such as wet fraction of the material, interferences of other components, presence of different kinds of bonds (sugar−sugar, sugar−acetyl group, etc.), and protector effect of the structure of the whole cell should also be considered (*23*−*25*).

The analytical methods (usually HPLC) measure sugars and other compounds (glucose, xylose, arabinose, and acetic acid), and these are expressed as homopolymers in the origin ligno-

cellulosic material (glucan, xylan, araban, and acetyl groups), even though in nature only glucan fundamentally corresponds to cellulose. Xylan, araban, and acetyl groups are linked in the hemicelluloses, forming arabanoxylan, the main compound of the agricultural materials (*11*).

The practical objective of studying the kinetic models is, on a first level, to optimize the process and, on a second level, to obtain equations useful for economical estimations (*18*).

The models proposed in the literature use pseudo-homogeneous irreversible first-order reactions. The first model used successfully was proposed by Saeman (*26*) for the hydrolysis of Douglas fir wood using sulfuric acid

$$\text{cellulose} \xrightarrow{k_1} \text{glucose} \xrightarrow{k_2} \text{decomposition products} \quad (3)$$

where k_1 is the rate of released glucose from cellulose and k_2 (min^{-1}) is the rate of decomposition of glucose, both having units of reciprocal time.

This model considers the hydrolysis of cellulose to glucose, which in severe conditions can be decomposed. Both reactions were considered to be first order and irreversible. The model of Saeman was also applied to the hydrolysis of the hemicellulosic fraction (*27*, *28*) and can be generalized as

$$\text{polymer} \xrightarrow{k_1} \text{monomer} \xrightarrow{k_2} \text{decomposition products} \quad (4)$$

where the polymer can be cellulose, xylan, or araban. Solving the differential equations for an isothermal reaction, the following model predicts the concentration of monomers:

$$M = M_0\, e^{-k_2 t} + P_0 \frac{k_1}{k_2 - k_1}(e^{-k_1 t} - e^{-k_2 t}) \quad (5)$$

M and P are concentrations of monomer and polymer expressed in g L^{-1}, t is time, and subscript 0 indicates initial conditions. Assuming that $[M_0]$ is close to zero, a simplification of the model yields

$$\frac{M}{P_0} = \frac{k_1}{k_2 - k_1}(e^{-k_1 t} - e^{-k_2 t}) \quad (6)$$

An alternative model called the two-fraction model considers that only a fraction of the polymer reacts. This is called the fast fraction, and the fraction that does not react or reacts slowly is called the slow fraction. The ratio between them is the parameter α. In the case that the slow fraction does not react, eq 7 explains the kinetic of the process.

$$\frac{M}{P_0} = \alpha \frac{k_1}{k_2 - k_1}(e^{-k_1 \cdot t} - e^{-k_2 \cdot t}) \quad (7)$$

In this work eq 7 has been applied to the hydrolysis of sugar cane bagasse using phosphoric acid.

Kinetic Modeling of Xylose Concentration. It can be observed that the hemicelluloses of sugar cane bagasse are mainly xylan. Therefore, the xylose is the main product of the acid hydrolysis of sugar cane bagasse. Equation 1 gave that the value of P_0 is 29.3 g of xylose L^{-1}. The two-fraction model did not fit better than the Saeman model. Thus, the latter was used because it is simpler and also can be considered a two-fraction model, where the fast fraction is 100%.

Table 1 shows the result of fitting Saeman's model for the xylan and the value of the statistical parameter r^2. **Figure 1** shows the comparison between experimental data of xylose concentration and those calculated with the Saeman model for the xylose concentration.

Table 1. Results of the Fitting of Models for the Hydrolysis of Sugar Cane Bagasse with Phosphoric Acid at 100 °C

	2% H_3PO_4	4% H_3PO_4	6% H_3PO_4
xylan			
$k_1 \times 10^3$ (min^{-1})	1.03	1.79	2.59
k_2 (min^{-1})	0.00	0.00	0.00
r^2	0.97	0.85	0.96
glucan			
$k_1 \times 10^3$ (min^{-1})	1.64	2.97	4.20
k_2 (min^{-1})	0.00	0.00	0.00
α_G (g g^{-1})	0.020	0.026	0.038
r^2	0.89	<0.80	<0.80
araban			
$k_1 \times 10^3$ (min^{-1})	4.98	11.8	11.8
$k_2 \times 10^3$ (min^{-1})	3.91	1.79	0.96
α_A (g g^{-1})	0.83	0.52	0.47
r^2	0.98	0.94	0.94
acetyl groups			
$k_1 \times 10^3$ (min^{-1})	4.00	5.68	9.20
Ac_0 (g L^{-1})	4.07	4.15	4.03
r^2	0.92	0.88	0.95
furfural			
$k_1 \times 10^3$ (min^{-1})	24.4	28.5	32.1
F_0 (g L^{-1})	0.24	0.21	0.22
r^2	0.98	0.98	0.99

The values of k_1 increased with acid concentration, whereas the values of k_2 were zero, suggesting that the rate of xylose release is high and the degradation reactions are negligible.

Kinetic Modeling of Glucose Concentration. During this process, a low concentration of glucose can be released from lignocellulosic material, either from cellulosic or hemicellulosic heteropolymers. However, because the cellulose is very resistant to dilute acids, its hydrolysis can be neglected and it can be supposed that all of the glucose released comes from the glucose fraction contained in the hemicellulose.

In a first approach, Saeman's model was applied to model glucose concentration. The potential concentration of glucose (Gn_0) was determined to be 54.0 g L^{-1}.

The results of fitting by the Saeman model were unsatisfactory, mainly showing values of r^2 in the range of 0.6−0.9. The bad fitting could be because the Saeman model considers that all glucan can be converted into glucose, but the experiments showed that the conversion is <3%. Therefore, it is realistic to suppose that the glucan has two fractions, where the main fraction corresponds to cellulose and does not react; the minor fraction corresponds to hemicellulosic heteropolymers in which glucose is susceptible to hydrolysis.

Therefore, α_G was defined as the glucose fraction susceptible to hydrolysis (grams of hydrolyzable glucan/total glucan) in a similar equation, which gives the concentration of glucose versus time.

$$\frac{G}{Gn_0} = \alpha_G \frac{k_1}{k_2 - k_1}(e^{-k_1 t} - e^{-k_2 t}) \quad (8)$$

Gn_0 is the glucose concentration corresponding to hypothetical quntitative conversion of glucan to glucose (54.0 g L^{-1}), k_1 is the kinetic coefficient of hydrolysis of glucan to glucose, and k_2 is the kinetic coefficient of glucose decomposition to hydroxymethylfurfural.

Table 1 shows the results of fitting glucose concentration using the model of two fractions, eq 8, for which r^2 values higher those observed with the Saeman model were obtained. **Figure 1** also shows the comparison between experimental and

calculated values using eq 8. Although the values of k_1 increased with phosphoric acid concentration, a negligible decomposition of glucose was observed, the coefficient k_2 being zero in all of the experiments.

The value of α_G increased with phosphoric acid concentration, being 0.016 g g^{-1} in experiments with 2% acid, 0.021 g g^{-1} with 4% acid, and 0.031 g g^{-1} with 6% acid. This corresponds to a susceptible glucan of 0.015 g g^{-1} sugar cane bagasse (on a dry basis) and means that the treatment with phosphoric acid is selective toward the xylan hydrolysis.

Kinetic Modeling of Arabinose Concentration. Arabinose is a sugar formed from arabinoxylans, hemicellulosic heteropolymers found in agricultural materials such as sugar cane bagasse. Arabinoxylans have a higher amount of xylose than arabinose. The kinetic models developed for glucose have been applied, the model of Saeman and the model of two fractions, considering two fractions of araban and only one susceptible to hydrolysis. The parameter α_A is the ratio between susceptible araban and total araban. Thus, eq 7 can be adapted to araban as

$$\frac{Ar}{Arn_0} = \alpha_A \frac{k_1}{k_2 - k_1}(e^{-k_1 t} - e^{-k_2 t}) \quad (9)$$

where $Arn_0 = 7.90$ g L^{-1}. Although the fitting was poor using the Saeman model, with r^2 between 0.6 and 0.9, the model of two fractions (eq 9) fitted better as it is shown in **Table 1** and **Figure 1**.

The value of α_A varied from 0.47 to 0.83 g g^{-1}. The fraction of susceptible araban decreased slightly with the concentration of phosphoric acid, and the average value was 0.60 g g^{-1}.

Kinetic coefficients for arabinose decomposition (probably to furfural) were distinct from zero in all experiments for the two-fractions model. The ratio k_1/k_2 increased with the acid concentration, with values of 1.3, 6.6, and 12.2 at acid concentrations of 2, 4, and 6% phosphoric acid, respectively. This means that the rate of the release increases more than the rate of decomposition with the concentration of catalyst. The araban was the only fraction in which decomposition of the monomer, arabinose in this case, was confirmed by the values of k_2 different from 0.

Kinetic Modeling of Acetic Acid Concentration. Some hemicellulosic monomers such as xylose are linked to acetyl groups (Ac), which can be hydrolyzed to acetic acid in acid media. The results showed that the acetic acid concentration increased until a constant value, according to the simple model proposed in the literature (*18*, *20*, *29*):

$$\text{acetyl groups} \xrightarrow{k_1} \text{acetic acid} \quad (10)$$

On the basis of this reaction model and solving the differential equation leads to eq 11, which expresses the acetic acid concentration (AcH) as a function of time (t)

$$AcH/Ac_0 = 1 - e^{-k_1 t} \quad (11)$$

where Ac_0 is the potential concentration of acetyl groups, expressed as acetic acid and introduced as a regression parameter, and k_1 the rate of acetic acid generation (min^{-1}). **Table 1** shows the coefficients obtained by the fitting, and **Figure 1** represents the experimental data and the prediction of the model of eq 11. Values of k_1 increased with phosphoric acid concentration, and Ac_0 was stable with an average value of 4.1 g L^{-1}.

Kinetic Modeling of Furfural Concentration. Furfural was generated as a decomposition product of pentoses in the hydrolysis of sugar cane bagasse. On the basis of the experimental data for furfural, a model similar to that for acetic acid can be proposed that expresses the furfural concentration (F) as a function of time (t)

$$F/F_0 = 1 - e^{-k_1 t} \quad (12)$$

where F_0, introduced as a regression parameter, is the potential concentration of furfural and k_1 is the rate of furfural generation (min^{-1}). **Table 1** shows the kinetic and statistical parameters obtained by the fitting of eq 12. **Figure 1** shows also the comparison between experimental data and predicted values. Whereas k_1 increased with acid concentration, F_0 was not affected and showed an average value of 0.23 g L^{-1}. This value is very low, which is favorable considering a posterior fermentation step.

Table 2. Parameters Fitted for the Models as a Function of Phosphoric Acid Concentration

fraction	ln a_1 (a_1 in min^{-1})	n (dimensionless)	r^2
xylose	–3.61	0.84	0.999
glucose	–3.06	0.86	1.000
arabinose	–1.96	0.83	0.834
acetic acid	–2.71	0.73	0.940
furfural	–3.57	0.84	0.999

Dependence of Kinetic Parameter on Phosphoric Acid Concentration. Kinetic parameters were correlated with phosphoric acid concentration (C) by means of the empirical eq 13

$$k_i = a_i C^n \quad (13)$$

where k_i represents kinetic coefficients ($i = 1$ for rate of monomer release and $i = 2$ for rate of decomposition), a_i and n are regression parameters, and C is the acid concentration expressed as % (w/w).

The values of k_2 were zero or close to zero in all of the models, and it was not possible to fit them using eq 13. This behavior is frequently found in this kind of hydrolysis (*18*, *30*). Therefore, **Table 2** shows only the values of a_i and n for k_1; the values for n were very similar for each fraction with an average value of 0.82. This table also shows the statistical parameter r^2 that showed that the model fitted very well.

Optimization of Composition of Hydrolysates for Fermentation Media. The main goal of this research was to develop kinetic equations that allow optimal conditions for the hydrolysis of sugar cane bagasse to obtain fermentable sugar solutions to be determined. It is required that the sugar solutions have high sugar concentration (carbon source for microorganism growth) and low concentration of growth inhibitors (acetic acid and furfural). The efficiency (E) as catalyst is a parameter that can help to find the optimal conditions and can be defined as the ratio

$$E = \sum_S / \sum_I \quad (14)$$

where Σ_S is the sum of the concentrations of sugars in the hydrolysates (xylose, arabinose, and glucose) and Σ_I is the sum of the concentration of all inhibitor in the hydrolysates (acetic acid and furfural). **Figure 4** shows the effect on E of the catalyst concentration and time. A similar behavior was observed for the acid concentration, with maximum values of E using short time. Using long time, it was observed that a high concentration of phosphoric acid provokes a high E of the process of hydrolysis toward the release of sugars. Short time with high E

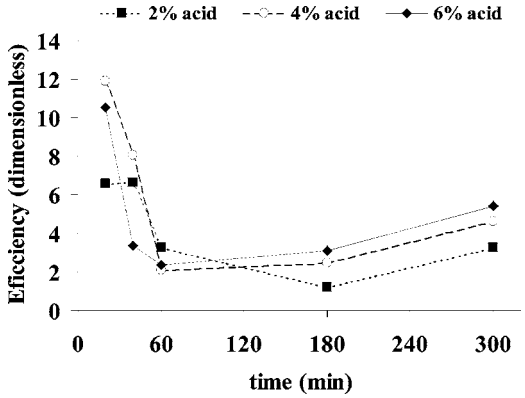

Figure 4. Dependence of efficiency (*E*) on time using different phosphoric acid concentrations at 100 °C.

Table 3. Comparison of Values of *E* (Catalytic Efficiency) for Different Acids in the Acid Hydrolysis of Sugar Cane Bagasse

acid	concn (wt %)	temp (°C)	time (min)	*E* (g/g)	ref
H_2SO_4	6	100	300	5.42	*6*
HCl	2	100	300	5.56	*7*
HNO_3	4	100	300	4.92	*8*
H_3PO_4	6	100	300	5.42	this work

is not interesting because the concentration of sugars was too low, <1.3 g L^{-1} as can be seen in **Figure 1**. **Table 3** shows *E* values for different acids used for this process. Phosphoric acid was in the range of efficiences of other acids. However, the main advantage of using phosphoric acid is that in neutralization of the hydrolysates with NaOH, sodium phosphate is obtained. This salt is a nutrient commonly added to fermentation media. Thus, operating conditions of 6% phosphoric acid concentration at 100 °C for 300 min were selected as optimal, where the model predicts fermentable solutions with 21.4 g of sugars L^{-1} and <4 g of inhibitors L^{-1}.

LITERATURE CITED

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