

Hydrolysis of Palm Tree Midribs with Hydrochloric Acid for Furfural Formation

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Abstract. Waste material samples as pentosan source of midribs from the Sukkaria date palm tree were collected from different Saudi Arabian agricultural areas, and hydrolyzed using hydrochloric acid (HCl) to produce furfural at different temperatures, liquid to solid ratios (LSR) and acid concentrations. A maximum furfural production with a concentration of 755 gm/m³ (72% furfural yield) was achieved, which was close to the theoretical yield at 15 wt% HCl and 100 ml/g LSR at 120°C. The kinetic model for the pentosan fractional hydrolysis towards the production of furfural was previously proposed and developed. Regression analysis of the experimental data was successfully performed using Ploymath software with acceptable predictions precision and regression coefficients of $R^2 \geq 0.96$. Furthermore, regressed rate constants of each reaction step in the proposed kinetic model were developed using modified Arrhenius model with an acceptable accuracy of $R^2 \geq 0.96$. Experimental data showed that hydrolysis using hydrochloric acid could achieve higher furfural yields with lower reaction times in comparison with sulfuric acid hydrolysis, due to lower activation energy of the involved steps.

Keywords: Furfural, Palm tree midribs, Hydrochloric acid, Hydrolysis.

1. Introduction

The industrial applications of furfural and its derivatives have gained more importance as strategic commodities^[1] since it is a feedstock for many chemical products. Furfuryl alcohol that is derived by furfural hydrogenation can be used in the production of furan resin and cement materials, which are characterized by their high structural resistances, as well as heat transfer properties^[2-4]. Furfural can be used to produce biofuels and value-added chemicals^[5-6]. Also, it is mainly used as an effective solvent that selectively dissolves and separates aromatics and olefins in oil refineries^[1]. Furfural has other important applications in the production of the key product tetrahydrofuran

(THF) and can be used also as a fungicide and herbicide^[7].

The main source of furfural production is the hydrolysis in acidic media of the lignocelluloses biomass and hemicelluloses with high pentosan content available in some agriculture residues, such as palm tree midribs^[8], olive trees^[9], sorghum straw^[10] and timber^[11]. It can be produced also from food processing plant waste, such as sugar cane bagasse^[12], olive stones^[13], corncobs^[14] and rice hulls^[1].

Mineral acids were used as a catalyst for hydrolyzing biomass waste materials to produce furfural. Among these acids are

hydrochloric acid (HCl) ^[15], nitric acid (HNO₃) ^[16], sulfuric acid (H₂SO₄) ^[17], and phosphoric acid (H₃PO₄) ^[18].

The higher the hydrolysis pressures (10-25 bar) and temperatures (220-240°C) the higher furfural yields ^[19] and shorter reaction times ^[20-21] are. Alternatively, furfural can be formed from hemi-cellulosic materials using the acidic ionic liquid (ILs) characterized by their low vapor pressures and flammability, low temperature sensitivity and high solubility with 60-70% furfural yield ^[22]. The catalytic coproduction of furfural and the important byproduct 5 hydroxymethyl furfural, 5HMF, has been investigated to improve the economic feasibility of the production process ^[23-27]. Metal oxides as solid acid catalysts and sulfonated biomass carbon materials have increasingly attracted researchers' attention, due to their strong acidity, high active surface area and low temperature sensitivity ^[28]. Furthermore, furfural was produced using alginic acid derived from macroalgae over Amberlyst-15 solid acid catalyst ^[29]. However, ILs and solid catalysts are currently expensive and difficult to synthesize. More extensive research is required to improve their performance. Additionally, the economic feasibility of their industrial synthesis process must be considered.

Hydrolysis of pentosan to pentose takes place in acidic solutions as catalysts to accelerate the dissociation of pentosan molecules, which is dehydrated in a subsequent step to furfural. The actual furfural yield that can be obtained is 50-65%, which is dependent on the hydrolysis reaction temperature and acid concentration ^[21], while the maximum reported furfural theoretical yield is 72.7 % ^[7].

Due to the complexity of the liquid phase hydrolysis reactions of solid phase lignocelluloses feedstocks ^[30], many

investigators proposed reaction steps and used simplified empirical expressions to model the kinetics parameters for each reaction step ^[31]. Both dilute and concentrated acid hydrolysis can be used to hydrolyze hemicellulose cellulose fractions ^[9].

Agriculture wastes are abundantly available with low cost and suitable to produce value-added products. They must be disposed properly. All these factors increase the opportunity of lignocellulosic materials to provide an alternative energy source ^[9,30]. Saudi Arabia has tremendous quantities of date palm trees. Therefore, it would be more attractive to investigate alternatives that utilize these abundant date palms to produce value-added products, such as furfural and its derivatives.

Recently, we have studied the kinetics and yields of furfural production by hydrolyzing midribs using sulfuric acid ^[8]. Hydrolysis of lignocellulosic agricultural wastes using hydrochloric acid resulted in a higher yield of furfural as compared to sulfuric acid at the same temperature and acid concentration conditions ^[32]. Hydrochloric acid is capable of hydrolyzing and breaking the hemi cellulosic biomass materials more easily and efficiently than sulfuric acid ^[33]. Therefore, the purpose of the present work is to study the formation of furfural through the hydrolysis process of the local palm tree midribs, using hydrochloric acid instead of sulfuric acid, which was used in previous work. The key operating parameters of the process, namely reaction temperature, liquid to solid ratio, acid concentration and reaction time were investigated to determine the optimum conditions based on the maximum furfural yield. The obtained experimental data were fit in the previously proposed kinetic model of the hydrolysis reaction to evaluate the derived model.

2. Experimental Procedures

2.1 Raw Materials Preparation and Characterization

Sukkaria palm tree was selected, and midrib samples were collected from agricultural areas in Saudi Arabia. Samples were prepared for analysis and hydrolysis reaction as reported in Bamufleh *et al.* [8]. In this previous study midrib samples were characterized for pentosan content using Association of Official Analytical Chemists AOAC-36D.

2.2 Hydrolysis Reaction

1500 ml and maximum 10 bars pressure Parr batch glass reactor (5112 model) jacketed and stirred, manufactured by Hastelloy B2 and stainless steel, was used in the hydrolysis reaction. The required acid volume of a given concentration and required raw material with given liquid to solid ratio (LSR) were placed in the reactor. Reaction time was recorded and samples were collected for chemical analysis at specific time intervals. Three values of acid concentrations of 5, 10, and 15 wt %, LSR of 25, 50, and 100 ml/g, and reaction temperatures of 100, 120, and 160°C were experimentally carried out. Detailed reaction procedures were reported in the reference [8].

2.3 Product Analysis

Most articles were likely to have only two levels of headings. 20 µl of periodically collected samples, filtered and diluted with water (1:100 v/v) were injected via a liquid sampling valve for analysis into a Shimadzu HPLC unit. The column 4.6 mm i.d. x 50 mm Shim-Pack XR-ODS was used to investigate the hydrolysis reaction products. A carrier liquid with a composition of 84% of 0.01 N H₂SO₄ and 16% of acetonitrile was utilized. Flow rate of 0.5 ml/min at 4.9 Mpa was regulated during the analysis. The following equation was used to calculate furfural yield:

$$Yield = Y_{act}/Y_{th} \times 100 \quad (1)$$

Where Y_{act} is the experimental yield (gm) and Y_{th} is the theoretical yield (gm) when reaction of pentosan to furfural is achieved with 100% conversion. These two yields were calculated as follows:

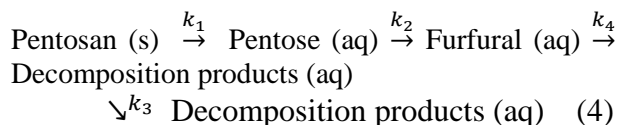
$$Y_{act} = C \times V \quad (2)$$

$$Y_{th} = (Mwt_F/Mwt_P) \times (\%P/100) \times W \quad (3)$$

Where C is the experimental furfural concentration (gm/m³), V is the mixture volume (m³), W is the midrib sample mass (gm), % P is the pentosan wt% available in the midrib, Mwt_F and Mwt_P are the furfural and pentosan molecular weights, respectively.

3. Kinetics Model

Based on reported literature complexity of the lignocellulosic materials, hydrolysis reactions kinetics were simplified by proposing pseudo-homogenous first order irreversible reactions [9,15,30]. This approach was applied with the assumption that a fraction of pentosan in the raw material was easy and fast to hydrolyze, while the remaining pentosan fraction was difficult and slow to hydrolyze. Accordingly, the parameter α was introduced in the kinetic model as the fast-decomposed mass fraction of pentosan [13,31]. The first reaction started with the formation of pentose from pentosan, then progressively continued to other undesired decomposition products, as shown below [9,15,30,31].



Where k_1 , k_2 , k_3 and k_4 are the rate constants in (min⁻¹). The previously derived kinetic model of the differential equations describing the above reactions system was as follows [8]:

$$C_P = \alpha C_{P0} e^{-k_1 t} \quad (5)$$

$$C_S = \frac{\alpha k_1 C_{P0}}{(k_2 + k_3) - k_1} (e^{-k_1 t} - e^{-(k_2 + k_3)t}) \quad (6)$$

$$C_F = \frac{\alpha k_1 k_2 C_{P0}}{(k_2 + k_3) - k_1} \left(\frac{e^{-k_1 t} - e^{-k_4 t}}{k_4 - k_1} - \frac{e^{-(k_2 + k_3)t} - e^{-k_4 t}}{k_4 - (k_2 + k_3)} \right) \quad (7)$$

Where C_P is the concentration of pentosane, C_{P0} is the initial concentration of pentosan in the raw material, C_S is the concentration of pontose, C_F is the furfural concentration (mol/liter) and t is hydrolysis time (min).

4. Experimental Data Analysis

4.1 Characterization of Midribs

Midribs' pentosan content was determined in the previous study by Bamufleh *et al.* [8] as 14.52 wt% providing a reasonable amount of pentosan in comparison to that available in other reported lignocellulosic materials employed as raw materials for furfural production.

4.2 Furfural Production

Various conditions of acid concentration, reaction temperature and LSR of the hydrolysis reaction were selected to study their parametric effects on furfural concentration and yield. The experimental results were analyzed and discussed in the following subsections.

4.3 Acid Concentration Parameter

Hydrolysis reactions were carried out at acid concentrations of 5, 10 and 15 wt%, at a LSR of 100 and a temperature of 120°C. Furfural concentrations at various elapsed times were plotted, as shown in (Fig. 1). As shown in this figure, higher furfural yields were obtained at faster times with higher acid concentrations. Figure 1 shows clearly that for 15% acid concentration maximum furfural concentration is achieved faster at 755 gm/m³ in 10 mins compared to 5% and 10% with maximum furfural concentrations at 640 gm/m³ in 210 min and 700 gm/m³ in 60 min respectively. Furfural concentration started to decrease after reaching its maximum value, the

point beyond which the rate of furfural production was expected to be less than the rate of furfural decomposition. The first point with 10 wt% acid didn't fall in the same trend with the rest of the points and it occurs in the early stage of the main reactions toward furfural production. It is apparently due to other rapid side reaction(s) that proceed to produce furfural and other side products.

4.4 Reaction Temperature Parameter

Hydrolysis reactions at temperatures of 100, 120 and 160 °C, at 10% acid concentration and 50 ml/g LSR were shown in Fig. 2. Data in this figure indicated that the maximum concentration of 1266 gm/m³ (a maximum furfural yield of 60%) was obtained at 120°C after 60 minutes of hydrolysis, after which it decreased rapidly, because the furfural loss rate was much faster than the formation rate. Increasing the reaction temperature from 100°C to 120°C increased the obtained furfural concentrations, indicating that higher furfural concentration and yield were favored by higher temperatures within this range. On the other hand, increasing the reaction temperature to 160°C, a maximum furfural concentration value of 400 gm/m³ (a maximum furfural yield of 19%) was obtained after 5 minutes hydrolysis time compared to 1266 gm/m³ (a maximum furfural yield of 60%) after 60 minutes hydrolysis time at 120°C. This clearly indicated that furfural competing reactions were more pronounced at 160°C. This might also be attributed to the effect of the higher temperature, which reduced hydrogen ion concentration, thus lowering the water dielectric constant and consequently making an insignificant impact of the acid concentration on the furfural formation kinetics data.

4.5 LSR Parameter

The effect of LSR at values of 25, 50 and 100 at 120 °C and 10 wt% acid concentration on

the measured furfural concentrations during the hydrolysis reaction was depicted in Fig. 3. Higher LSR values, which implied a lower limiting reactant, decreased the obtained furfural concentration with time. The maximum furfural concentration for all LSRs was obtained at 60 minutes. Moreover, the maximum achievable furfural concentration was decreased from 2097 gm/m³ (50% furfural yield) to 1266 gm/m³ (60% furfural yield) and 700 gm/m³ (66% furfural yield) at LSR of 25, 50 and 100 respectively since only LSR changed, while the kinetic parameters (k_1 - k_4) remained unchanged at the same reaction temperature and acid concentration.

4.6 Side Products Formation

The cost of the furfural production process was considerably influenced by the maximum achievable furfural yield with the accompanied side products. Moreover, the formation of side products required a separation process for a treatment purpose to achieve the desired product specifications. Table 1 summarizes the reaction time required to produce the maximum furfural yield and concentration obtained at different operating conditions, along with the corresponding concentration of furfuryl alcohol, 5 hydroxymethyl furfural (5HMF), 5 methyl furfural (5MF) and 2 acetyl furan side products. Table 1 shows that the highest achieved furfural yield was 72%, which was produced in 20 minutes at an acid concentration of 15 wt%, LSR of 100 and 120°C. Figure 4 shows furfural yield at this operating condition measured at different reaction times.

Side products were considered as valuable products, due to their industrial applications. For example, furfuryl alcohol was used for the production of tetrahydrofurfuryl alcohol, fibers, rubbers and for enforcing ceramic resins [34]. Also, 5

Hydroxymethyl furfural (5HMF) was used for plastics productions [35]. However, it should be noted that the side product content of 5 methyl furfural (5MF) should be less than 1% in furfural product specification [7]. Side products concentrations with time at the optimum operating condition are shown in Fig. 5.

4.7 Kinetics Parameters

Derived nonlinear model presented in Eq. 7 was used to fit the collected kinetic data of furfural yield from palm tree midribs at different experimental conditions. Polymath 5.1 software was used in the nonlinear regression analysis. Table 2 presents the optimum regression analysis values of k_1 to k_4 , and α for all acid hydrolysis reactions at different operating conditions.

Table 2 shows that all k values increased with reaction temperature and acid concentration. Regressed α values, (0.60-0.94), fell within the same reported ranges of (0.84-0.86) and (0.55-1) reported by Eken-Saracoglu *et al.* [20] and Aguilar *et al.* [31] respectively. Regression of the experimental data at different acid concentrations and reaction temperatures using Eq. 7 resulted in satisfactory fit, as evidenced by $R^2 \geq 0.9$ as shown in Fig. 1-3. The higher value of k_1 compared to k_2 - k_4 values indicated a faster rate of pentosan to pentose reaction step, and the reaction steps that followed controlled the final furfural production.

The modified Arrhenius equation was used to estimate the rate constant for a given reaction temperature and acid concentration. It was expressed as follows [9,13,30,31,36].

$$k_i = aC^b \exp(-E/RT) \quad (8)$$

Where a and b are regression parameters, C is the acid concentration in wt%, E is the activation energy in kJ/mol, R is the universal gas constant in kJ/(mol K), and T is the reaction temperature in K.

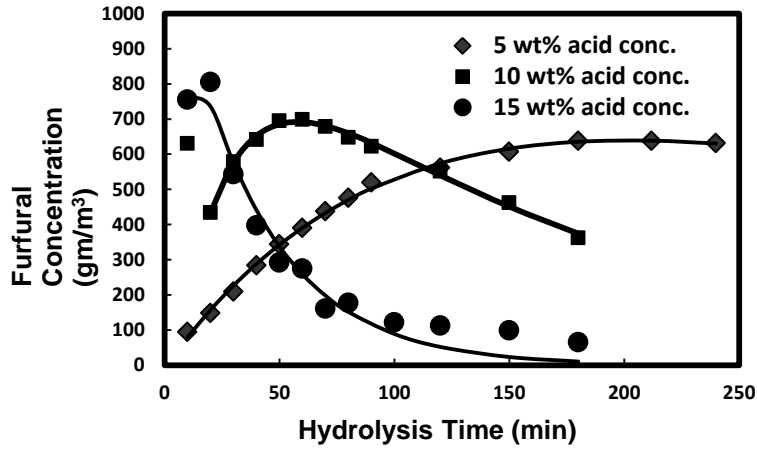


Fig. 1. Date Tree midribs, 0.25-0.5mm, Acid = HCl, 5-15wt%, LSR =100, Hydrolysis Temp = 120°C.

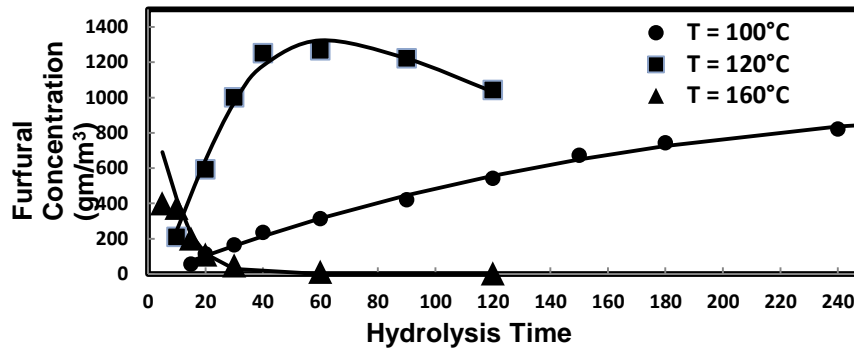


Fig. 2. Date Tree midribs, 0.25-0.5mm, Acid = HCl, 10wt%, 250ml, LSR =50 Hydrolysis Temp = 100-160°C.

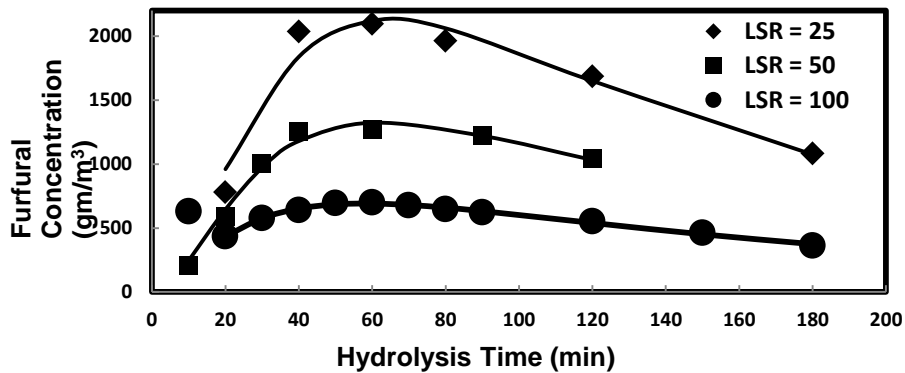


Fig. 3. Date Tree midribs, 0.25-0.5 mm, Acid = HCl, 10wt%, LSR =25-100, Hydrolysis Temp = 120°C.

Table 1. Summary of different reaction conditions with corresponding maximum furfural yields and concentrations using hydrochloric acid.

Acid Conc. (wt%)	LSR (ml/g)	Temp, (°C)	Time (min)	Max Yield (%)	Max Furfural Concentration (ppm)	Concentration of side products corresponding to maximum furfural concentration (ppm)			
						5HMF	5MF	Furfural Alcohol	2 Acetyl Furan
5	100	120	210	60	640	15	2	7	10
5	100	140	30	41	435	15	2	9	0
10	25	120	60	50	2097	70	14	21	7
10	50	100	330	44	924	16	2	12	4
10	50	120	60	60	1266	37	5	12	3
10	50	160	5	19	400	71	3	9	4
10	100	120	60	66	700	18	2	8	2
15	25	120	5	25	1063	72	1	332	145
15	100	120	10	72	755	15	2	45	2

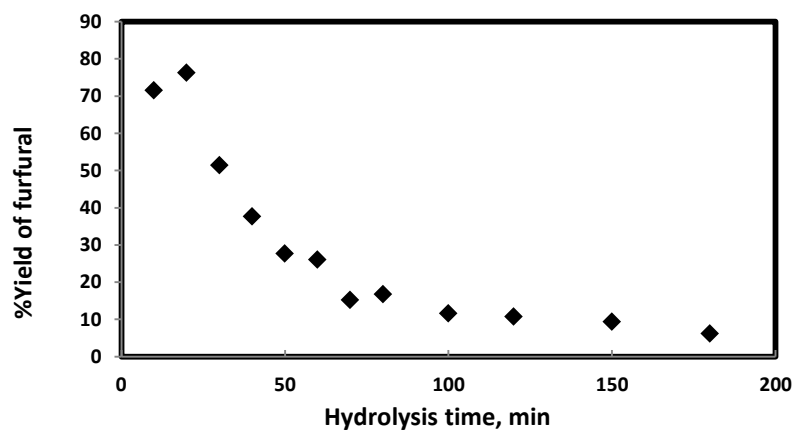
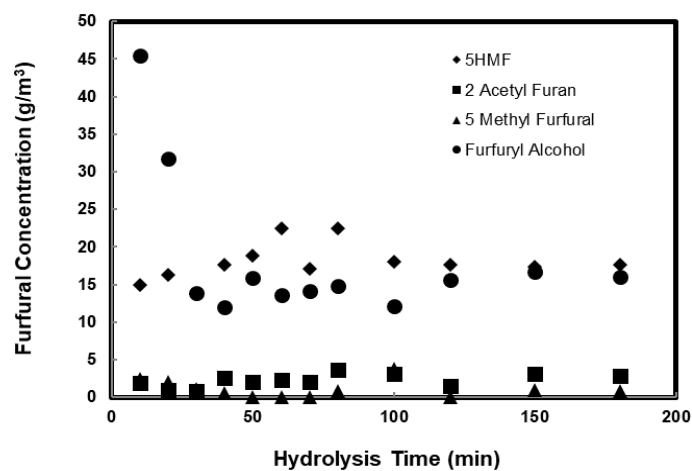
**Fig. 4.** Furfural yield using 0.25-0.5 mm date tree midribs, 15 wt% HCl, LSR=100, Temp=120°C.**Fig. 5.** Side products distribution using 0.25-0.5 mm date tree midribs, 15 wt% HCl, LSR=100, Temp=120°C.

Table 2. Regression values of k₁- k₄ and α at different acid concentrations and temperatures.

HCl % wt	T °C	α.g/g	k ₁ (min) ⁻¹	k ₂ (min) ⁻¹	k ₃ (min) ⁻¹	k ₄ (min) ⁻¹	R ²
5	120	0.600	0.111	0.015	0.001	0.001	0.99
5	140	0.658	0.221	0.152	0.069	0.009	0.97
10	100	0.741	0.326	0.004	0.0001	0.003	0.99
10	120	0.843	0.390	0.080	0.037	0.012	0.96
10	160	0.917	0.447	0.410	0.269	0.136	0.99
15	120	0.940	0.996	0.136	0.065	0.031	0.99

It is advantageous to validate and compare the model prediction of k values with reported models in the literature that used closer acid concentrations, temperature ranges and different agricultural wastes. Herrera and his workers^[30] proposed the kinetic parameters k₁ and k₂ for the hydrolysis of sorghum, using 2-6 wt% HCl at 122°C as follows:

$$k_1 = 0.00261C_a^{1.41} \quad (9)$$

$$k_2 = 0.0009C_a^{0.93} \quad (10)$$

Where C_a is the wt% acid concentration. Eq. 9 and 10 underpredict the value of k₁ (0.016 compared to regressed value of 0.111) and k₂ (0.004 compared to regressed value of 0.015) at 5wt% HCl and 120°C. This might be due to different raw materials used in both cases and thus different side products.

Since there was no correlation available in literature that was suitable for predicting k values at acid concentrations higher than 6 wt%, modified Arrhenius correlations to predict k₁-k₄, at acid concentrations in the range of 5 to 15 wt%, could be developed by nonlinear regression analysis of k values at different conditions, using Polymath 5.1 software. The resulted correlations showed satisfactory predictions with the correlation coefficients R² ≥ 0.96 as presented in Table 3.

Table 3. Modified Arrhenius correlations for k₁-k₄.

Correlations	R ²
$k_1 = 0.0172 \times C^{2.152} e^{(-0.5874 \times 10^4)/RT} \quad (11)$	0.96
$k_2 = 1.01 \times 10^5 C^{0.749} e^{(-5.093 \times 10^4)/RT} \quad (12)$	0.96
$k_3 = 1.008 \times 10^4 C^{1.028} e^{(-5.49 \times 10^4)/RT} \quad (13)$	0.96
$k_4 = 9.991 \times 10^5 C^{1.702} e^{(-6.295 \times 10^4)/RT} \quad (14)$	0.97

Where C is HCl concentration in wt %, T is the hydrolysis reaction temperature in Kelvin and R is the universal gas constant in kJ/mol K. It was observed from Equation (11) that the pentosan hydrolysis to pentose reaction (k₁) had the lowest activation energy which indicated that this reaction was the fastest step relative to the other reaction steps and thus highest k₁ values. The activation energies for the other reactions were higher than the first reaction, due to lower k₂-k₄ values and slower reaction rates accordingly.

Natural log of k₁, k₂, k₃, and k₄ versus the reciprocal of the absolute reaction temperature (1/T) were plotted as shown in Fig. 6 at 10 wt % acid concentration and LSR of 50. Modified Arrhenius equation was satisfied, since kinetic data were fit in almost straight lines for all k values with their corresponding reaction temperatures. The low R² value associated with fitting k₂ and k₃ are probably due to other side reactions beside k₂ and k₃ corresponding reaction steps which were not considered in the proposed full reaction configuration.

Romero and his workers^[9] proposed a correlation that predicted insoluble fraction, 100(1-α) g/100 g raw material, linearly with temperature and nonlinearly with acid concentration. With an attempt to correlate α regression output of this work with the corresponding temperatures and acid concentrations using similar proposed correlation, the following correlation was obtained:

$$\beta = (842.524 - 4.172T)C^{-1.299} \quad (15)$$

Where $\beta = 100(1 - \alpha) \quad (16)$

The regression output for fitting the experimental data with (5-15 wt%) HCl and (100-160°C) to Eq. 15 yields $R^2 = 0.95$. The regression parameters of Eq. 15 were quite different from Remero's correlation, which might be attributed to the difference in the raw material composition used in both cases. However, this correlation, beside Eq. (11-14), could be used in the hydrolysis of midribs from date palm tree reactor design.

5. Comparison with Sulfuric Acid Hydrolysis

Hydrolysis data of midribs with hydrochloric acid was compared with sulfuric acid hydrolysis data in our previous work [8]. The optimum condition obtained with HCl hydrolysis gave an excellent furfural yield (72%), which was close to the theoretical yield (72.7%) at 15 wt% HCl, 120°C and 100 LSR compared to H₂SO₄ hydrolysis, which gave a furfural yield of (53%) at 15wt% and 120°C and 50 LSR. In addition to the higher furfural yield obtained with HCl hydrolysis, a lower initial concentration was required as compared to hydrolysis with H₂SO₄ (LSR of 100 with HCl compared to 50 with H₂SO₄).

Furthermore, faster reactions and higher furfural yields were observed with HCl acid as compared to H₂SO₄ at the same conditions. For example, at 5 wt% HCl and 120°C, maximum furfural yield of 60% was achieved at 210 minutes, while it took 240 minutes to reach a maximum yield of 22% at the same conditions with sulfuric acid hydrolysis. Similarly, at 10 wt% HCl and 120°C the maximum furfural yield of 60% was achieved at 60 minutes as compared to 180 minutes to reach a maximum yield of 25% at the same conditions. Increasing HCl concentration from 5 to 15 wt% expedited the reaction significantly, while in the case of H₂SO₄ the concentration increase did not affect the

hydrolysis time, until 15% was used. On the other hand, increasing the temperature with HCl hydrolysis caused faster reactions and higher furfural yields than H₂SO₄ hydrolysis. This could be attributed to lower activation energy values for furfural formation reactions steps with HCl as compared to the corresponding ones using H₂SO₄ hydrolysis as shown in Table 4. The activation energy for the reaction steps k_1 through k_4 are estimated from the natural exponential term ($e^{-E/RT}$) in the Equations 11 through 14 respectively.

So, hydrolysis of palm tree midrib in hydrochloric acid produced more furfural as compared to sulfuric acid, and hence it was recommended to consider the application of hydrochloric acid with higher concentrations as a catalyst in the industrial hydrolysis process of palm tree midribs to achieve higher yields and produce more desirable furfural products.

6. Conclusions

Furfural could be produced by HCl hydrolysis of pentosane that exists in palm tree midribs as an agricultural waste with an achievement of 72% maximum furfural yield. This actual yield was close to the theoretical yield (72.7 %) at reaction conditions of temperature as 120°C, acid concentration as 15 wt% and LSR as 100. Experimental data showed that furfural yield is function of reaction temperature, acid concentration and LSR. The kinetic model of the furfural production reactions that was derived in a previous work was used in the regression of the experimental furfural concentrations obtained in this work with acceptable predictions and regression coefficients of $R^2 \geq 0.96$. Furthermore, the rate constants of the reaction steps as well as the hydrolyzed fraction were correlated using modified Arrhenius model at the reaction conditions. The derived correlations could provide a

preliminary design basis for the optimization of the hydrolysis reactor configuration. Finally, comparison with the sulfuric acid hydrolysis showed that using hydrochloric

acid higher furfural yields were achieved and lower reaction times were required due to lower activation energy of the involved step.

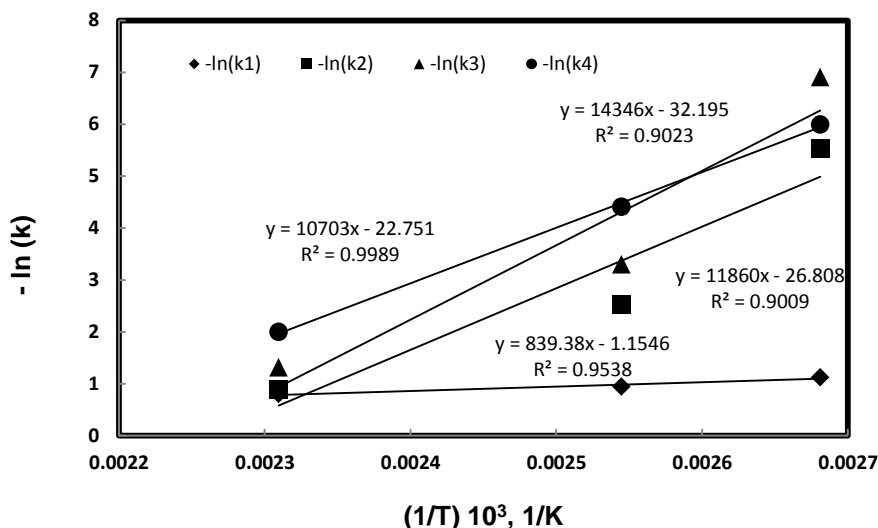


Fig. 6. Fitting k_1 - k_4 values with $(1/T)$ at 10 wt% HCl.

Table 4. Activation energy comparison for the reactions steps with HCl and H₂SO₄.

Reaction Step	Activation Energy, kJ/mol	
	With HCl This work	With H ₂ SO ₄ (Bamufleh <i>et al.</i>) [8]
k_1	5.87	15.99
k_2	50.93	94.97
k_3	54.90	127.6
k_4	62.95	59.54

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التحلل المائي لسعف شجرة النخيل في حمض الهيدروكلوريك لإنتاج مادة الفورفورال

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المستخلص. تم جمع عينات من مخلفات سعف النخيل من نوع السكري كمصدر للبينتوزان من مختلف المناطق الزراعية بالمملكة العربية السعودية، والقيام بتحليلها باستخدام حمض الهيدروكلوريك (HCl) لإنتاج مادة الفورفورال في درجات حرارة، ونسب حجم المادة السائلة إلى وزن العينة الصلبة (LSR) وتراكيز حمض مختلفة. أُنتجت مادة الفورفورال كحد أقصى بتركيز ٧٥٥ جم/م^٣ (٧٢٪ من الناتج الأقصى للفورفورال)، الذي كان على مقربة من العائد النظري عند ١٥٪ بالوزن من حمض الهيدروكلوريك و ١٠٠ مل/جرام LSR عند ١٢٠ درجة مئوية. في دراسة سابقة تم اقتراح وتطوير النموذج الرياضي للتحلل الجزئي للبينتوزان لإنتاج الفورفورال. أوضحت نمذجة النتائج التجريبية باستخدام برنامج Ploymath أنها متطابقة بنجاح وأعطت دقة تنبؤ مقبولة ومعاملات تحديد بلغت $R^2 \geq 0.96$. علاوة على ذلك، تم اقتراح نموذج لثابت تفاعل كل خطوة باستخدام نموذج Arrhenius المعدل بدقة مقبولة ومعاملات تحديد بلغت $R^2 \geq 0.96$. كما أظهرت النتائج التجريبية أن التحلل المائي باستخدام حمض الهيدروكلوريك يمكن أن ينتج كميات فورفورال أعلى في أوقات أقل بالمقارنة مع تحلل حمض الكبريتيك، وذلك بسبب انخفاض طاقة التنشيط للخطوة المعنية.

كلمات مفتاحية: فورفورال، سعف النخيل، حمض الهيدروكلوريك، التحلل المائي.

