Optimization of Glucose Production from Waste Office Paper by Sulfuric Acid Hydrolysis Using Response Surface Methodology (RSM)

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Abstract--The depletion of conventional energy resources has increased global interest in renewable and sustainable biofuels. Wastepaper is a major biodegradable component of municipal solid waste and a promising feedstock for bioethanol production because of its high cellulose content. This study aimed to optimize glucose production from waste office paper through concentrated sulfuric acid hydrolysis using Response Surface Methodology (RSM) based on a Central Composite Design (CCD). Waste office paper was pretreated and hydrolyzed to evaluate the effects of acid concentration, acid loading, and reaction temperature, while the hydrolysis time was fixed at 3 h. The experimental results were used to develop a quadratic regression model, which adequately described the relationship between the process variables and glucose yield. The optimized hydrolysis conditions resulted in improved glucose production from wastepaper, demonstrating the feasibility of concentrated acid hydrolysis as an effective pretreatment method. The highest sugar concentration (16.00 g/L) was obtained at 30% sulfuric acid concentration, 175 mL acid loading, and 100°C after 3 h of hydrolysis. The developed model showed statistically significant results ($p<0.0001$) with a high coefficient of determination ($R^2 = 0.987$) and adjusted R^2 of 0.969, indicating good agreement between the predicted and experimental values. The glucose-rich hydrolysate can subsequently be fermented using *Saccharomyces cerevisiae* for bioethanol production. These findings indicate that waste paper is a promising renewable resource for sustainable biofuel production while contributing to waste minimization and environmental protection. Furthermore, the properties of the produced glucose were found to agree with Sudan's standard specification for glucose.

The novelty of this study lies in systematically optimizing concentrated sulfuric acid hydrolysis of waste office paper using RSM to maximize glucose production, thereby improving the potential ethanol yield during subsequent fermentation.

Keywords: Bioethanol, Cellulosic feedstock, Fermentation, Glucose yield, Pretreatment, Response Surface Methodology (RSM).

المستخلص--أدى استنزاف مصادر الطاقة التقليدية إلى تزايد الاهتمام العالمي بمصادر الطاقة المتجددة والمستدامة والوقود الحيوي. وتمثل نفايات الورق مكونًا رئيسيًا من المكونات القابلة للتحلل في النفايات الصلبة البلدية، كما تُعد مادة أولية واعدة لإنتاج الإيثانول الحيوي نظرًا لارتفاع نسبة السليلوز بها. هدفت هذه الدراسة إلى تحسين إنتاج الجلوكوز من نفايات ورق المكاتب بالاعتماد على التصميم المركب (RSM) باستخدام التحلل المائي بحمض الكبريتيك المركز، وتطبيق منهجية سطح الاستجابة. وقد خضعت نفايات ورق المكاتب للمعالجة المسبقة ثم للتحلل المائي بهدف تقييم تأثير تركيز الحمض، والحرارة، وحجم تحميل الحمض، ودرجة حرارة التفاعل، مع تثبيت زمن التحلل المائي عند 3 ساعات. وأُستخدمت النتائج التجريبية لتطوير نموذج انحدار تربيعي لوصف العلاقة بين متغيرات العملية وإنتاج الجلوكوز. وأظهرت النتائج أن أعلى تركيز للجلوكوز بلغ 16.00 g/L عند استخدام تركيز 30% من حمض الكبريتيك، وحجم تحميل للحمض قدره 175 مل، ودرجة حرارة 100 درجة مئوية بعد 3 ساعات من التحلل المائي. وأظهر النموذج المطور دلالة إحصائية عالية ($p<0.0001$)، مما يشير إلى توافق جيد بين (Adjusted $R^2 = 0.969$) ومعامل تحديد معدل ($R^2 = 0.987$) مع معامل تحديد مرتفع للقيم التجريبية والمتنبأ بها. ويمكن استخدام المحلول المائي الغني بالجلوكوز الناتج لاحقًا في عملية التخمير باستخدام *Saccharomyces cerevisiae* لإنتاج الإيثانول الحيوي. وتؤكد هذه النتائج أن نفايات الورق تمثل موردًا متجددًا واعدًا لإنتاج الوقود الحيوي المستدام، مع إمكانية الإسهام في الحد من تراكم النفايات وتعزيز حماية البيئة. كما أظهرت الخصائص الفيزيائية والكيميائية للجلوكوز المنتج توافقًا مع المواصفات القياسية المعتمدة للجلوكوز في السودان. تتمثل جدة هذه الدراسة في التحسين المنهجي لعملية التحلل المائي لورق المكاتب المستعمل باستخدام حمض الكبريتيك المركز ومنهجية سطح الاستجابة، بهدف تعظيم إنتاج الجلوكوز، بما يعزز إمكانية الحصول على مردود أعلى من الإيثانول في مراحل التخمير اللاحقة.

I. Introduction

The increasing demand for sustainable energy and the urgent need to reduce greenhouse gas emissions have accelerated research on second-generation bioethanol produced from lignocellulosic wastes. Among the available feedstocks, waste paper has attracted considerable attention because of its high cellulose content, low lignin concentration, wide availability, and minimal competition with food resources. Converting wastepaper into fermentable sugars and subsequently into bioethanol represents an environmentally friendly strategy that simultaneously supports renewable energy production and effective municipal solid waste management [1]

In recent years, efforts have increased to use renewable municipal solid waste, including wastepaper, more efficiently [2]. Wastepaper is usually recycled into low-grade paper products, such as newspaper, paper towels, toilet paper, and cardboard [3]. The shortening of cellulose fibers with repeated reuse tends to decrease the quality of the paper products [4].

Because of this phenomenon, the upper limit of wastepaper to paper recycling is said to be 65%. This means that the rest of the paper must be disposed of by incineration or landfill. However, because of environmental restrictions, lack of suitable new sites, and concerns about the greenhouse effect, incineration or disposal by landfill may become practically impossible in the coming years. Finding new uses for recycled paper is a pressing demand [5].

Among paper, the most limited in its use is computer printouts, which are superabundant in the business districts of civilized countries [3]. Generally, waste computer printouts are shredded before disposal to keep office matters confidential; this practice has the unintended consequence of shortening the constituent cellulose fibers beyond utilization. Therefore, incineration is the usual fate of such materials. However, recent studies have explored other industrial routes. A better approach to utilizing wastepaper is its conversion into bioethanol [6].

Provided that the wastepaper contains a high carbohydrate content, it could be converted into bioethanol. Cellulose, a major building block of wastepaper, can be converted to reducing sugars including glucose; one use of glucose is fermentation into ethanol. Also, paper sludge after deinking has been traditionally disposed of by burning or landfilling, but could be used as an organic amendment in agricultural soils and filler for erosion control [7].

Basically, the recycling of wastepaper can be done by reusing wastepaper after pulping it by a machine called a pulper, followed by removal of printing ink, a treatment specifically called 'deinking ', to break down holocellulose for conversion of wastepaper to glucose; the cellulose and hemicellulose must be broken down to corresponding monomers (sugars). The hydrolysis step may be carried out either enzymatically or by acid treatment. The hydrolysis is conducted under mild conditions but requires pretreatment of the raw material to improve the process and a longer retention time [8].

Moreover, the production and recovery of enzymes may affect this option from an economic point of view; Acid hydrolysis may be carried out either at diluted or concentrated acid conditions. Diluted acid hydrolysis attacks polysaccharides, especially those from the hemicellulose fraction, which is easier to hydrolyze than cellulose. In addition, no acid recovery steps are required, and acid losses are not important [9]. On the negative side, the yield of glucose from cellulose is low. Concentrated acid hydrolysis enables high glucose yield, thereby improving the potential ethanol yield during subsequent fermentation, although acid recovery is required as well as more resistant reactors. Acid hydrolysis needs the optimization of process parameters, including the concentration of sulfuric acid, reaction time, reaction temperature, and substrate loading for efficient hydrolysis [10].

Sulfuric acid is the most used acid in lignocellulosic residue hydrolysis, although other mineral acids like hydrochloric acid, nitric acid, or phosphoric acid have also been assayed. Acid hydrolysis residue includes inorganic compounds such as ash and lignin. This residue is used primarily as an organic amendment rather than as fertilizer, because of its mineral nutrient content. The inorganic Compounds will affect soil improvement [11].

Optimization of hydrolysis conditions involves varying one factor at a time and keeping other variables constant. On the other hand, the response surface method can effectively use variables simultaneously and determine the optimum conditions required [12]. Response surface methodology is a statistical technique used to model and optimize multiple variables, and it can be used to determine the optimum conditions by combining experimental design with interpolation of first- or second-order polynomial equations in a sequential testing procedure. Central composite design and response surface methodology (RSM) were used to design a systematic experimental method, and it can map a response surface over a particular region of interest; there are no reports on combined concentrated acid hydrolysis and RSM of wastepaper [6]. Recent studies have confirmed the potential of wastepaper as an effective lignocellulosic feedstock for biofuel production due to its high cellulose content and availability [13] investigated the biochemical conversion of wastepaper slurries into bioethanol and reported that cellulose fibers from wastepaper could be hydrolyzed into glucose and subsequently fermented into ethanol [14].

The fermentation process is carried out using *Saccharomyces cerevisiae* [15]. The hydrolysate is inoculated with 1% (w/v) *S. cerevisiae* and incubated at 36–37 °C under controlled acidic conditions (pH 4.0–4.5) for 72 h. During fermentation, the fermentable sugars are converted into bioethanol and carbon dioxide. Following fermentation, the ethanol produced is recovered from the fermented broth by distillation [16].

A. Research Gap

Although several studies have investigated the conversion of lignocellulosic materials into fermentable sugars, limited attention has been given to the optimization of acid hydrolysis of waste paper using Response Surface Methodology (RSM) [17]. Recent studies have further demonstrated the potential of wastepaper as a lignocellulosic feedstock for biofuel production [13], investigated the biochemical conversion of waste paper slurries into bioethanol, and reported that cellulose fibers from waste paper could be hydrolyzed into glucose and subsequently fermented into ethanol.

Therefore, this study aimed to investigate and optimize glucose production from waste office paper through sulfuric acid hydrolysis using Response Surface Methodology (RSM) and Central Composite Design (CCD). The effects of acid concentration, sulfuric acid loading, and reaction temperature on glucose conversion were evaluated to identify the optimum hydrolysis conditions.

Although waste office paper has been studied for bioethanol production, systematically optimizing its concentrated sulfuric acid hydrolysis remains necessary. Specifically, evaluating the combined effects of acid concentration, acid loading, and reaction temperature is essential to maximize sugar recovery while minimizing degradation.

B. Objectives and Novelty

This study aims to investigate and optimize glucose production from waste office paper via sulfuric acid hydrolysis. The novelty of this work lies in applying Response Surface Methodology (RSM) in conjunction with Central Composite Design (CCD). Unlike conventional one-factor-at-a-time approaches, this research reveals the combined effects and interactions of acid concentration, sulfuric acid loading, and reaction temperature on glucose conversion, as shown below, to determine the optimum hydrolysis conditions.

II. Materials And Methods

A. Materials and Equipment

1) Reagents:

Waste office paper (A4 standard format), Sulfuric acid (H_2SO_4, 98% purity used to prepare a 15% to 30% V/V working solution), Distilled Water, Fehling's reagents (A and B), and Methylene Blue indicator.

2) Equipment and Apparatus:

Office paper shredder, plastic sieve, mechanical mixer/crusher, sealed round-bottom flask, thermostatic heating bath, standard glass funnel with filter paper for gravity filtration, burette, volumetric flasks, Erlenmeyer flasks, desiccators, and Oven.

3) Raw Material:

The wastepaper samples (A_4) printed exclusively with black ink were collected from various administrative offices at the Industrial Research and Consultancy Center (IRCC). The collected wastepaper was reduced to small pieces by using a standard office shredder. The moisture content of wastepaper (A_4) was calculated.

B. Pretreatment of Waste Office Paper

Pretreatment was conducted to understand the effects of disintegration time and paper fiber loosening, which makes it easier to separate the cellulose, hemicelluloses, and lignin components from the fibers. 1 kg of the paper was weighed and soaked in water at a ratio of 1:20 (w/v) individually [18].

Soaking was conducted at ambient temperature, about 25 C^O for 24 hours, followed by mechanical disintegration using a commercial hand blender for 5 min to disaggregate the fibers. The resulting slurry was then filtered through a fine-mesh sieve to drain the excess water, yielding a wet pulp cake ready for subsequent hydrolysis.

C. Concentrated Acid Hydrolysis of Waste Office Paper

1) Acid Hydrolysis:

Concentrated acid hydrolysis (TABLE I) was performed according to the method originally described as a first step (15 - 30)% (V/V) H_2SO_4 at 90 - 100°C and a reaction time of 3 hr. After the reaction was completed, solids were separated from the aqueous solution by filtration. The filtrate was analyzed for glucose [19].

2) Design of Experiment:

The effect of three independent variables (acid concentration, loading sulfuric acid, and reaction temperature) on the response (glucose conversion) was studied using a response surface methodology (RSM), which is a collection of mathematical and statistical techniques for designing experiments, analyzing the effects of variables, developing models, and optimizing the process variables for the optimum response. The experimental data were fitted using a low-order polynomial equation to evaluate the effect of each independent variable on the response, which was later analyzed to determine the optimum process conditions; second-order models were fitted, which are commonly used in RSM [20].

The CCD consisted of 8 factorial points, 4 axial points, and 3 center points, with an alpha (α) value of 1.0, resulting in a total of 15 experimental runs. A face-centered design was selected for the range of the experimental operating process.

TABLE I
EXPERIMENTAL DESIGN FACTORS AND CORRESPONDING VALUES

No. of experiment	Acid Concentration%	Acid volume(ml)	Reaction temperature(C)
1	15	150	95
2	15	175	90
3	15	175	100
4	15	200	95
5	22.5	150	90
6	22.5	150	100
7	22.5	175	95
8	22.5	175	95
9	22.5	175	95
10	22.5	200	90
11	22.5	200	100

12	30	150	95
13	30	175	90
14	30	175	100
15	30	200	95

The pretreated waste office paper pulp was subjected to concentrated sulfuric acid hydrolysis. For each experimental run, a pre-weighed 5 g sample of the pretreated pulp was mixed with sulfuric acid at the volume and concentration specified by the experimental design. Hydrolysis was carried out in a glass reaction vessel equipped with a thermometer to monitor the reaction temperature, using a heating mantle. Agitation was maintained throughout the process. The hydrolysis time was fixed at 3 h for all experimental runs and was not included as an optimization variable. After hydrolysis, the resulting hydrolysate was separated from the solid residue and neutralized using sodium hydroxide solution (NaOH) to pH 4.5 to 5.5 before glucose analysis and subsequent fermentation.

D. Determination of Glucose Concentration by Manual Titration

The glucose (reducing sugar) concentration in the hydrolysate was determined manually using the Lane–Eynon titration method with Fehling's reagents. Before titration, the acidic hydrolysate samples were neutralized to pH 7.0 using 2 N NaOH. Equal volumes (5 mL each) of Fehling's solution (Copper sulfate) and Fehling's solution B (alkaline sodium potassium tartrate) were transferred into an Erlenmeyer flask and brought to a gentle boil. The neutralized hydrolysate sample was then manually titrated from a burette into the boiling Fehling's mixture using 0.2% methylene blue as an indicator. The endpoint was identified by the disappearance of the blue color and the formation of a brick-red precipitate of cuprous oxide (Cu_2O).

1) Calculation of Glucose Concentration:

The glucose concentration was calculated based on the volume of the neutralized hydrolysate required to reach the titration endpoint, according to the following equation:

$$\text{Glucose Concentration}(g/L) = \frac{F*1000}{V} \qquad (1)$$

Where:
F = Fehling factor, representing the mass of glucose equivalent to the Fehling's reagent used in the titration (F = 0.5 g).
\V = volume (mL) of the neutralized hydrolysate consumed during titration.
1000 = conversion factor from g/mL to g/L.

III. Results and Discussion

A. Pretreatment of Waste Office Paper

The pretreatment process effectively disintegrated the waste office paper into a homogeneous pulp, facilitating the exposure of cellulose fibre for subsequent acid hydrolysis. Soaking and mechanical mixing promoted fibre swelling, improved cellulose accessibility, and enhanced sugar recovery from wastepaper.

B. Modelling and Optimization of Concentrated Acid Hydrolysis

The optimization of glucose production was carried out using Response Surface Methodology (RSM) based on a Central Composite Design (CCD). The effects of sulfuric acid concentration, acid loading, and reaction conditions on glucose conversion were evaluated using a second-order polynomial model.
The developed regression model showed an excellent agreement with the experimental data, with a coefficient of determination (R^2) of 0.987, indicating that 98.7% of the variation in glucose conversion could be explained by the selected process variables. Furthermore, the adjusted R^2 value confirmed the adequacy and reliability of the developed model for predicting glucose production within the investigated experimental range.
Analysis of variance (ANOVA) demonstrated that sulfuric acid concentration was the most influential factor affecting glucose conversion, whereas the interaction effects among the investigated variables also contributed to the overall response. The response surface plots clearly illustrated the interactions among the independent variables.
Overall, the optimized hydrolysis conditions improved glucose production from waste office paper, confirming that concentrated sulfuric acid hydrolysis combined with Response Surface Methodology is an effective approach for maximizing fermentable sugar production from lignocellulosic waste materials.
The optimization of concentrated acid hydrolysis was carried out based on the three variables (acid concentration(C), sulfuric acid loading (V), and reaction temperature (T)) which were in the range of experimental runs. The experimental design and corresponding responses of the dependent variables (glucose conversion) are listed in TABLE I. A Central composite design was used to develop a correlation between the concentrated acid hydrolysis variables and glucose conversion. The glucose conversion was found to range between 5.95 and 16 g/l. Runs 5, 9, and 11 at the centre point were used to estimate the experimental error.

TABLE II
EXPERIMENTAL DATA FOR CONCENTRATED ACID HYDROLYSIS OF COMPUTER PRINTOUT

Time of experiment (t) = 3 hr

No. of experiment	Acid Concentration %	Acid volume(ml)	Reaction temperature(C)	Sugar cont by titration %
1	15	150	95	8.57
2	15	175	90	5.95
3	15	175	100	11.58
4	15	200	95	9.85
5	22.5	150	90	13.60
6	22.5	150	100	14.53
7	22.5	175	95	15.43
8	22.5	175	95	15.43
9	22.5	175	95	15.43
10	22.5	200	90	13.90
11	22.5	200	100	15.60

12	30	150	95	15.55
13	30	175	90	15.50
14	30	175	100	16.00
15	30	200	95	15.70

Coded value of acid concentration (%), loading sulfuric acid (ml), and reaction temperature (C^O)

TABLE III
STATISTICAL SUMMARY OF THE REGRESSION MODEL

Summary	
|R|	0.993
R^2	0.987
R^2 adjusted	0.969
Standard Error	0.545
# Points	15
PRESS	18.36
R^2 for Prediction	0.863
Durbin-Watson d	1.656
First Order Autocorrelation	0.080
Collinearity	0.000
Coefficient of Variation	4.034

The quality of the developed model was evaluated using the coefficient of determination R^2 and the standard error. R^2 = 0.987. This indicates = 98.7%

TABLE IV
ANALYSIS OF VARIANCE (*ANOVA)* RESULT FOR REGRESSION MODEL

Source	***SS***	***SS%***	***MS***	***F***	***F Signif***	***df***
Regression	132.64	99	16.58	55.83	4.5218E-05	8
Residual	1.782	1	0.297	-	-	6
Total	134.42	100	-	-	-	14

The ANOVA results demonstrated that the regression model was highly significant (F = 55.83, $p < 0.001$), confirming that the model adequately described the variation in sugar production. The high R^2 value (0.987), together with the adjusted R^2 of 0.969 and predicted R^2 of 0.863, further indicated a good model fit and satisfactory predictive capability.

The experimental data were used to calculate the coefficients of the second-order polynomial equation. The response surface regression models were expressed in terms of coded variables, without considering the statistically non-significant terms at $\alpha = 0.05$. In other words, only the model terms with p-values less than 0.05 were determined to be significant in the model equations. The coefficients βi are displayed in Table 2. %. The regression model for the glucose conversion was presented in Eq. (2). Additionally, the p-values suggest that the variables C had significant effects on the glucose conversion.

The effects of the three variables (acid concentration, sulfuric acid loading, and reaction temperature) on glucose conversion were further evaluated using RSM. The experimental data were fitted to the developed responses and used to generate three-dimensional response surface plots. The interactive effects of two were evaluated simultaneously while the third variable was maintained at its central level.

TABLE V
REGRESSION COEFFICIENTS AND STATISTICAL PARAMETERS OF THE RESPONSE SURFACE MODEL FOR SUGAR PRODUCTION

Resp_1 = b0 + b1*C + b2*T + b3*C*C + b4*V*V + b5*T*T + b6*C*V + b7*C*T + b8*V*T							
		P value	Std Error	-95%	95%	t Stat	VIF
b0	-306.04	0.02537	103.48	-559.25	-52.83	-2.957	
b1	6.001	0.000234	0.769	4.119	7.883	7.803	896.31
b2	4.995	0.05995	2.159	-0.287	10.28	2.314	3137.8
b3	-0.04576	9.9784E-05	0.00504	-0.05809	-0.03344	-9.086	78.84
b4	-0.000541	0.185	0.000362	-0.00143	0.000344	-1.495	270.60
b5	-0.02336	0.08486	0.01133	-0.05109	0.00437	-2.062	3122.9
b6	-0.00141	0.366	0.00144	-0.00494	0.00212	-0.977	115.19
b7	-0.03420	0.00330	0.00727	-0.05198	-0.01642	-4.707	741.00
b8	0.00247	0.116	0.00134	-0.000818	0.00576	1.839	312.48

$$Y = b0 + b1 * C + b2 * T + b3 * C * C + b4 * V * V + b5 * T * T + b6 * C * V + b7 * C * T + b8 * V * T \quad (2)$$

$$Y = -306.04 + 6.001(C) + 4.995(T) - 0.04576(C * C) - 0.000541(V * V) - 0.02336(T * T) - 0.00141(C * V) - 0.03420(C * T) + 0.00247(V * T)$$

The statistical analysis showed that acid concentration (C) had a significant effect on sugar production (p = 0.000234). The quadratic term of acid concentration (C^2) was also highly significant ($p < 0.001$. The interaction between acid concentration and reaction temperature ($C \times T$) was statistically significant, whereas the other model terms were not significant at the 5% significance level ($p > 0.05$)
As presented in Table 2, high Variance Inflation Factor (VIF) values are observed across several linear, quadratic, and interaction terms, most notably b_1 (896.31), b_2 (3137.80), b_5 (3122.90), and b_7 (741.00).

C. Optimization and Model Validation

Model validation was performed by conducting an additional experiment under the optimized hydrolysis conditions predicted by the RSM model. The predicted glucose concentration was 16 g/L, whereas the experimentally obtained value was 16.02 g/L. The relative error between the predicted and experimental values was 0.125%.

$$\text{Relative Error}(\%) = \left\{\frac{\text{Expermental value} - \text{Predicted value}}{\text{Predicted value}}\right\} * 100 \quad (3)$$

$$\text{Relative Error}(\%) = \left\{\frac{16.02 - 16.00}{16.00}\right\} * 100 = 0.125\%$$

These plots provide a graphical representation of the individual and interactive effects of the process variables on glucose conversion within the investigated experimental range.

Figure 1 illustrates the combined effects of acid concentration and sulfuric acid loading on glucose conversion. An increase in acid concentration resulted in a pronounced increase in glucose conversion, particularly at moderate to high sulfuric acid loading. In contrast, the individual effect of sulfuric acid loading was less pronounced, which agrees with the nonsignificant quadratic V^2 term ($p > 0.05$).

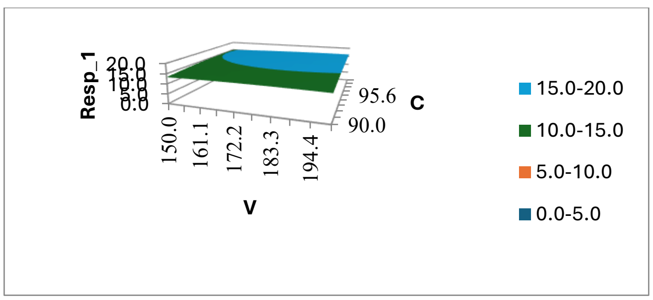

Fig.1.Three-dimensional response surface plot showing the interactive effects of sulfuric acid loading (V ml) and acid concentration (C %) on glucose conversion

Figure 2 shows the interactive effects of sulfuric acid loading and reaction temperature on glucose conversion. The response surface demonstrates that glucose conversion varied with changes in both variables; however, the V×T interaction was not statistically significant ($p > 0.05$). This suggests that the combined effect of sulfuric acid loading and temperature was relatively limited compared with the effect of acid concentration. Although increasing temperature can accelerate cellulose hydrolysis by increasing reaction rates and improving acid penetration into the cellulose structure, severe hydrolysis conditions may also promote the degradation of released sugars into secondary products. Therefore, controlling the reaction temperature is important for maintaining glucose recovery.

Figure 3 represents the interaction between acid concentration and reaction temperature. A marked change in glucose conversion was observed across the response surface, indicating a strong interaction between these two variables. This observation is supported by the significant C×T interaction term ($p < 0.05$).

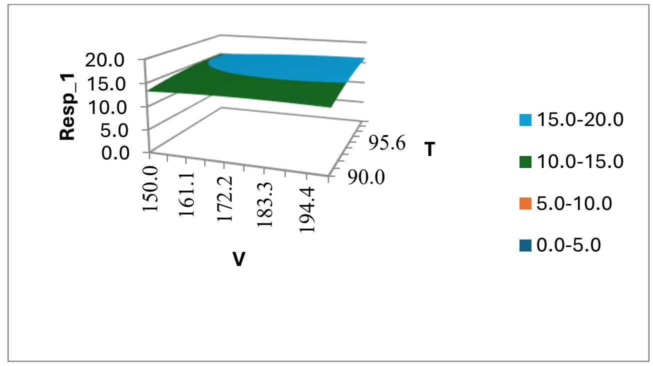

Fig.2. Three-dimensional response surface plot showing interactive effects of sulfuric acid loading (V ml) and reaction temperature (T C°) on glucose conversion.

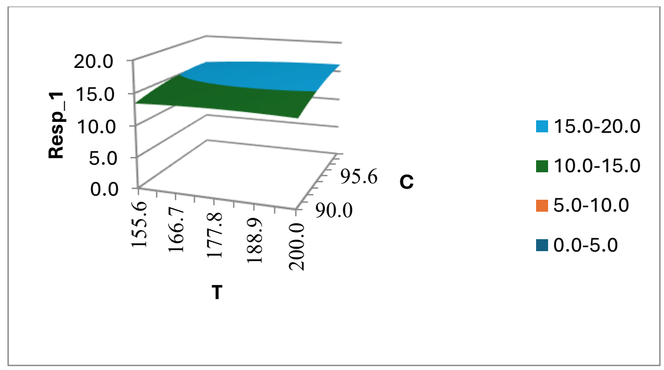

Fig.3. Three-dimensional interactive effects of reaction temperature (T C°) and acid concentration (C %) on glucose conversion

D. Discussion and Recommendation

The elevated VIF values observed in the response surface model can be attributed to multicollinearity among the polynomial and interaction terms, particularly the higher-order terms included in the model. Such correlations are commonly encountered in polynomial response surface models and may increase the standard errors of individual coefficient estimates. Therefore, interpret the VIF values in conjunction with overall model performance rather than independently. The high coefficient of determination ($R^2 = 0.987$), adjusted R^2 (0.969), and predicted R^2 (0.863) indicate that the model provided a good fit to the experimental data and had satisfactory predictive capability within the investigated experimental region. Furthermore, the model validation experiment demonstrated excellent agreement between the predicted glucose concentration (16.00g/L) and the experimentally obtained value (16.02g/L), yielding a negligible relative error of 0.125%, which further confirms the accuracy and reliability of the predictive model.

Regarding the process variables, the positive effect of sulfuric acid concentration on sugar production can be attributed to the enhanced disruption of the cellulose structure and cleavage of glycosidic bonds under acidic conditions, thereby promoting the release of soluble sugars. However, the response surface exhibited a nonlinear trend, which is consistent with the significant quadratic effect of acid concentration (C^2, $p < 0.05$). This indicates that increasing acid concentration does not result in a proportional increase in sugar production across the entire experimental range. At higher acid concentrations, the increased severity of hydrolysis may also promote the degradation of released sugars and reduce the net sugar recovery.

The interaction effects among the process variables also provided important insights into the hydrolysis behavior. The nonsignificant interaction between acid loading and reaction temperature ($V \times T$, $p > 0.05$) indicates that their combined effect was less influential than the effect of acid concentration. Although increasing temperature can accelerate hydrolysis by increasing reaction rates and facilitating the penetration of acid into the cellulose matrix, excessive thermal severity may promote the degradation of released sugars into secondary products. Therefore, appropriate control of reaction temperature is important for maintaining effective sugar recovery.

In contrast, the significant interaction between acid concentration and reaction temperature ($C \times T$, $p < 0.05$) indicates that the effect of acid concentration on sugar production depended on the reaction temperature. The combined action of acid concentration and temperature can enhance cellulose depolymerization and glycosidic bond cleavage, thereby increasing sugar release. However, excessively severe acidic and thermal conditions may accelerate sugar degradation and the formation of inhibitory compounds such as furfural and 5-hydroxymethylfurfural (HMF). Thus, the interaction between acid concentration and reaction temperature is an important consideration when determining suitable hydrolysis conditions.

Overall, the response surface analysis identified sulfuric acid concentration as the dominant process variable affecting sugar production. The significant quadratic effect of acid concentration and the significant interaction between acid concentration and reaction temperature demonstrate that the hydrolysis variables should be optimized simultaneously rather than evaluated independently. These findings support the use of RSM as an effective approach for identifying suitable operating conditions for maximizing sugar production from waste office paper and providing an appropriate hydrolysate for subsequent fermentation.

The present study demonstrated that sulfuric acid concentration was the dominant factor influencing sugar production during the hydrolysis of waste office paper, with a significant quadratic effect and a significant interaction between acid concentration and reaction temperature. This finding is consistent with the work of [6], who demonstrated that sulfuric acid concentration, reaction temperature, acid-to-solid ratio, and hydrolysis time significantly affected the hydrolysis of paper waste sludge. Using response surface methodology with a Box–Behnken design, they successfully identified an optimized operating region for acid hydrolysis. The agreement between these findings supports the importance of simultaneously optimizing hydrolysis variables when processing paper-based lignocellulosic feedstock, and the differences in the optimal conditions and hydrolysis performance between the two studies are expected because of differences in feedstock composition, acid concentration, solid-to-liquid ratio, temperature, hydrolysis time, and the selected response variables. In the present study, the particularly strong effect of acid concentration and its interaction with temperature highlights the importance of controlling acid severity to promote effective cellulose hydrolysis while minimizing the degradation of released sugars. Therefore, the present findings provide specific optimized conditions for the conversion of waste office paper into a sugar-rich hydrolysate suitable for subsequent bioethanol fermentation.

1) Future Work and Recommendations:

Further research is recommended to investigate the recovery and recycling of the acid used to improve process sustainability. Additionally, optimizing the fermentation conditions using different microbial strain combinations should be explored to refine the overall ethanol yield and quality. Finally, scaling up the process to an industrial level, alongside evaluating its economic feasibility and environmental impact (Life Cycle Assessment), will be essential for commercial application.

Iv. Conclusions

This study demonstrated the potential of waste office paper as a low-cost and renewable cellulosic feedstock for glucose production through sulfuric acid hydrolysis. Response Surface Methodology (RSM) combined with Central Composite Design (CCD) was successfully applied to evaluate the effects and interactions of acid concentration, sulfuric acid loading, and reaction temperature on glucose conversion.

The developed quadratic model showed an excellent fit to the experimental data, with an R^2 value of 0.987 and an adjusted R^2 value of 0.969. Acid concentration was identified as the dominant process variable, while the significant interaction between acid concentration and reaction temperature confirmed the importance of considering the combined effects of hydrolysis conditions.

The highest experimental sugar concentration (16.00 g/L) was obtained at an acid concentration of 30%, sulfuric acid loading of 175 mL, a reaction temperature of 100°C, and a reaction time of 3 h. Overall, the findings confirm that optimized acid hydrolysis can enhance the conversion of waste paper cellulose into fermentable sugars. The produced sugar-rich hydrolysate has potential for subsequent bioethanol production through fermentation. Further studies should focus on glucose recovery, acid recycling, fermentation performance, process scale-up, and techno-economic and environmental assessment.

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REFERENCES

[1] R. A. Quevedo Amador, E. P. Escalera-Velasco, A. Ramírez Arias, H. E. Reynel-Avila, L. Giraldo, and A. Bonilla-Petriciolet, "Application of waste biomass for the production of biofuels and catalysts: A review," *Clean Technol. Environ.Policy*, vol. 26, pp. 943–997, 2024.

[2] F. A. Malla, S. A. Bandh, S. A. Wani, A. T. Hoang, and N. A. Sofi, "Biofuels: Potential alternatives to fossil fuels," in *Biofuels*, Springer, 2023.

[3] J. J. Abdullah, R. N. Ibbett, D. Greetham, C. Du, and G. A. Tucker, "Optimization of parameters for sugar releasing from municipal solid waste (MSW)," *J. Environ. Sci.Public Health*, vol. 2, no. 1, pp. 1–12, 2018.

[4] R. P. Martins, F. Masarin, and M. Brienzo, "Optimized dilute acid pretreatment of agro-industrial and urban wastes for maximum fermentable sugars production," *Biomass Convers. Biorefin.*, 2026. doi: 10.1007/s13399-025-06981-z.

[5] J. Brandenburg, J. Blomqvist, J. Pickova, N. Bonturi, M. Sandgren, and V. Passoth, "Oleaginous yeasts respond differently to carbon sources present in lignocellulose hydrolysate," *Biotechnol. Biofuels*, vol. 14, p.124, 2021.

[6] T. T. Nguyen Ngo, N. T. Le Tan, T. T. N. Nguyen, T. T. H. Vo, K. G. H. Tran, N. P. T. Le, T. P. Vo, Q. Huynh, and D. Q. Nguyen, "Optimization of the hydrolysis process of paper waste sludge to produce bacterial cellulose through fermentation," *Chem. Eng. Trans.*, vol. 106, pp. 271–276, 2023. doi: 10.3303/CET23106046.

[7] X. T. Nguyen, "Study of some properties of curcumin-loaded 3D-nano-cellulose networks produced by *Acetobacter xylinum*," *TNU J. Sci. Technol.*, vol. 184, no. 8, pp. 83–88, 2018.

[8] N. T. L. Tan, Q. P. Dam, T. P. Mai, and D. Q. Nguyen, "The combination of acidic and alkaline pretreatment for a lignocellulose material in simultaneous saccharification and fermentation (SSF) process," *Chem. Eng. Trans.*, vol. 89, pp. 43–48, 2021.

[9] H. A. Jan, H. A. J. Issa, and M. M. Badr, "Biodiesel production from *Sisymbrium irio* as a potential novel biomass waste feedstock using homemade Titania catalyst," *Sci. Rep.*, vol. 13, p. 11282, 2023.

[10] T. Turner, R. Wheeler, and I. W. Oliver, "Evaluating land application of pulp and paper mill sludge: A review," *J. Environ.Manage.*, vol. 317, p. 115439, 2022.

[11] C. Cherian and S. Siddiqua, "Pulp and paper mill fly ash: A review," *Sustainability*, vol. 11, no. 16, p. 4394, 2019.

[12] S. Jain, "Utilization of waste paper sludge in construction industry," Ph.D. dissertation, Indian Institute of Technology, Delhi, India, 2015.

[13] T. Kolajo, O. J. Elohor, O. Oribayo, and J. A. Omoleye, "Biochemical conversion of waste paper slurries into bioethanol," *Sci. Afr.*, vol. 20, p. e01703, 2023.

[14] C. Chen, W. Ding, H. Zhang, L. Zhang, Y. Huang, M. Fan, Y. Jiazhi, and D. Sun, "Bacterial cellulose-based biomaterials: From fabrication to application," *Carbohydr. Polym.*, vol. 278, p. 118995, 2022.

[15] K. Gengiah, G. I. P. Moses, and G. Baskar, "Bioethanol production from *Codium tomentosum* residue," *Energy Sources Part A Recovery Util. Environ. Eff.*, pp. 1–10, 2020. doi: 10.1080/15567036.2020.1771481.

[16] H. Mohamed, H. Marbawi, J. A. Gansau, and R. Abdullah, "Coculturing of *Mucor plumbeus* and *Bacillus subtilis* as an efficient fermentation strategy to enhance fungal lipid and gamma-linolenic acid (GLA) production," *Sci. Rep.*, vol. 12, p. 1, 2022.

[17] H. Xu, L. Qu, Y. Li, T. R. Hawkins, and M. Wang, "Life cycle greenhouse gas emissions of biodiesel and renewable diesel production in the United States," *Environ. Sci. Technol.*, vol. 56, pp. 7512–7521, 2022.

[18] V. P. Zambare and L. P. Christopher, "Integrated biorefinery approach to utilization of pulp and paper mill sludge for value-added products," *J. Clean. Prod.*, vol. 274, p. 122791, 2020

[19] M. A. I. Malik, M. A. Kalam, M. A. Mujtaba, and F. Almomani, "A review of recent advances in the synthesis of environmentally friendly, sustainable, and nontoxic biolubricants: Recommendations for future implementations," *Environ. Sci. Pollut. Res.*, vol. 32, p. 103366, 2023.

[20] A. N. Amenaghawon, C. O. Okisimen, and S. E. Ogbeide, "Modeling and statistical optimization of dilute acid hydrolysis of eucalyptus wood chips using response surface methodology," *Pacific J. Sci. Technol.*, vol. 15, no. 1, pp. 245–256, 2014