OPTIMIZATION OF ETHYLENE GLYCOL PRODUCTION PROCESS FROM BIO MASS (CORN COB) USING RESPONSE SURFACE METHODOLOGY (RSM)

Abstract:

This study focuses on the increasing global demand for Monoethylene Glycol (MEG) and its production from corncob through Catalytic Hydrogenation. The process was optimized using Design of Experiment (DOE) and Response Surface Methodology (RSM). Physiochemical properties of the produced MEG were found to align with ASTM standards. Physiochemical properties of the produced Monoethylene glycol (MEG) was determined to have the following; density 2.19g/cm^3, specific gravity 1.077 at 20 ^{o}C, flash point 116.20 ^{o}C and viscosity 12.32mm^2/s at 40 ^{o}C, this values is in agreement with the ASTM standard values for monoethylene glycol. The study utilized a central composite design (CCD) with 21 runs to assess the impact of key parameters on biomass hydrogenation, revealing a quadratic model, also Analysis of variance (ANOVA) shows a high coefficient of determination (R^2) of >0.9932. Four parameters (mass ratio of binary catalyst, hydrogen pressure, temperature and mass ratio of catalyst to feedstock) were varied with two center points to determine the effects of process parameters and eventually to get optimum monoethylene glycol (MEG) yield. The optimized conditions yielded a MEG yield of 70.2wt.%, demonstrating the potential of corncob as a viable source for MEG production. This finding proved that corncob can be utilized to produce monoethylene glycol (MEG) which could be potentially used in many way.

Keywords: Monoethylene Glycol, Catalytic Hydrogenation, Response Surface Methodology (RSM), Corncob

1. Introduction

The exorbitant cost of petroleum-based polymer products in Nigeria has prompted a quest for sustainable alternatives. Lignocellulosic biomass, particularly corncob, emerges as a natural fiber source with eco-friendly properties, offering a viable substitute for petroleum-based polymers [1]; [2]. Moreover, agricultural and forest biomass waste, like corncob, presents a promising feedstock for producing high-performance materials without competing with human or animal food chains [3].

"The global monoethylene glycol (MEG) capacity was 56.97 MTPA in 2022 and is expected to grow at an AAGR of more than 5% during 2022 – 2027. In 2022, China, Saudi Arabia, the US, Taiwan and India are the key countries in the world accounting for over 77.2% of the total monoethylene glycol capacity" [4]. "Currently, industrial production of ethylene glycol (EG) exclusively relies on chemical synthesis which proceeds through steam cracking of petrol to obtain ethylene, and the oxidation of ethylene to ethylene oxide which is followed by thermal hydrolysis to yield monoethylene glycol (MEG)" [5]. "The decreasing availability of petrol and the increasing environmental concerns and increasing market prices have prompted the search for other economical, biochemical and energy-efficient processes to synthesize value-added chemicals from renewable resources" [2]. "These rise have stimulated considerable interest in the development of environmentally sustainable materials, which are composed of cellulose, hemicellulose, and lignin as a means of overcoming environmental problems" [6]. "Lignocellulose materials are the most abundant biomass found in almost all plant-derived materials, from wood and grass to agricultural residues and municipal solid wastes that can be used as a substitute for petroleum-based resources and sustainability production" [7].

"Biomass is a convenient substitute for fossil resources because it can be transformed into useful organic compounds. Indeed, glucose can be considered as a potentially promising feedstock for the production of MEG because it is available for continuous processing on a large scale. For this purpose, agricultural wastes can be treated to obtain cellulose, which may be subsequently hydrolyzed to glucose" [8]. "Then, glucose is transformed into glycolaldehyde with a homogeneous catalyst. Finally, the aldehyde is hydrogenated to MEG with a solid catalyst dispersed in the mixture. The conversion of glucose into MEG constitutes an opportunity to benefit from a renewable raw material and generate a massive reduction in CO_2 emission" [9]. However, the main drawback of this synthesis route is associated with the presence of several side reactions that decrease considerably the yield of the chemical process. For this reason, this technique requires a thorough analysis for determination of the operating conditions that will enhance the conversion of glucose into MEG. Previously, Zhao *et al.*, [10] developed "a kinetic model for the main reactions of this process with an approach based on power law equations with apparent constants. Extensive work has been carried out by researchers around the world who have studied the effect of process parameters to monoethylene glycol (MEG) yield". Law *et al.*, [11] carried out "optimization study of biomass hydrogenation to ethylene glycol using response surface methodology. The following results were

gotten, Using Malaysian oil palm empty fruit bunches (EFB) fibres as feedstock, the central composite design (CCD) technique was employed and 18 runs were generated by CCD when four parameters (mass ratio of binary catalyst, hydrogen pressure, temperature and mass ratio of catalyst to feedstock) were varied with two center points to determine the effects of process parameters and eventually to get optimum ethylene glycol (EG) yield". Jifeng-Pang *et al.,* [12] evaluate "the catalytic hydrogenation of corn stalk to ethylene glycol and 1,2-Propylene glycol", similarly Xi *et al.,* [13] produced "ethylene glycol and Its Monoether Derivative from Cellulose. Here, an interesting catalytic process was reported related to converting cellulose into ethylene glycol (EG) and ethylene glycol monoether (EGME) in methanol over a Ru/$NbOPO_4$ catalyst, with the cleavage of a C−C bond by $NbOPO_4$ and further hydrogenation by supported Ru particles".

"Among all the aforementioned studies, the effect of initial hydrogen pressure as well as reaction duration to EG yield was also widely reported. The finding of effects of different biomass loading, feeding speed, effect of additive/co-catalyst effect, cellulose to catalyst loading, different feedstock, reactor type and continuous hydrogen feeding towards EG yield were also reported. Although high numbers of papers and patents were published for EG conversion for more than one decade, most research groups performed their studies using the one-factor-at-a-time (OFAT) approach. Maize is one of the important cereal crops grown in Nigeria. It is accompanied by an enormous amount of agro-waste generation, is a potential feedstock for the production of biogas, biodiesel, and bioethanol to fulfill the increasing demand for biofuels, and about 30 % of maize agro waste is corncob, and it is underexplored" [14].

"Optimization is to make the best or most effective use of a situation or resource. Referring to this statement, the production of Monoethylene glycol (MEG) requires optimization for; energy consumption reduction, maximizing productivity, reduction of side products, minimizing feed requirements" [15]. "These objectives usually conflict with one another and thus most industries prioritized only one resulting in efficient plant operations. In the ethylene glycol (MEG) process, there are conflicting objective functions, i.e. maximum production and minimum energy consumption which cannot be solved by single objective optimization technique" [16].

"The significance of producing ethylene glycol from cellulose extracted from corncob can be used in different ways for the whole environment. This study contributes to a significant improvement in inefficient resource utilization by converting waste to wealth and for the researcher, it will provide

opportunities to increase practical knowledge. The economic benefit extracting of monoethylene glycol (MEG) from corncob will decrease the cost for the importation of the ethylene glycol from petroleum-based resources using a renewable and abundant natural resource such as corncob for the production of ethylene glycol which can provide a viable solution to overcome the issues concerning global environmental problem" [17]. Also the direct catalytic conversion of cellulose to MEG (DCE process) will contribute to a reduction of the dependence on non-renewable petroleum and a lowering of the net emission of CO_2 to the environment. Thus, the aim of this work is to produce ethylene glycol from corncob and optimizing the process using design of experiment (DOE).

2. Materials and Methods

2.1. Materials and Chemicals

Corncob were sourced from a local from a local market at Ogbogonogo, Asaba Metropolis, Delta State, Nigeria. All reagent were purchased from chemical stores in Asaba, the reagent were analytical grade and used as received without further purification. Also all solutions were prepared with deionized water.

2.2. Alkaline Pre-Treatment of Corn-cob

The corncob utilized in this study underwent alkaline pre-treatment, following the method outlined by Zawawi *et al.* [18]. The pre-treatment involved placing 20 g of untreated corncob in a stainless-steel autoclave (100 mL), along with 180 g of a 0.438 mol L^{-1} H_2O_2 solution at a ratio of one to nine (1:9) parts of corncob to the base solution. Alkaline pre-treatment was conducted at 150 °C for 120 minutes, with stirring at a rate of 500 rpm. After cooling, the pre-treated corncob was obtained through filtration, followed by repeated washing until a neutralized pH was achieved. The solid samples were subsequently dried in an oven until the moisture content reduced to < 10wt.%, making them suitable for the catalytic hydrogenation process.

2.3. Production of Ethylene Glycol from Corn-cob

Monoethylene Glycol (MEG) was produced using the process called Catalytic Hydrogenation. The optimization was carried out using the following range of parameters as specified in Table 1. Catalytic conversion of pre-treated Corn-cob to monoethylene glycol (MEG) was carried out in a stainless-steel autoclave (100 mL). The production was carried out following the parameters specified in Table 2 generated by design of experiment. The experiment was conducted using stainless-steel

autoclave (100mL), a fixed resident time and stirring rate of 120min and 500rpm were use respectively. After completion of the reaction, the stainless-steel autoclave (100mL) was depressurized, product gas were released as waste gas, and product liquor (liquid-phase) was collected through filtration. The residue were dried and used to calculate the percentages of cellulose conversion. The composition of the liquid-phase (product) Monoethylene glycol yield were analyzed using High Liquid Chromatography (HPLC).

Table 1. Independent variables and levels for central composite design (CCD)

Independent variables	Low level (-1)	High level (+1)
Raney Nickel to Tungstic acid ratio	0.8	1.2
Temperature ^{o}C	230	250
Pressure bar	18	25
Tungstic acid to corn-cob ratio	0.06	0.1

Table 2: Design Runs from Design Expert for (MEG) Production from Corn-corb

		Factor 1	Factor 2	Factor 3	Factor 4	Response 1
Std	Run	A:Raney Nickel to Tungstic acid ratio	B:Temperature ^{o}C	C:Pressure bar	D:Tungstic acid to corn-cob ratio	Monoethylene Glycol Yield %
11	1	1	223.182	21.5	0.08	
10	2	1.33636	240	21.5	0.08	
5	3	1.2	230	18	0.1	
13	4	1	240	15.6137	0.08	
14	5	1	240	27.3863	0.08	
18	6	1	240	21.5	0.08	
20	7	1	240	21.5	0.08	
4	8	0.8	250	18	0.1	
16	9	1	240	21.5	0.113636	
8	10	0.8	230	18	0.06	
6	11	0.8	230	25	0.06	
17	12	1	240	21.5	0.08	
7	13	0.8	250	25	0.1	
12	14	1	256.818	21.5	0.08	
1	15	1.2	250	25	0.06	
15	16	1	240	21.5	0.0463641	
9	17	0.663641	240	21.5	0.08	
2	18	1.2	250	18	0.06	
19	19	1	240	21.5	0.08	
3	20	1.2	230	25	0.1	
21	21	1	240	21.5	0.08	

2.4. Design of Experiment, Statistical Analysis and Optimization

The Monoethylene glycol (MEG) production was fitted using a second-order polynomial equation and multiple regression of the data were carried out for obtaining an empirical model related to the most significant factors. Equation (1) shows the general form of the second-order polynomial.

$$\gamma = \beta_0 + \sum_{j=1}^{k} B_j x_j + \sum_{i<j} \sum B_{ij} x_i x_j + \sum_{j=1}^{k} B_{ij} x_j^2 + \varepsilon \quad \text{Eq. (1)}$$

Where: Y is the predicted response, x_i and x_j are independent factors, β_0 is the model intercept, β_i is the linear coefficient, β_{ii} is the quadratic coefficient and β_{ij} is the interaction coefficient.

2.5 Characterization of the Produced Mono-ethylene Glycol (MEG)

The liquid product obtained from the catalytic biomass hydrogenation was characterized for some of its physical properties, which include flash point, specific gravity, viscosity, density.

2.6 Determination of Monoethylene Glycol Yield

The approach described by Law *et al.,* [11] was utilized to determine the yield of the monoethylene glycol produced in this study. This was conducted using High-Performance Liquid Chromatography (HPLC) equipped with a refractive index detector (RID). Two (2) units of SC-1011 (8.0 mm I.D, 300 mm length) analytical columns connected in Processes equipped with its guard column SC-LC (6.0 mm I.D., 50 mm length) was installed in a column holder with a column temperature set at 80 ^{o}C. The flow rate of Deionized water was set to 0.4 mlmin^{-1} and RID temperature was maintained at 40 ^{o}C while 10 µL of product liquor was injected into the system.

3. Results and Discussion

3.1 Physiochemical Properties of Monoethylene Glycol (MEG)

Table 3: Physicochemical Properties of the Produced Monoethylene Glycol (MEG)

Properties	Experimental Values	ASTM Standards Method Values
Density g/cm^3	2.19	1.113
Specific Gravity @ 20 ^{o}C	1.072	1.1153
Flash Point ^{o}C (Open Up)	116.20	111.11
Viscosity [mm^2/s] at 40 ^{o}C	12.32	19.83

The study evaluated the physical properties of the produced Monoethylene Glycol (MEG) against ASTM standards as shown in Table 3. The density of the MEG was found to be 2.19, exceeding the ASTM D-4052 standard of 1.115 by a difference of 1.075. Specific gravity at 20°C was measured as 1.072, falling within the acceptable limit compared to the ASTM D4439 standard of 1.1153. The flash point of the MEG was determined to be 116.20°C, slightly higher than the ASTM D-93 standard of 111.11°C, suggesting lower flammability compared to petroleum-based ethylene glycol. Viscosity at 40°C was 12.32mm^2/s, within the acceptable range and comparable to the ASTM D-2270 standard. Overall, the physical properties of the produced MEG align with standards, indicating its suitability for various applications.

3.2. Response Surface Analysis and Analysis of Variance (ANOVA)

In this study, Response Surface Modeling based on the Central Composite Design (CCD) was employed to assess the impact of various parameters on the yield of Monoethylene Glycol (MEG). The analysis involved developing multiple regression equations through Design-Expert version (11) software to articulate the relationship between factors and the yield of MEG. The quadratic model was determined to be the most fitting based on the experimental results as shown Table 4. Temperature (factor B) and hydrogen pressure (factor C) were chosen as focal parameters due to their significant influence on product yield and selectivity, as reported in previous studies by Ji et al., [19]. Additionally, hydrogen partial pressure and temperature were identified as key factors affecting hydrogenation efficiency and retro-aldol reaction, ultimately impacting MEG yield [20]. Two new parameters, the mass ratio of binary catalyst (RN: H2WO4) (factor A) and mass ratio of catalyst to biomass (H2WO4:CC) (factor D), were introduced in this study to address limited information reported previously by Law *et al.*, [11]. A total of 21 experimental runs were conducted in a randomized order to minimize variability from extraneous factors. The Monoethylene Glycol (MEG) yields ranged from 20% to 70.2%, with run no. 8 yielding the lowest (20%) and run no. 6 yielding the highest (70.2%). Notably, temperatures below 230°C resulted in 20% of biomass remaining unreacted, consistent with findings that higher temperatures favor cellulose hydrolysis. Previous studies also affirmed the critical role of temperature in cellulose conversion, with optimal conditions ranging from 200 to 370°C and a pressure of 4 to 20 MPa to maintain water in its liquid state [11].

Table 4. Model Fit Summary of Statistics.

Source	Sequential p-value	Lack of Fit p-value	Adjusted R^2	Predicted R^2	
Linear	0.0357	0.2140	0.3198	0.1112	
2FI	0.8680	0.1149	0.1190	-4.0666	
Quadratic	**0.0191**	**0.0120**	**0.9932**	**0.9882**	**Suggested**
Cubic	0.7620		0.6605		Aliased

The regression model was highly significant, with correlation coefficients of determination (R^2, adjusted R^2, and predicted R^2) reaching 0.9932 and 0.9882, respectively. This implies that 98% of the total variation in the data was explained by the regression model, indicating a robust fit between the model and experimental data. R-squared serves as a measure of goodness-of-fit for linear regression models, revealing the percentage of variance in the dependent variable collectively explained by the independent variables.

Table 5. Fit Statistics

Std. Dev.	**2.77**	**R^2**	**0.9974**
Mean	19.06	Adjusted R^2	0.9932
C.V. %	14.56	Predicted R^2	0.9882
		Adeq Precision	0.8972

3.3. Model Equation in Terms of Coded Factors

The model equation was developed to show the correlation between the hydrolysis parameters and yield of monoethylen glycol (MEG). A quadratic model was found to be adequate for the prediction of the given yield as shown in Equation 2.

Monoethylene Glycol Yield = 61.59 + 6.83A – 8.91B + 3.80C -8.107D - 5.95AB + 1.285AC - 2.63AD + 3.84BC + 1.64BD + 3.6425CD - 7.05A^2- 6.76B^2-1.47C^2 - 1.70D^2 Eq. (2)

Table 6. Central Composite Design (CCD) and (MEG) Yield

		Factor 1	**Factor 2**	**Factor 3**	**Factor 4**	**Response**
Std	Run	A:Raney Nickel to Tungstic acid ratio	B:temperature ^oC	C:Pressure bar	D:Tungstic acid to corn-cob ratio	MONOETHYLENE GLYCOL YIELD %
11	1	1	223.182	21.5	0.08	56.97
10	2	1.33636	240	21.5	0.08	52.65
5	3	1.2	230	18	0.1	48.06
13	4	1	240	15.6137	0.08	53.703
14	5	1	240	27.3863	0.08	60.21

18	6	1	240	21.5	0.08	70.2
20	7	1	240	21.5	0.08	48.87
4	8	0.8	250	18	0.1	20
16	9	1	240	21.5	0.113636	42.66
8	10	0.8	230	18	0.06	51.84
6	11	0.8	230	25	0.06	44.55
17	12	1	240	21.5	0.08	64.8
7	13	0.8	250	25	0.1	42.66
12	14	1	256.818	21.5	0.08	27
1	15	1.2	250	25	0.06	52.65
15	16	1	240	21.5	0.0463641	69.93
9	17	0.663641	240	21.5	0.08	29.673
2	18	1.2	250	18	0.06	39.42
19	19	1	240	21.5	0.08	64.26
3	20	1.2	230	25	0.1	60.48
21	21	1	240	21.5	0.08	61

Table 7. ANOVA for Quadratic Model of Monoethylene Glycol Yield

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	433.11	14	30.94	4.02	0.0482	Significant
A-Raney Nickel to Tungstic acid ratio	36.21	1	36.21	4.71	0.0731	
B-temperature	51.00	1	51.00	6.63	0.0421	
C-Pressure	20.31	1	20.31	2.64	0.1554	
D-Tungstic acid to corn-cob ratio	51.00	1	51.00	6.63	0.0421	
AB	21.17	1	21.17	2.75	0.1482	
AC	5.12	1	5.12	0.6654	0.4458	
AD	3.33	1	3.33	0.4330	0.5349	
BC	9.68	1	9.68	1.26	0.3049	
BD	2.87	1	2.87	0.3725	0.5640	
CD	8.41	1	8.41	1.09	0.3362	
A^2	113.57	1	113.57	14.76	0.0085	
B^2	91.33	1	91.33	11.87	0.0137	
C^2	7.08	1	7.08	0.9205	0.3744	
D^2	8.98	1	8.98	1.17	0.3216	
Residual	46.17	6	7.69			
Lack of Fit	4.20	2	2.10	0.2001	0.8264	not significant
Pure Error	41.97	4	10.49			
Cor Total	479.28	20				

The Model F-value of 4.02 (as shown in Table 7) suggests the model's significance, with only a 0.01% probability that such a large Model F-value could occur due to random variation. Prob > F values less than 0.0500 indicate the significance of model terms, with terms A, B, C, D, A2, B2, C2, D2, AB, AC, AD, BC, and BD all proving significant. The ANOVA results affirm the coherence of the response surface models in predicting the yield of monoethylene glycol (MEG). Additionally, the ANOVA outcomes demonstrate favorable agreement with the adjusted R^2, reinforcing the applicability of quadratic models for optimization under consistent conditions, as opposed to conventional methods. Notably, the temperature of the reaction significantly influences the response, as indicated by the P value being less than 0.05 (Table 7). The adequate precision ratio and low coefficient of variation (CV) values further validate the reliability and precision of the models (Table 5). This is in line with the findings of Law *et al.*, [11].

3.4 Effects of Experimental Variables on the Monoethylene Glycol (MEG) Yield

3.4.1 Effect of Raney Nickel to Tungstic Acid Ratio on the Yield of MEG

The impact of the acid binary catalyst ratio (Raney Nickel to tungstic acid, RN:H2WO4) concentration on Monoethylene Glycol (MEG) yield is depicted in Figure 1. At a temperature of 240°C, tungstic acid ratio to corncob of 0.08, and a pressure of 18 bar, the findings indicate that MEG yield initially increases with rising acid concentration during hydrolysis. This is attributed to enhanced cellulose conversion to MEG facilitated by the increased acid penetration into the amorphous cellulose region. The optimum yield is achieved at an acid concentration of 0.04 wt.%, after which further increases lead to a decline in yield due to excessive cellulose degradation into undesired by-products this is in agreement with the finding of jifeng-pange *et al.*, [12].

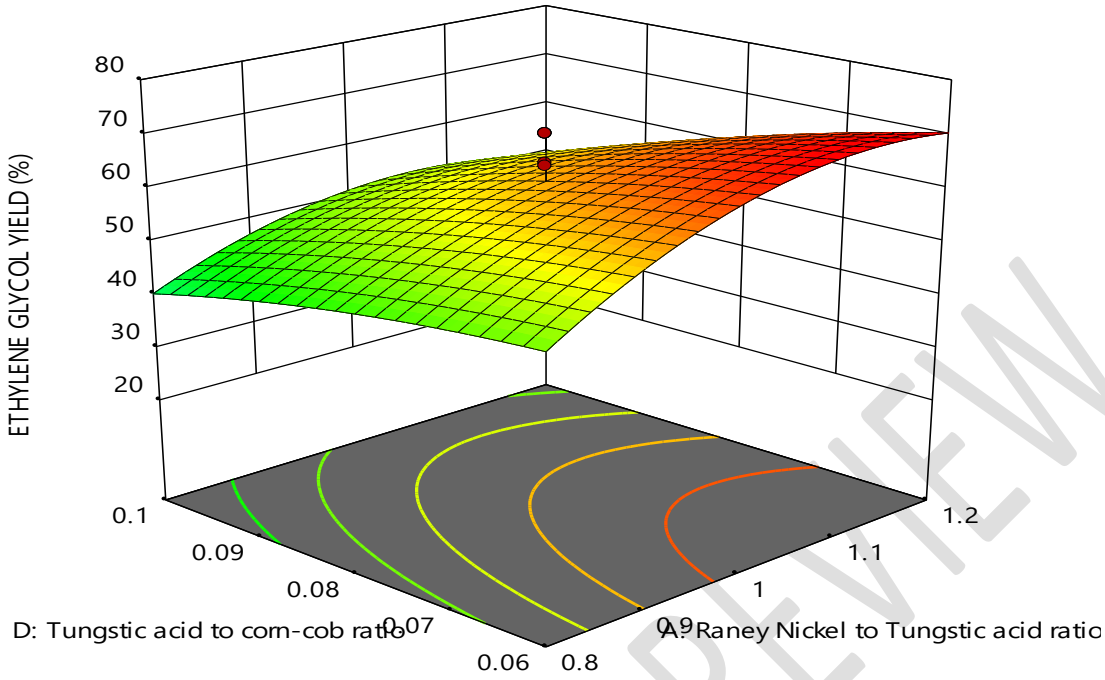

Figure 1. Effect Raney nickel to tungstic acid Concentration on the Yield of MEG

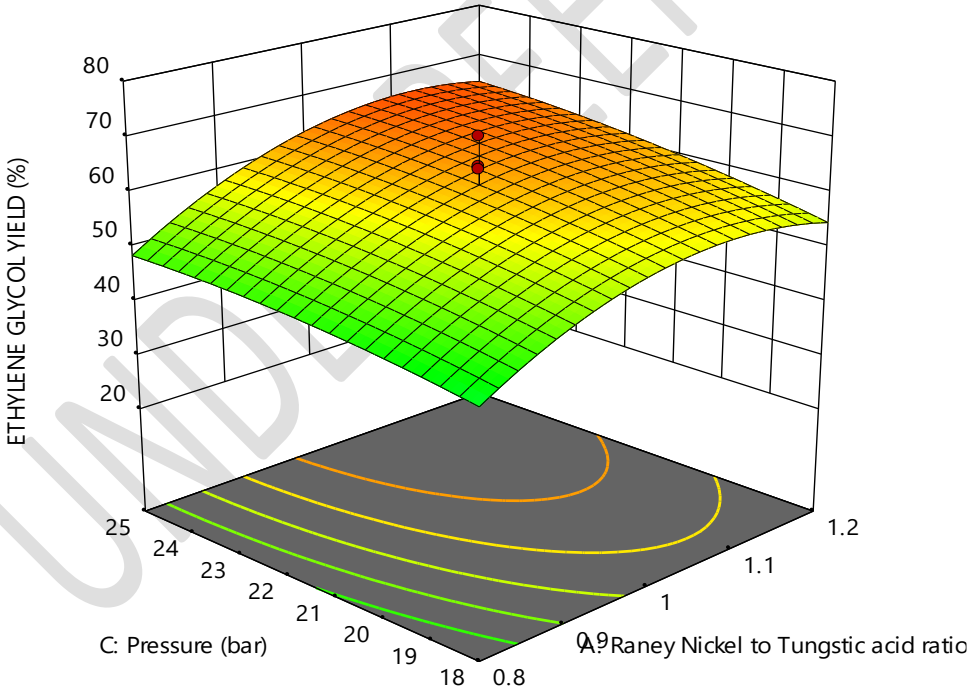

Figure 2**.** Effects of Pressure on the Yield of Monoethylene Glycol (MEG)

Figure 2 illustrates the influence of pressure on the yield of Monoethylene Glycol (MEG). The data suggests that variations in pressure have a discernible impact on the yield of MEG. As pressure levels change, there is observable variation in the production of MEG. Analyzing the trends and patterns in this figure can provide insights into the optimal pressure conditions for maximizing the yield of MEG in the catalytic hydrogenation process.

3.4.2 Effect of Temperature on the Yield of Monoethylene Glycol (MEG)

"The effect of temperature on the yield of monoethylene glycol as shown in Figure 3, when the acid concentration was 0.06 % and the hydrolysis pressure was 18 bar, at the lower level of temperature, the yield decrease and increased with increasing the temperature since the increment of the temperature enhances the hydrolysis reaction at the starting of the reaction. After it reaches the optimum value at around 245℃, increasing the temperature lowers the values of the yield as a result of the degradation of cellulose as temperature further increased", Law *et al.*, [11].

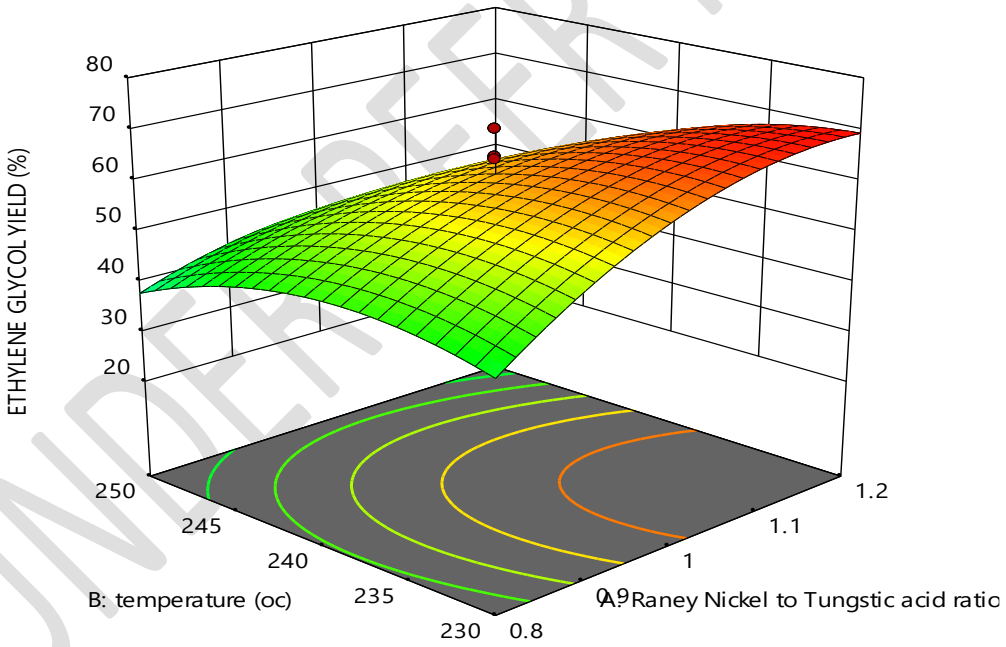

Figure 3. Effects of Temperature on the Yield of Monoethylene Glycol (MEG)

3.5 Optimization of the Monoethylene Glycol (MEG) Yield and Verification

Numerical optimization was used to identify the optimum level of catalytic hydrogenation process factors. By using this model and employing "Optimization", the constraints was set for each

factor which included their corresponding goal, limit and importance, in order to maximize MEG yield, as shown in Table 8.

Table 8. Constraints for each of the factors used in the Optimization

Factor/Response	Goal	Lower Limit	Upper Limit	Importance
A:Raney Nickel to tungstic acid	is in range	0.8	1.2	3
B:Temperature	is in range	230	250	3
C:Pressure	is in range	18	25	3
D:Tungstic acid to (CC)	is in range	0.06	0.1	3
Response: MEG yield	maximize	20	70.2	5

The maximum yield MEG of 70.2% was obtained at the interaction parameter of binary catalyst ratio of (RN:H_2WO_4) =1, Temperature 240℃, Pressure 21.5bar and Ratio of H_2WO_4 : CC (0.08). Under this condition of parameter interaction, the predicted yield of MEG obtained was 70.2%. This shows that the predicted values of the MEG yield agreed with that obtained from experimental work. From the response optimization technique used in this study, the yield of MEG was optimized to 70.2 %, at a desirable parameter interactions.

3.6 Validation of an Optimization Model

To confirm the optimized model, the actual validation experiment was carried out at optimum conditions that were obtained in a design expert. Thus, the optimum yield was 70.02%. To validate the optimum conditions predicted by the response surface methodology model results, triplicate experiments were conducted at the specified optimum process conditions predicted by the model as shown in Table 9 and which was then related to the data obtained from optimization analysis using the desirability function.

Table 9. Result of Optimization and Model Validation

Number	(RN:H_2WO_4)	Temperature (℃)	Pressure (bar)	(H_2WO_4:CC)	Yield (%)
Predicted	1	240	21.5	0.08	70.2
Experimental	1	240	21.5	0.08	69.7

The mean percentage of yield obtained by triplicate experiments 69.7% which is not significantly different from the predicted value of 70.2 % yield of the optimal conditions. Therefore, the model was valid and capable of predicting the maximum MEG yield i.e. numerical optimization can be taken as an optimal value because the predicted value was close enough to the experimental value.

4. Conclusions:

This research look into harnessing the potential of corncob, an underexplored biomass rich in cellulose, hemicellulose, and lignin, for Monoethylene Glycol (MEG) production through Catalytic Hydrogenation. The process optimization employs Design of Experiment (DOE) and Response Surface Methodology (RSM), envisioning a promising path for MEG production from renewable corncob resources. Beyond advancing green chemistry, the study emphasizes the crucial optimization of MEG production for energy efficiency and productivity, navigating conflicting objectives through multi-objective optimization. The findings hold significant implications for the sustainable development of the chemical industry.

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