



Effect of Pre-Treatment of Waste Aluminium for the Production of Catalytic Hydrogen using Alkali Solutions

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Abstract.

Hydrogen gas with a high level of purity is essential for use in hydrogen and oxygen fuel cells to generate electricity. However, producing high-purity hydrogen can be challenging. Among the various methods for hydrogen production from metal waste, aluminum is a popular choice due to its ability to react with water in the presence of an alkali to produce hydrogen without emitting greenhouse gases. Numerous attempts have been made to produce hydrogen through the aluminum-water reaction using sodium hydroxide, with variations in concentration levels. Waste aluminum cans and foils were utilized to generate hydrogen by reacting them with aqueous sodium hydroxide. The rate of hydrogen production was initially slow due to the thin layer of plastic coating on the aluminum cans. To address this, an organic solvent treatment was used to remove the plastic layer from aluminum cans before reacting them with alkali. The rate of hydrogen production was then measured and compared with that from untreated aluminum cans and aluminum foils. A multivariable regression analysis is used to forecast the relationship between the variables assessed and found rate constant representing a function of the mass of aluminium and the alkali concentration.

Keywords: Green Hydrogen, Alkali, Metal wastes, Aluminium, Kinetics, Optimization.

Introduction

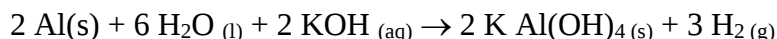
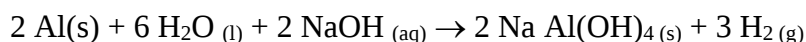
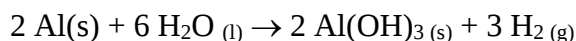
Hydrogen, renowned for its high energy density per unit weight and eco-friendly attributes, is increasingly being explored as an alternative energy source across diverse applications [1-3]. Extensive research has been conducted to produce hydrogen from various sources, with potential applications in transportation, heating and cooling systems, energy storage, and industrial sectors such as ammonia production, oil, and food [4].

Furthermore, the utilization of hydrogen in fuel cells results in the production of water as a by-product through the interaction of hydrogen and oxygen [4]. The separation of hydrogen and oxygen from water primarily employs thermal and electrolytic methods [5–6]. Among these



methods, the technique of water splitting using aluminum has emerged as particularly efficient and promising [7-12]. Aluminum, abundant and cost-effective, stands out as a preferred material for generating hydrogen from water [13-14].

Aluminium, being a reactive metal, undergoes a reaction with moisture to form aluminium oxide, creating a protective layer over the metal surface. This oxide layer significantly impacts the interaction between aluminium and water. Consequently, researchers have devised numerous techniques to eliminate this oxide layer, allowing aluminium to effectively react with water to produce hydrogen [15-16]. To eradicate the oxide layer from aluminium metal, promoters such as sodium hydroxide (NaOH) and potassium hydroxide (KOH) are commonly employed. When sodium hydroxide is introduced to water, it dissociates into sodium (Na⁺) and hydroxide (OH⁻) ions. Upon adding scrap aluminium to this solution, the oxide layer on the aluminium surface readily reacts with these ions. This reaction results in the removal of the oxide layer by the dissociated ions in the aqueous solution, facilitating the metal's ability to react with water and produce hydrogen [17-20].



The hydrogen produced from the reaction can be utilized in fuel cells to generate power [21-23], enabling the charging of various electronic devices using the electricity generated. Unlike many electrochemical cells available on the market that store chemical molecules internally, fuel cells continuously draw in reactants from outside as needed to produce electricity through a redox reaction. Fuel cells offer high efficiency, low emissions, minimal noise during operation, and a long operational lifespan. Since hydrogen is supplied from the reaction between aluminium and water, and oxygen is obtained from the air, there is no need to store or transport hydrogen gas along with the cell.

Multivariable regression analysis is an efficient technique for optimizing these parameters to attain maximum hydrogen yield. Integrating multiple variables into a statistical model facilitates the quantification of the relationships between input factors and the hydrogen production rate. This methodology enables researchers to predict optimal conditions for hydrogen production and identify the most significant factors affecting the reaction. The insights obtained from this analysis can improve the catalytic process, making it more efficient and scalable for industrial applications. In addition to optimizing reaction conditions, multivariable regression analysis provides a systematic framework for understanding the interactions between variables. The relationship between alkali concentration and aluminum particle size may significantly influence the rate of hydrogen production. Similarly, variations



in temperature may intensify the reactivity of aluminum and the solubility of the alkali. By analysing these complex relationships, it is possible to optimize hydrogen production while simultaneously reducing resource consumption, including minimizing excess alkali and regulating reaction temperatures for improved energy efficiency [24, 25].

Moreover, the integration of waste aluminum introduces variability into the process, as its composition may vary depending on the source. Multivariable regression can enhance model calibration to address this variability, ensuring the hydrogen production process remains efficient across various waste streams. This makes the approach both flexible and practical for real-world applications, where the standardization of waste inputs is often unattainable. This analysis promotes the development of more cost-effective and environmentally sustainable hydrogen production techniques, aligned with the broader goals of sustainable energy and waste recycling [26].

Through the application of multivariable regression, researchers and engineers can obtain significant insights into reaction mechanisms, thus enhancing catalytic hydrogen production from waste materials. The application of multivariable regression extends beyond the optimization of hydrogen yield; it also enhances process control and scalability. In large-scale hydrogen production, variations in waste aluminum composition and operational parameters are inevitable. A robust regression model facilitates the prediction of these fluctuations and the adjustment of operational parameters in real-time, ensuring consistent performance across different scales. This capability is crucial for industrial applications, where maintaining efficiency and minimizing downtime is essential for economic viability [27, 28].

Moreover, the insights obtained from regression models can guide the design of future experiments and processes. By identifying the variables that most profoundly affect hydrogen production, researchers can focus on optimizing those aspects of the process. If alkali concentration and aluminum surface area are recognized as the primary determinants, initiatives can be directed towards enhancing these variables via material engineering or process alterations. If certain variables show negligible impact, resources can be preserved by diminishing their importance in the process design [29].

Furthermore, multivariable regression enables the assessment of environmental and economic trade-offs. Modeling the influence of operational variables on hydrogen yield and energy consumption facilitates the identification of conditions that enhance production and sustainability. For example, reduced temperatures may decrease energy input while still generating sufficient hydrogen, thereby reducing the carbon footprint of the process. Similarly, utilizing lower concentrations of alkali can reduce chemical costs and environmental impacts, making the process more sustainable and economically attractive. The integration of statistical models with experimental and industrial data improves understanding of the waste aluminium-



alkali reaction system. The amalgamation of multivariable regression analysis with process optimization and sustainable design principles positions hydrogen production from waste aluminum as a notable asset in the renewable energy sector. This method enables a worldwide transition to cleaner energy by providing a scalable and efficient technique for hydrogen production from waste materials [30].

In the current study, aluminium samples were collected from the waste aluminium cans. Low concentrations of NaOH, KOH, were tested as potential promoters for the removal of the oxide layer.

Methods and Materials

Materials

Panreac provided the sodium hydroxide and potassium hydroxide pellets, which were used exactly as they were delivered. Laboratory Grade Acetone, purchased from the suppliers, is used for the pretreatment process. For the preparation of all the aqueous solutions, deionized water was employed. Waste Aluminium cans collected from the garbage (0.11 mm thickness) was used in this study. The aluminium cans were cut into small pieces and stored in a dry container kept at room temperature away from direct sunlight without moisture content.

Methodology

According to the experimental design below, the hydrogen production was done under different concentrations of sodium hydroxide and potassium hydroxide with untreated aluminium and treated aluminium. In this experiment, the aluminium samples were treated with aluminium for 4 days (tAl-4) and 7 days (tAl-7) before the reaction with the alkali solutions. A fixed mass of 1-gram aluminium samples was taken during the process. The concentration of sodium hydroxide and potassium hydroxide varied from 0.1 M to 0.5 M. Batch experiments of this type were carried out in a glass reactor. A spontaneous reaction began when the aluminium samples are added into the reactor and aqueous alkali was added. Water displacement was used to determine how much hydrogen was created from the reaction because hydrogen is not very soluble in water. The reaction's hydrogen was directed toward a glass container containing water, forcing the water out of the container as mentioned in our previous work [31]. A digital thermometer was used to measure the reaction's temperature. Aluminium waste is treated with acetone for 4 days and 7 days to remove the plastic and paint coating. Later the treated samples are air dried before being used as a raw material in the aluminium water technique of producing hydrogen gas. Also studies were carried out with untreated aluminium samples and alkali solutions to produce hydrogen gas.



RESULTS AND DISCUSSION

Multivariable Regression Analysis

The approach known as "multiple regression analysis" refers to a collection of techniques that are used to investigate the linear connections that exist between two or more variables. Estimates of the variables in the equation $y_j = \beta_0 + \beta_1 x_{1j} + \beta_2 x_{2j} + \dots + \beta_p x_{pj} + \varepsilon_j$ are obtained through the process of multiple regression [32].

The Xs are the independent variables. Y is the variable that is dependent on. The number of the observation, which constitutes the row, is denoted by the subscript j. The symbols denote the regression coefficients that have not been identified. The letter B is used to signify their approximations. An approximation of each parameter is denoted by the letter b, and each represents the initial population parameter that was unknown. The error, often known as the residual, of observations j is at its lowest [33].

In order to determine the count, arithmetic mean, standard deviation, minimum, and maximum values for each variable, calculations are performed. For the purpose of ensuring that the appropriate variables were selected, this report is highly supportive. In this part, the values of the regression coefficients as well as the significance tests for those coefficients are provided. It is determined whether or not the hypotheses are correct. For example, collinearity might result in inaccurate conclusions from a t-test as well as incorrect information regarding the magnitude or sign of the regression coefficient [33].

After taking into account the impacts of all other Xs, this is the outcome of the t-test that is used to compare the alternative, which is $\beta_j = 0$, to the null hypothesis, which is $\beta_j \text{ NOT } = 0$. In this particular t-value, there are n-p-1 degrees of freedom possible [32].

Analysis of hydrogen production using KOH at different treatment days [34].

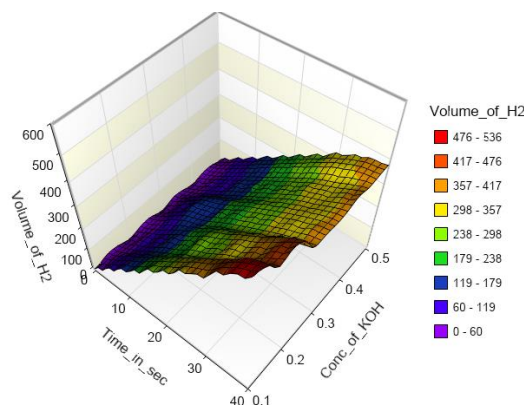


Figure 1A. surface plot of volume of hydrogen production in l/kg against time in sec and concentration of KOH in N for without treatment of aluminium

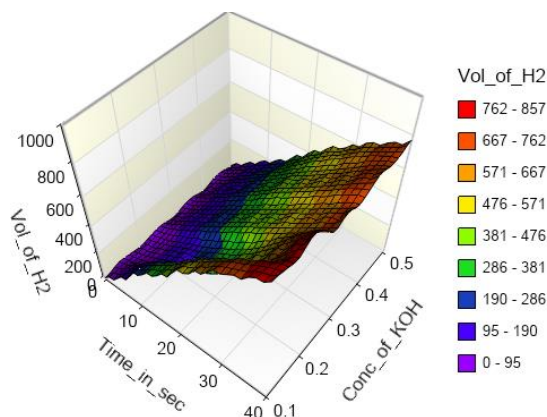


Figure 1B. surface plot of volume of hydrogen production in l/kg against time in sec and concentration of KOH in N for 4 days treatment of aluminium

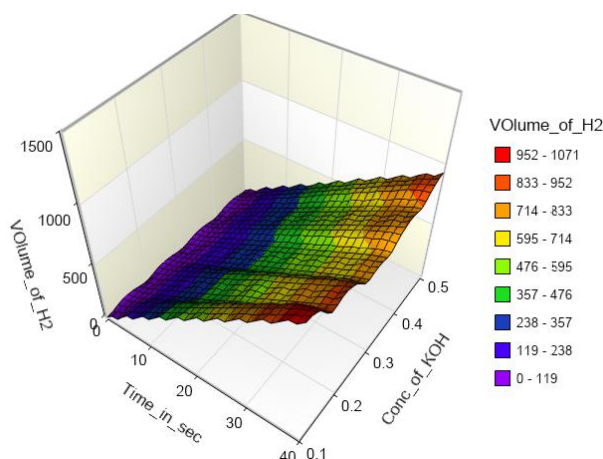


Figure 1C. surface plot of volume of hydrogen production in l/kg against time in sec and concentration of KOH in N for 7 days treatment of aluminium

An inventory of the names of the independent variables is presented below. The regression coefficients are the estimations of the parameters that are derived from the least squares method. Under the assumption that all other Xs remain unchanged, the result reveals the degree to which Y shifts for each unit change in X. These coefficients are usually referred to as partial-regression coefficients. This is due to the fact that the impact of the other Xs is reduced [33].

Figures 1A, 1B, and 1C depict surface plots of the volume of hydrogen production in liters per kilogram against time in seconds, as well as the concentration of potassium hydroxide at various treatment times (without the treatment of aluminum, a treatment lasting four days, and a treatment lasting seven days). Surface plots are a type of diagram that is used to show numerical data in three dimensions. As opposed to displaying the individual data points, surface plots illustrate the functional association between a designated variable that is dependent (the



volume of hydrogen production) and a pair of independent variables (the amount of time in seconds and the concentration of KOH). Having a solid understanding of the construction of these plots is really necessary. A two-dimensional grid of KOH concentration and Al mass is produced as a result of this project. It is the range of the data that corresponds to the range of this grid. Next, the volume of each grid point is examined and calculated.

When calculating the volume of hydrogen generation, the weighted average of all the data values that are "near" this grid point is utilized. It is up to the user to determine the number of points that should be averaged. For the purpose of constructing the three-dimensional surface, these averaged values are utilized. As a result, the surface plot does not adequately represent the variance that exists at each and every point on the grid. The purpose of these graphs is to illustrate the relationship that exists between a dependent variable and a pair of independent variables within the framework of regression analysis. It is important to keep in mind that multiple regression makes the assumption that this surface is completely flat. Through the use of the surface plot, it is therefore easy to visually determine whether or not multiple regression is required.

The estimated equation which can be fit into those curve is given below with V is volume of H₂, T is reaction time in sec and C is the Normality (concentration) of KOH.

For without treatment

$$V = 54.8 + 10.72 T - 156.57 C \dots\dots\dots (1)$$

For 4 days' treatment time,

$$V = 14.34 + 19.89T - 94.88C \dots\dots\dots (2)$$

For 7 days' treatment time,

$$V = 49.21 + 22.64T - 168.28C \dots\dots\dots (3)$$

Table 2A. Regression Coefficient T-Tests (T-Test of H₀: $\beta(i) = 0$) of variables volume of hydrogen production in l/kg, time in sec and concentration of KOH in N for without treatment of aluminium [35]

Independent Variable	Regression Coefficient	Standard Error	Standardized		
	Reject H ₀ b(i) at $\alpha = 0.05$?	Sb(i)	Coefficient	T-Statistic	P-Value
Intercept	54.8	7.007281	0.0000	7.817	0.0000



	Yes				
Time_in_sec	10.72	0.2017232	0.9689	53.154	0.0000
	Yes				
Conc_of_KOH	-156.57	17.27454	-0.1652	-9.064	0.0000
	Yes				

Table 3A. Analysis of Variance for variables volume of hydrogen production in l/kg, time in sec and concentration of KOH in N for without treatment of aluminium

Source	DF	R ² Lost If Term(s) Removed	Sum of Squares	Mean Square	F-Ratio	P-Value
Intercept	1		5186574	5186574		
Model	2	0.9661	1821990	910995.1	1453.729	0.0000
Time_in_sec	1	0.9388	1770511	1770511	2825.311	0.0000
Conc_of_KOH	1	0.0273	51479.01	51479.01	82.148	0.0000
Error	102	0.0339	63919.39	626.6607		
Total (Adjusted)	104		1885910	18133.75		

Table 2B. Regression Coefficient T-Tests (T-Test of H₀: $\beta(i) = 0$) of variables volume of hydrogen production in l/kg, time in sec and concentration of KOH in N for 4 days treatment of aluminium

Independent Variable	Coefficient Reject H ₀ b(i) at $\alpha = 0.05$?	Regression Error Sb(i)	Standard Standardized Coefficient	T-Statistic	P-Value
Intercept	14.34	13.04891	0.0000	1.099	0.2742
	No				
Time_in_sec	19.89	0.3756475	0.9808	52.961	0.0000
	Yes				
Conc_of_KOH	-94.88	32.16853	-0.0546	-2.949	0.0039
	Yes				



Table 3B. Analysis of Variance for variables volume of hydrogen production in l/kg, time in sec and concentration of KOH in N for 4 days treatment of aluminium

Source	DF	R ² Lost If Term(s) Removed	Sum of Squares	Mean Square	F-Ratio	P-
Value						
Intercept	1		1.546467E+07	1.546467E+07		
Model	2	0.9650	6114182	3057091	1406.781	
	0.0000					
Time_in_sec	1	0.9620	6095278	6095278	2804.864	
	0.0000					
Conc_of_KOH	1	0.0030	18903.34	18903.34	8.699	
	0.0039					
Error	102	0.0350	221657.2	2173.11		
Total (Adjusted)	104		6335839	60921.52		

Table 2C. Regression Coefficient T-Tests (T-Test of H0: $\beta(i) = 0$) of variables volume of hydrogen production in l/kg, time in sec and concentration of KOH in N for 7 days treatment of aluminium

Independent Variable	Regression	Standard			
	Coefficient	Error	Standardized		
	Reject H0 b(i) at $\alpha = 0.05$?	Sb(i)	Coefficient	T-Statistic	P-Value
Intercept	49.21 Yes	14.93272	0.0000	3.295	0.0014
Time_in_sec	22.64 Yes	0.4298781	0.9786	52.660	0.0000
Conc_of_KOH	-168.28 Yes	36.81256	-0.0849	-4.571	0.0000



Table 3C. Analysis of Variance for variables volume of hydrogen production in l/kg, time in sec and concentration of KOH in N for 7 days treatment of aluminium

Source	DF	R ² Lost If Term(s) Removed	Sum of Squares	Mean Square	F-Ratio	P-
Value						
Intercept	1		2.140148E+07	2.140148E+07		
Model	2	0.9648	7951234	3975617	1396.990	
	0.0000					
Time_in_sec	1	0.9576	7891764	7891764	2773.082	
	0.0000					
Conc_of_KOH	1	0.0072	59469.77	59469.77	20.897	
	0.0000					
Error	102	0.0352	290276.2	2845.845		
Total (Adjusted)	104		8241510	79245.29		

In order to determine the count, arithmetic mean, standard deviation, minimum, and maximum values for each variable, calculations are performed. For the purpose of ensuring that the appropriate variables were selected, this report is highly supportive. In this part, the values of the regression coefficients as well as the significance tests for those coefficients are provided. It is determined whether or not the hypotheses are correct. For example, collinearity might result in inaccurate conclusions from a t-test as well as incorrect information regarding the magnitude or sign of the regression coefficient.

After taking into account the impacts of all other Xs, this is the outcome of the t-test that is used to compare the alternative, which is $\beta_j = 0$, to the null hypothesis, which is $\beta_j \text{ NOT} = 0$. In this particular t-value, there are n-p-1 degrees of freedom possible.

An inventory of the names of the independent variables is presented below. The regression coefficients are the estimations of the parameters that are derived from the least squares method. Under the assumption that all other Xs remain unchanged, the result reveals the degree to which Y shifts for each unit change in X. These coefficients are usually referred to as partial-regression coefficients. This is due to the fact that the impact of the other Xs is reduced.

The regression coefficient T test is presented in Figure. 2A, 2B and 2C for without the treatment of aluminum, a treatment lasting four days, and a treatment lasting seven days and the details



of the analysis of variance are presented in Tables 3A, 3B and 3C without the treatment of aluminum, a treatment lasting four days, and a treatment lasting seven days, respectively. In this analysis of variance table, there is a line that corresponds to each term that is included in the model. It is of great use to each and every individual who possesses categorical independent variables. When this component is removed from the model, the number of degrees of freedom, which can range anywhere from one to nine with a total of eleven, is reduced. This is a representation of the numerator degrees of freedom that are measured by the F-test.

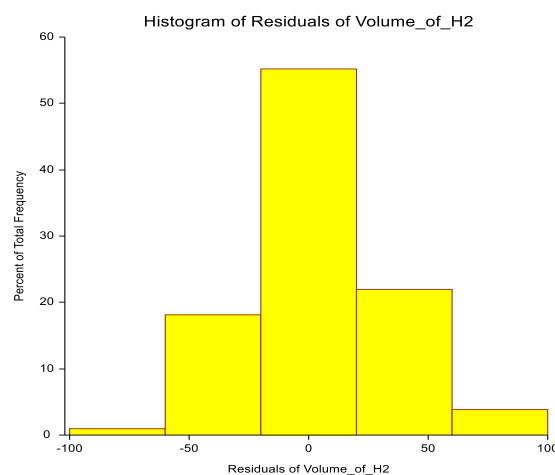


Figure 4A Histogram of residuals of volume of hydrogen production in l/kg for without treatment of aluminium [36]

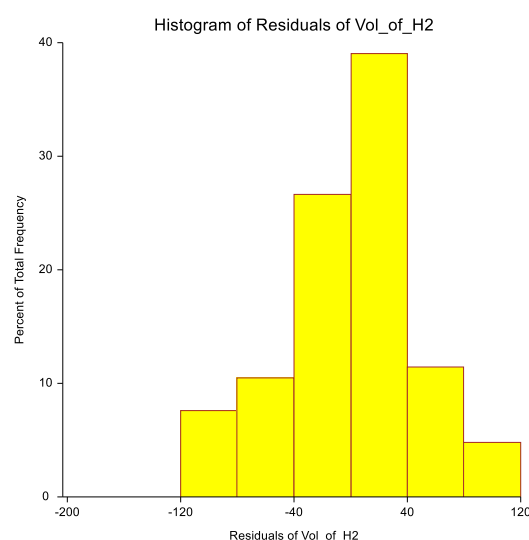


Figure 4B Histogram of residuals of volume of hydrogen production in l/kg for 4 days treatment of aluminium

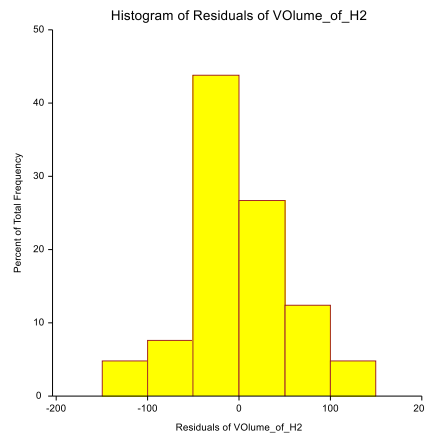


Figure 4C Histogram of residuals of volume of hydrogen production in l/kg for 7 days treatment of aluminium

Figure 4A, 4B and 4C depicts the histogram of the residual of the of volume of hydrogen production in l/kg for without the treatment of aluminum, a treatment lasting four days, and a treatment lasting seven days after it has been calculated. The histogram is utilized in order to ascertain whether or not the residuals are distributed in a consistently regular manner. This diagram illustrates that the residual of the volume of H₂ is distributed in a regular manner on the surface. Through the utilization of a dot plot, which can be incorporated into the histogram, it is possible to bring attention to the distribution of points that are contained inside each bin of the histogram. Due to the relatively small size of the sample collection, it is recommended that the histogram not be utilized in order to visually evaluate the normality of the residuals. Using the usual probability chart would be the choice that would be most suitable.

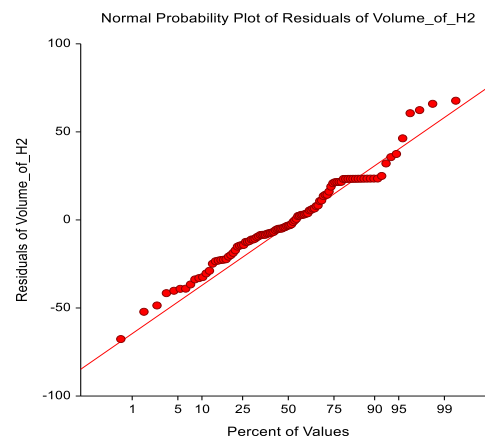


Figure 5A Normal probability plot of residual volume of hydrogen production in l/kg for without treatment of aluminium.

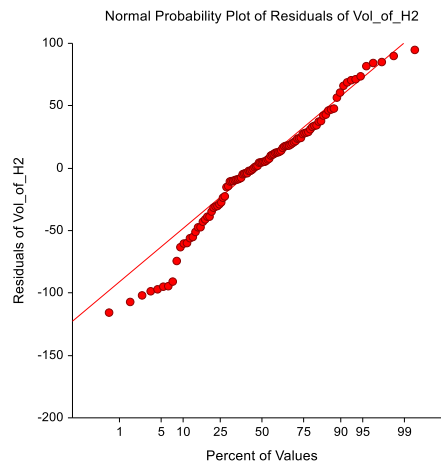


Figure 5B. Normal probability plot of residual volume of hydrogen production in l/kg for 4 days treatment of aluminium.

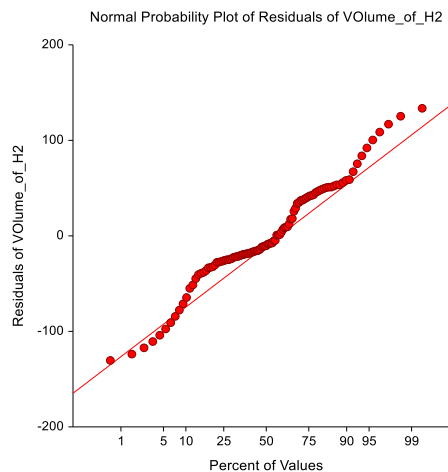


Figure 5C. Normal probability plot of residual volume of hydrogen production in l/kg for 7 days treatment of aluminium.

An example of a typical probability plot of the residual of volume of hydrogen production in l/kg without the treatment of aluminum, a treatment lasting four days, and a treatment lasting seven days is shown in 4A, 4B and 4C. If the residuals have a normal distribution, then the data locations in the normal probability chart will fall along a straight route over the origin along a slope of 1.0. This is the case if the residuals have a normal distribution. There are departures from the norm that are represented by significant variances from this idealized depiction. Straggling at the top or bottom of the normal probability plot indicates an outlier; curvature at either end of the plot indicates a short or long distributional tail; convex or concave curvature indicates a lack of symmetry; and gaps, plateaus, or classification in the normal probability plot



may indicate that a more in-depth analysis of the data or model is necessary. It should go without saying that it is not recommended to use this visualization tool with sample numbers that are exceedingly small.

In the event that the residuals are not normally distributed, the t-tests on regression coefficients, the F-tests, and any interval estimations will be invalid. However, in this particular scenario, it is evident that the points are normally distributed. Verifying this premise is of the utmost importance.

Analysis of hydrogen production using NaOH at different treatment days.

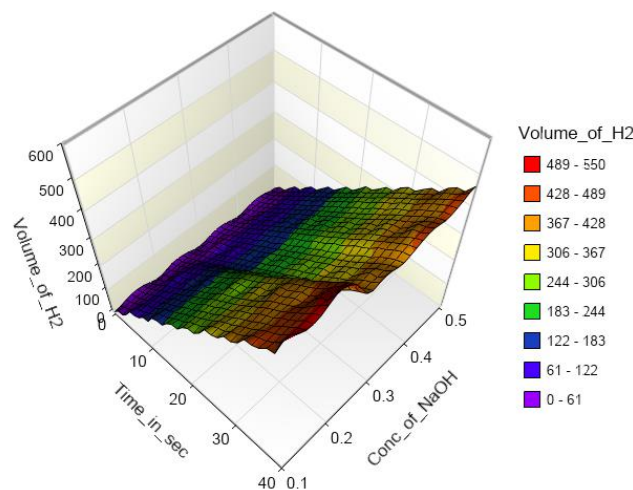


Figure 6A. surface plot of volume of hydrogen production in l/kg against time in sec and concentration of NaOH in N for without treatment of aluminium

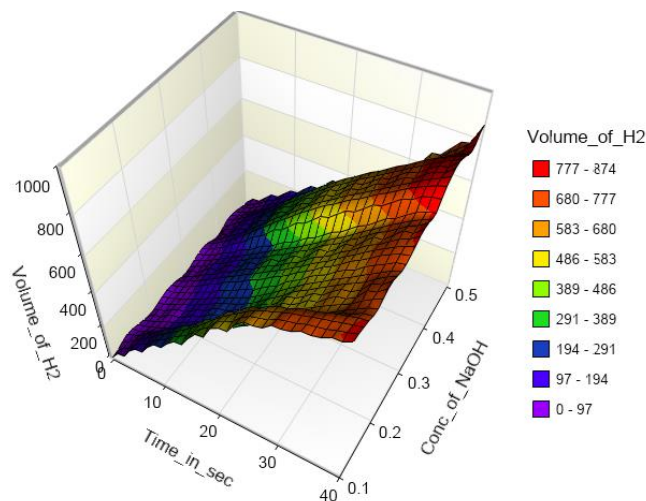


Figure 6B. surface plot of volume of hydrogen production in l/kg against time in sec and concentration of NaOH in N for 4 days treatment of aluminium

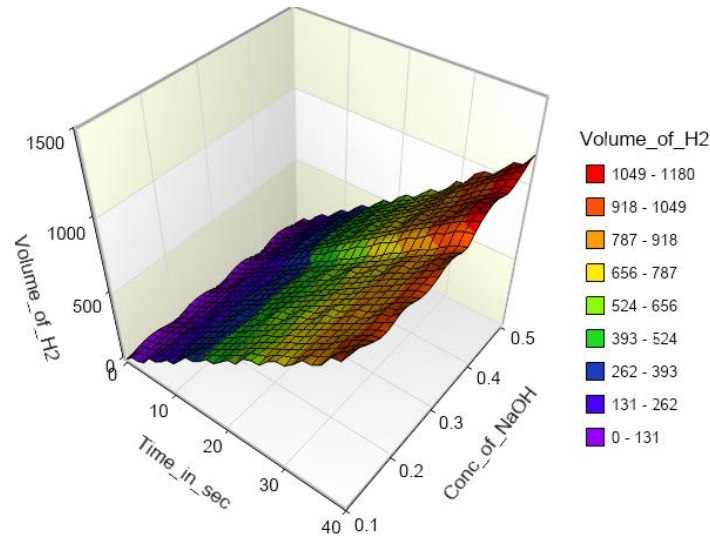


Figure 6C. surface plot of volume of hydrogen production in l/kg against time in sec and concentration of NaOH in N for 7 days treatment of aluminium

Figures 6A, 6B, and 6C depict surface plots of the volume of hydrogen production in liters per kilogram against time in seconds, as well as the concentration of sodium hydroxide at various treatment times (without the treatment of aluminum, a treatment lasting four days, and a treatment lasting seven days). Surface plots are a type of diagram that is used to show numerical data in three dimensions. As opposed to displaying the individual data points, surface plots illustrate the functional association between a designated variable that is dependent (the volume of hydrogen production) and a pair of independent variables (the amount of time in seconds and the concentration of NaOH).

Through the use of the surface plot, it is therefore easy to visually determine whether or not multiple regression is required.

The estimated equation which can be fit into those curve is given below with V is volume of H₂, T is reaction time in sec and C is the Normality (concentration) of NaOH.

For without treatment

$$V = 26.86 + 11.74 T - 94.17 C \dots\dots\dots (4)$$

For 4 days' treatment time,

$$V = 19.37 + 20.54 T - 56.13 C \dots\dots\dots (5)$$

For 7 days' treatment time,

$$V = -59.09 + 6.7 T + 174.88 C \dots\dots\dots (6)$$



Table 7A. Regression Coefficient T-Tests (T-Test of $H_0: \beta(i) = 0$) of variables volume of hydrogen production in l/kg, time in sec and concentration of NaOH in N for without treatment of aluminium

Independent Variable	Regression Coefficient Reject H_0 $b(i)$ at $\alpha = 0.05$?	Standard Error $Sb(i)$	Standardized Coefficient	T-Statistic	P-Value
Intercept	26.86 Yes	5.189376	0.0000	5.176	0.0000
Time_in_sec	11.74 Yes	0.14939	0.9876	78.580	0.0000
Conc_of_NaOH	-94.17 Yes	12.79299	-0.0925	-7.361	0.0000

Table 8A. Analysis of Variance for variables volume of hydrogen production in l/kg, time in sec and concentration of NaOH in N for without treatment of aluminium

Source	DF	R ² Lost If Term(s) Removed	Sum of Squares	Mean Square	F-Ratio	P-Value
Intercept	1		5719389	5719389		
Model	2	0.9839	2140811	1070405	3114.473	0.0000
Time_in_sec	1	0.9753	2122189	2122189	6174.765	0.0000
Conc_of_NaOH	1	0.0086	18621.46	18621.46	54.181	0.0000
Error	102	0.0161	35056.12	343.6874		
Total (Adjusted)	104		2175867	20921.79		



Table 7B. Regression Coefficient T-Tests (T-Test of $H_0: \beta(i) = 0$) of variables volume of hydrogen production in l/kg, time in sec and concentration of NaOH in N for 4 days treatment of aluminium

Independent Variable	Coefficient Reject H_0 $b(i)$ at $\alpha = 0.05?$	Regression Error		Standard Standardized		P-Value
		$Sb(i)$		Coefficient	T-Statistic	
Intercept	19.37	13.67144		0.0000	1.417	0.1595
Time_in_sec	No					
	20.54	0.3935688		0.9813	52.189	0.0000
Conc_of_NaOH	Yes					
	-56.13	33.70322		-0.0313	-1.665	0.0989
	No					

Table 8B. Analysis of Variance for variables volume of hydrogen production in l/kg, time in sec and concentration of NaOH in N for 4 days treatment of aluminium

Source	DF	R ² Lost If Term(s) Removed	Sum of Squares	Mean Square	F-Ratio	P-
Value						
Intercept	1		1.793832E+07	1.793832E+07		
Model	2	0.9639	6503655	3251827	1363.219	
	0.0000					
Time_in_sec	1	0.9630	6497038	6497038	2723.663	
	0.0000					
Conc_of_NaOH	1	0.0010	6616.436	6616.436	2.774	
	0.0989					
Error	102	0.0361	243311.2	2385.404		
Total (Adjusted)	104		6746966	64874.67		



Table 7C. Regression Coefficient T-Tests (T-Test of $H_0: \beta(i) = 0$) of variables volume of hydrogen production in l/kg, time in sec and concentration of NaOH in N for 7 days treatment of aluminium

Independent Variable	Regression Coefficient Reject H_0 $b(i)$ at $\alpha = 0.05$?	Standard Error Sb(i)	Standardized Coefficient	T-Statistic	P-Value
Intercept	-59.09 Yes	7.172205	0.0000	-8.239	0.0000
Time_in_sec	26.7 Yes	0.206471	0.9941	129.301	0.0000
Conc_of_NaOH	174.88 Yes	17.68112	0.0760	9.891	0.0000

Table 8C. Analysis of Variance for variables volume of hydrogen production in l/kg, time in sec and concentration of NaOH in N for 7 days treatment of aluminium

Source Value	DF	R ² Lost If Term(s) Removed	Sum of Squares	Mean Square	F-Ratio	P-
Intercept	1		2.919581E+07	2.919581E+07		
Model	2	0.9940	1.104015E+07	5520075	8408.261	
	0.0000					
Time_in_sec	1	0.9882	1.097593E+07	1.097593E+07	16718.693	
	0.0000					
Conc_of_NaOH	1	0.0058	64225.03	64225.03	97.829	
	0.0000					
Error	102	0.0060	66963.63	656.5062		
Total (Adjusted)	104		1.110711E+07	106799.2		



The regression coefficient T test is presented in Figure. 7A, 7B and 7C for without the treatment of aluminum, a treatment lasting four days, and a treatment lasting seven days and the details of the analysis of variance are presented in Tables 8A, 8B and 8C without the treatment of aluminum, a treatment lasting four days, and a treatment lasting seven days, respectively for NaOH. In this analysis of variance table, there is a line that corresponds to each term that is included in the model. It is of great use to each and every individual who possesses categorical independent variables.

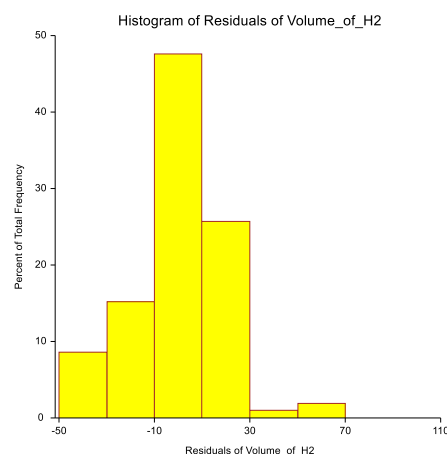


Figure 9A Histogram of residuals of volume of hydrogen production in l/kg for without treatment of aluminium

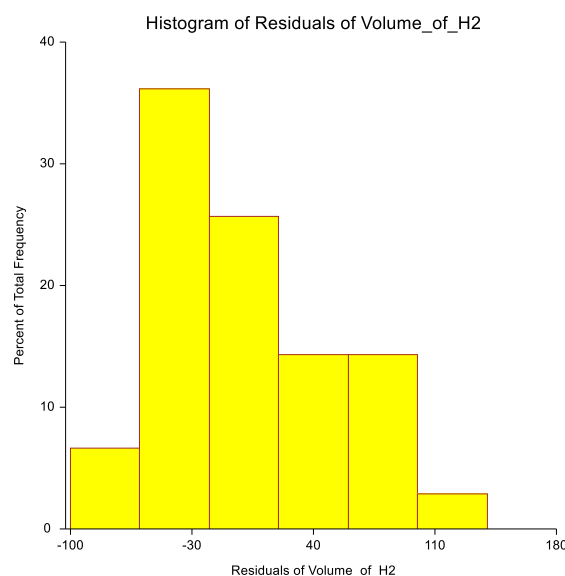


Figure 9B Histogram of residuals of volume of hydrogen production in l/kg for 4 days



treatment of aluminium

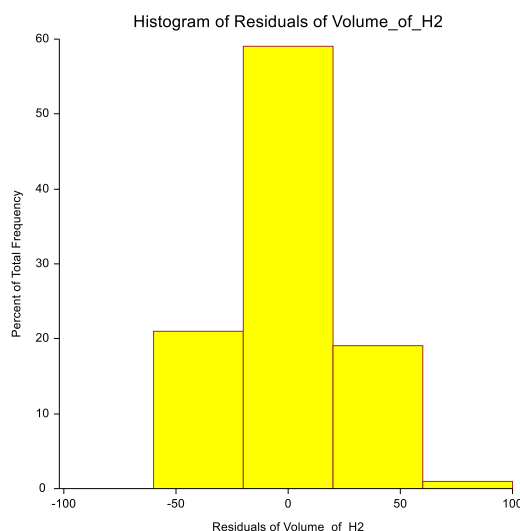


Figure 9C. Histogram of residuals of volume of hydrogen production in l/kg for 7 days treatment of aluminium

Figure 9A, 9B and 9C depicts the histogram of the residual of the of volume of hydrogen production in l/kg for without the treatment of aluminum, a treatment lasting four days, and a treatment lasting seven days with NaOH after it has been calculated. The histogram is utilized in order to ascertain whether or not the residuals are distributed in a consistently regular manner. This diagram illustrates that the residual of the volume of H_2 is distributed in a regular manner on the surface.

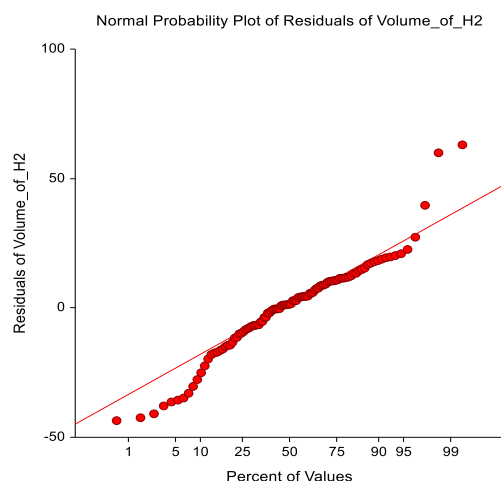


Figure 10A. Normal probability plot of residual volume of hydrogen production in l/kg for without treatment of aluminium.

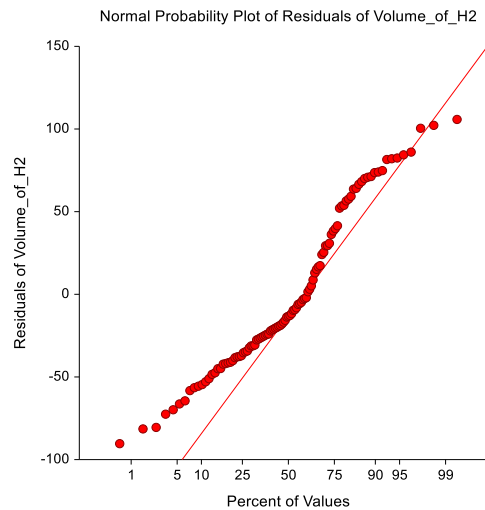


Figure 10B. Normal probability plot of residual volume of hydrogen production in l/kg for 4 days treatment of aluminium.

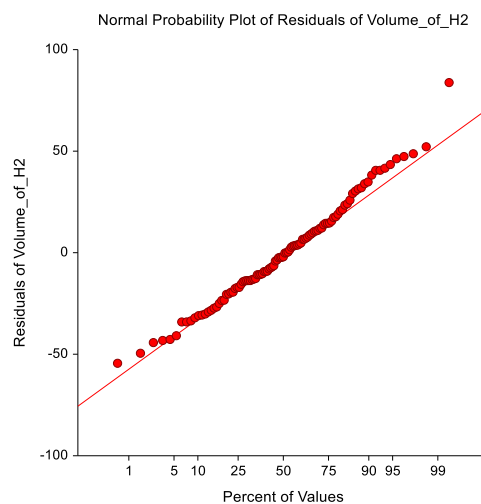


Figure 10C. Normal probability plot of residual volume of hydrogen production in l/kg for 7 days treatment of aluminium.

An example of a typical probability plot of the residual of volume of hydrogen production in l/kg without the treatment of aluminum, a treatment lasting four days, and a treatment lasting seven days is shown in 4A, 4B and 4C. If the residuals have a normal distribution, then the data locations in the normal probability chart will fall along a straight route over the origin along a slope of 1.0. This is the case if the residuals have a normal distribution. There are departures from the norm that are represented by significant variances from this idealized depiction.



Analysis of Equilibrium hydrogen production with KOH for different treatment days

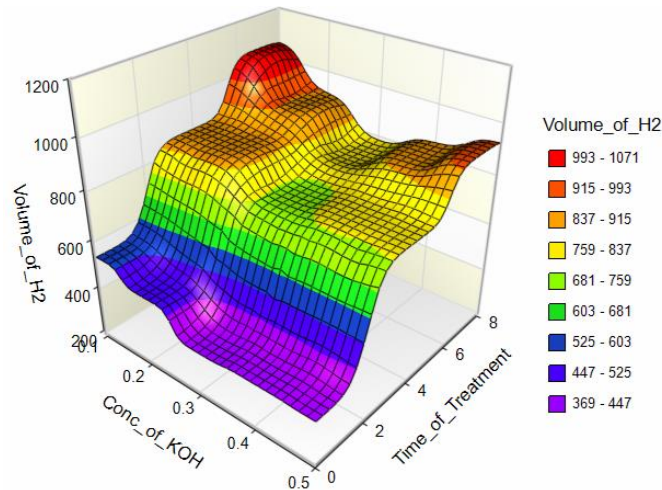


Figure 11A. surface plot of final (equilibrium) volume of hydrogen production in l/kg against time of treatment in days and concentration of KOH in N

Figures 11A depict surface plots of the final (equilibrium) volume of hydrogen production in l/kg against time of treatment in days and concentration of KOH in N.

The estimated equation which can be fit into those curve is given below with W is final (equilibrium) volume of H₂, T₁ is time of treatment in days and C is the Normality (concentration) of KOH.

$$W = 557.76 - 343.75 T_1 - 156.57 C \dots\dots\dots (7)$$

Table 12A. Regression Coefficient T-Tests (T-Test of H₀: $\beta(i) = 0$) of variables, final (equilibrium) volume of hydrogen production in l/kg, time of treatment in days and concentration of KOH in N.

Independent	Regression	Standard	Standardized		
Variable	Coefficient	Error	Coefficient	T-Statistic	P-Value
	Reject H0				
	b(i)	Sb(i)			
	at $\alpha = 0.05$?				
Intercept	557.76	56.03398	0.0000	9.954	0.0000
	Yes				
Conc_of_KOH	-343.75	148.3322	-0.2223	-2.317	0.0389
	Yes				



Time_of_Treatment	69.92	7.315698	0.9166	9.558	0.0000
Yes					

Table 13A. Analysis of Variance of variables, final (equilibrium) volume of hydrogen production in l/kg, time of treatment in days and concentration of KOH in N.

Source	DF	R ² Lost If Term(s) Removed	Sum of Squares	Mean Square	F-Ratio	P-Value
Intercept	1		7583069	7583069		
Model	2	0.8896	638408.3	319204.2	48.359	0.0000
Conc_of_KOH	1	0.0494	35449.22	35449.22	5.370	0.0389
Time_of_Treatment	1	0.8402	602959.1	602959.1	91.347	0.0000
Error	12	0.1104	79208.77	6600.73		
Total (Adjusted)	14		717617.1	51258.36		

The regression coefficient T test is presented in Figure. 12A and the details of the analysis of variance are presented in Tables 13A, for KOH. In this analysis of variance table, there is a line that corresponds to each term that is included in the model. It is of great use to each and every individual who possesses categorical independent variables.

Analysis of Equilibrium hydrogen production with NaOH for different treatment days

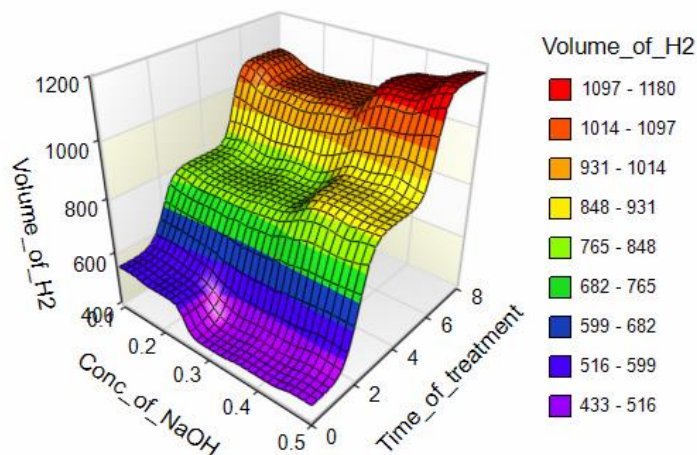


Figure 11B. surface plot of final (equilibrium) volume of hydrogen production in l/kg against time of treatment in days and concentration of NaOH in N



Figures 11B depict surface plots of the final (equilibrium) volume of hydrogen production in l/kg against time of treatment in days and concentration of NaOH in N.

The estimated equation which can be fit into those curve is given below with W is final (equilibrium) volume of H₂, T₁ is time of treatment in days and C is the Normality (concentration) of NaOH.

$$W = 458.16 - 85.77 T_1 + 86.67 C \dots\dots\dots (8)$$

Table 12B. Regression Coefficient T-Tests (T-Test of H₀: $\beta(i) = 0$) of variables, final (equilibrium) volume of hydrogen production in l/kg, time of treatment in days and concentration of NaOH in N.

Independent Variable	Regression Coefficient Reject H ₀ b(i) at $\alpha = 0.05$?	Standard Error Sb(i)	Standardized		
			Coefficient	T-Statistic	P-Value
Intercept	458.16 Yes	37.10474	0.0000	12.348	0.0000
Time_of_treatment	85.77 Yes	4.84433	0.9802	17.706	0.0000
Conc_of_NaOH	86.67 No	98.22302	0.0488	0.882	0.3949

Table 13B. Analysis of Variance for variables volume of hydrogen production in l/kg, time in sec and concentration of KOH in N for without treatment of aluminium

Source	DF	R ² Lost If Term(s) Removed	Sum of Squares	Mean Square	F-Ratio	P-Value
Intercept	1		9568027	9568027		
Model	2	0.9632	909631.3	454815.7	157.140	0.0000
Time_of_treatment	1	0.9608	907378	907378	313.502	0.0000
Conc_of_NaOH	1	0.0024	2253.333	2253.333	0.779	0.3949
Error	12	0.0368	34731.95	2894.329		
Total (Adjusted)	14		944363.3	67454.52		



The regression coefficient T test is presented in Figure. 12B and the details of the analysis of variance are presented in Tables 13B, for NaOH. In this analysis of variance table, there is a line that corresponds to each term that is included in the model. It is of great use to each and every individual who possesses categorical independent variables.

Conclusion:

The paper presents research on ecologically friendly and economically feasible hydrogen extraction technologies, focusing on the use of aluminum or similar metals to produce hydrogen. It addresses the challenges associated with commercializing various aluminum-based hydrogen generation methods and introduces a novel concept for the cogeneration of electrical and hydrogen energy. The study employs a multivariable regression analysis to forecast the relationship between the assessed variables and the rate constant, which represents a function of the mass of aluminum and the alkali concentration.

The discussion emphasizes the urgent need for renewable and clean alternatives to fossil fuels, highlighting hydrogen as a regenerative, eco-friendly fuel with a high calorific value. The paper emphasizes the significance of effective hydrogen production to facilitate the transition to a successful hydrogen-based economy. It also examines various methods for hydrogen production using aluminum and similar metals, discussing their limitations and challenges for commercialization.

In conclusion, the paper stresses the significance of developing environmentally friendly and commercially viable hydrogen production technologies for the successful establishment of a hydrogen-based economy. It emphasizes the role of aluminum in the production of hydrogen and highlights the importance of understanding the factors influencing the hydrogen production rate. Finally, the paper suggests avenues for future research and development in the field of hydrogen production technologies.

The multivariable regression analysis reveals a significant correlation between waste aluminum and alkali solutions in hydrogen production. The findings indicate that both variables enhance the reaction's efficiency, with waste aluminum exhibiting a positive correlation with hydrogen yield. The concentration of alkali is pivotal; as elevated levels accelerate the reaction rate. The interaction between waste aluminum and alkali solutions suggests that optimizing their combination can enhance hydrogen production. These findings underscore the potential for employing waste materials in sustainable hydrogen production processes, providing both environmental advantages and economic viability.



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