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# OPTIMIZATION OF PROCESS PARAMETERS TO ENHANCE INHIBITION EFFICIENCY IN CORROSION PREVENTION THROUGH $SIO_2$ COATING

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**Abstract**

This study thoroughly investigates the inhibition of corrosion efficiency using silica sand ($SiO_2$), specifically tailored for coating applications in aerospace, marine, and industrial sectors. The primary objective was to enhance corrosion efficiency beyond 90%, making it suitable for various industrial applications. To further ensure the reliability of this result, the Box-Behnken statistical design, implemented in Minitab, was used to optimize and refine the process parameters to improve corrosion efficiency. Various influencing factors, such as particle size, concentration, and pH, were systematically analyzed to determine their impact on corrosion resistance. Experimental validation confirmed that silica sand ($SiO_2$), coatings significantly enhance durability and performance under harsh environmental conditions. This research provides a foundation for developing advanced protective coatings with enhanced longevity, contributing to cost-effective and sustainable corrosion prevention solutions across multiple industries.

***Keywords:*** *Corrosion, Silica sand, $SiO_2$ coating, Corrosion prevention, Response surface methodology*

## 1. Introduction

Metal corrosion is a major problem across various industries, which causes huge economic losses every year. To overcome this issue, the protective coating is one of the resources for an effective solution. Among so many studies, it is observed that $SiO_2$ coatings have significant attention due to their exceptional barrier properties, durability, and chemical stability. These coatings can shield metal surfaces from direct exposure to corrosive environments, significantly enhancing their resistance to oxidation and degradation and increasing the lifespan of materials; silicon dioxide coating is a critical application in marine, aerospace, and other industrial sectors. There is a severe impact of corrosion on structural integrity and economic sustainability; different researchers continue to explore advanced protective coating methods for solving the industrial problem. SiO2 coatings are highly effective for enhancing corrosion resistance by acting as a robust barrier between metal surfaces and corrosive agents, thereby minimising material deterioration and

*Corresponding author email: sunitaroutray77@gmail.com prolonging operational lifespan. This study evaluated the corrosion inhibition efficiency of silicon dioxide coating by using different parameters such as pH, concentration, and particle size. These factors play a vital role in determining the coating's performance, providing insight into the effectiveness of $SiO_2$ coatings under different conditions. Corrosion efficiency in percentage was measured as the final output for optimising the silicon dioxide coatings can enhance material durability and longevity in harsh environments. Researchers are generally focused on eco-friendly methods to alleviate metal corrosion, primarily by surface treatments that reduce contact between the metal and corroding agents. Among various surface treatments, superhydrophobic surfaces have gained a significant role in enhancing corrosion resistance, making them valuable in both fundamental research and industrial applications. Numerous studies have focused on the development of silica-based composite coatings to enhance the corrosion resistance and mechanical properties of metal substrates. Fazlolahzadeh et al. (2024) examined the co-electrodeposition of Ni/$SiO_2$-$(CH_2)_3SH$ composite coatings on stainless steel under various bath conditions. Their analysis, using SEM and EDS, revealed insights into the morphology and particle distribution of the coatings [1]. Liu et al. (2023) introduced Ni-W/$SiO_2$ coatings on Q235B steel via electrodeposition, demonstrating that optimal $SiO_2$ concentrations enhance cathodic current, increase surface hardness, and reduce coating roughness [2]. Farooq et al. (2022) emphasised the significant role of corrosion in tribocorrosion performance and analysed how surface treatments impact composite coatings [3]. Li et al. (2021) proposed a corrosion protection coating through silane-functionalized rGO/$SiO_2$ nanocontainers that can reduce the rate of corrosion. They studied XRD, FTIR, XPS, SEM & TEM the confirm of the successful preparation of silane–functionalized rGO/$SiO_2$ nanocontainers. [4]. Shang et al. (2021) studied the severe corrosion

issues in the oil and gas industry, which have encouraged the shift towards eco-friendliness. The survey shows that the plant extracts effectively protect various metals, and modern stimulation tools help predict their performances [5]. Yang et al. (2020) investigated the electrodeposition of a silica-Ni hybrid layer on Q235 steel. Using FESEM, EDS, and XRD, they characterised the surface morphology, composition, and crystal structure of the coatings [6]. Pourhashem et.al. (2020) studied the polymer nanocomposite coatings reinforced with inorganic nanomaterials for superior corrosion protection due to enhanced corrosion resistance and their mechanical properties. A study shows that well-dispersed nanofillers for environmentally friendly and achieve the highest corrosion resistance [7]. Liang. Et al. (2020) Study on the galvanized steel through the immersion process the superhydrophobic surfaces containing nano-$SiO_2$ with excellent water repellence and effective corrosion resistance was prepared by a simple one-step process [8]. Rouhollahi et al. (2018) employed an electrochemical technique to deposit Ni-$SiO_2$ nanocomposite coatings on carbon steel. With ALES as an additive, the silica content reached approximately 14 vol%, significantly improving corrosion resistance, hardness, and wear resistance [9]. Kurokawa. et.al. (2018) The study investigates that $SiO_2$ forms two types of alloys, such as $CrSi_2$-Ni and CoNiCrAlY-Si, that have high resistance to inhibit corrosion very clearly in NaCl and $Na_2SO_4$ environments. These two materials provide superior high-temperature corrosion protection for the boiler systems [10]. Stambolova. Et al. (2018) They prepared a protective $SiO_2$ coating by the sol gel method plating on the stinless steel. $SiO_2$ coated steels are dipped in the NaCl medium for 346 hrs to check the corrosion resistance [11]. Bahadormanesh et al. (2017) demonstrated that Zn-Ni alloy coatings exhibit superior mechanical properties and corrosion resistance compared to standard zinc coatings, especially under high-temperature conditions [12]. Ammar. et.al. (2017)

Developing the hybrid coating epoxy-PDMS with the $SiO_2$ nanoparticle to enhance corrosion. That nanoparticle has a dispersion quality with

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improved hydrophobicity. The best corrosion resistance is shown by the 2wt% of $SiO_2$ content with increased surface hydrophobicity [13]. Kouch. (2017) The cost of corrosion is about 3-4% of their GDP, amounting to an estimated US$2.5 trillion globally. The study emphasises the integration of corrosion management into the corporate systems to achieve a significant economic rate [14]. Wang et al. (2012) explored Ni-W-P-based coatings incorporating $CeO_2$ and $SiO_2$ nanoparticles. Their findings showed that $SiO_2$ concentration plays a critical role in determining microstructural uniformity [15]. Fedel. Et al. (2012) Studies have explored that $CeO_2$ and $SiO_2$ particle fillers for the active in to an epoxy-polyester to make an organic coating. The electrochemical galvanized and neutral salt spray test results proved the effectiveness of the corrosion coating [16].

## 2. Materials And Methods

***2.1 Materials:*** Stearic acid (SA) from Shiva Chrome Chemicals Pvt. Ltd., hydrogen peroxide from Surgiplast India, ethanol from CDH, sodium hydroxide from CDH, and silicon dioxide ($SiO_2$) are commonly used in coatings due to their essential chemical properties and functionalities. Additionally, an ASTM A36 steel plate, hot-dipped in a zinc bath, was also used for the experiment.

***2.2 Methods:*** Chemical analysis of nano silica was conducted by XRF analysis. *A* hydrophobic coating was prepared using stearic acid ethanol solution, followed by a dropwise addition of hydrogen peroxide with constant stirring for 5 minutes. To this solution, nano-size silica particles were added in different weight fractions and stirred for about one hour to achieve uniform dispersion. The steel plate was cleaned with deionized water, ethanol, and a sodium hydroxide solution to ensure proper cleaning. The steel samples were immersed in this solution at 70°C for 2 hours. After immersion, they are rinsed with ethanol and dried at 70°C for 6 hours.

Electrochemical Impedance Spectroscopy (EIS) was used to measure the material's corrosion behavior and properties in a medium containing 3.5% NaCl, varying the process parameters; pH of the coating, particle size of silica, and concentration of silica to see their effect on corrosion inhibition efficiency. With the variation of the process parameters, at each instance, the corrosion inhibition efficiency was calculated by using the following formula

Inhibition Efficiency (%) = [ (Corrosion rate without coating - Corrosion rate with coating) / Corrosion rate without coating] x 100 ---------(1)

**2.3 Statistical design and modeling using Response Surface Methodology (RSM):**

RSM optimizes outcomes by analyzing the influence of multiple factors and developing models that represent their relationships. A Box–Behnken design using Minitab 22 was employed to examine the effects of three factors: cutoff particle size, concentration, and pH on corrosion inhibition efficiency. Each factor was evaluated at a low and a high level. The experimental design, including three factors and two levels, is summarized in Table 1.

**Table 1**. Levels of different Variables using Minitab 22.

| Sl. No. | Variables | Levels | |
|---|---|---|---|
| | | **Low** | **High** |
| 1 | Cut off particle Size, nm ($X_1$) | 10 | 100 |
| 2 | Concentration, % ($X_2$) | 1 | 10 |
| 3 | pH ($X_3$) | 2 | 8 |

## 3. Result & Discussion

The chemical analysis result shows that nano silica used in the coating contains 84.09% of $SiO_2$ and other impurities in small amounts (Table 2). It also contains 7.46 % of $Al_2O_3$.

**Table 2.** Chemical analysis of nano-silica particles

| **Compound** | **$Al_2O_3$** | **$SiO_2$** | **$P_2O_5$** | **Cl** | **$K_2O$** | **CaO** | **$TiO_2$** | **$Fe_2O_3$** |
|---|---|---|---|---|---|---|---|---|
| Conc. Unit | 7.46% | 84.1% | 0.50% | 0.39% | 4.0% | 0.68% | 1.34% | 0.93% |

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From the experiments, the corrosion rate is measured for each combination of the process parameters; cutoff particle size, concentration, and pH. The Inhibition Efficiency (%) is calculated using Equation 1 and the results are presented in

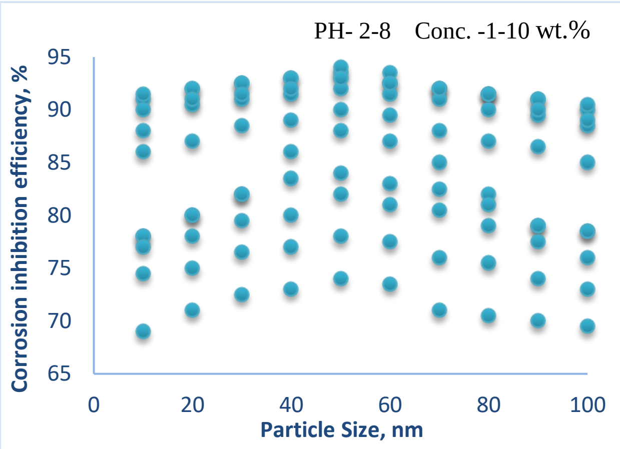



Figure 1.
Fig.1 Effect of Expected Particle Size (nm), pH, and Concentration (wt.%) on Corrosion inhibition efficiency, %.

Figure 1 illustrates the effects of different parameters on corrosion inhibition efficiency. To achieve better corrosion resistance, various parameters are considered, including particle size (ranging from 10 nm to 100 nm), pH (ranging from 0 to 8), and concentration (ranging from 1 to 10 wt.%). The corrosion inhibition efficiency varies with these parameters. When the particle size is too small, proper coating is not achieved due to the brittleness of $SiO_2$ and the presence of impurities. Similarly, extreme pH values (either too low or too high) hinder proper coating formation due to excessive acidity or alkalinity. Concentration also plays a crucial role, as too low or too high concentrations lead to reduced corrosion inhibition. Optimal corrosion resistance is observed at moderate parameter values. Specifically, a particle size of 50 nm, a concentration of 5 wt.%, and a pH of 5 yields the highest corrosion inhibition efficiency of 94%. Any deviation from these optimal conditions whether by increasing or decreasing the particle size, concentration, or pH results in a noticeable decline in corrosion inhibition efficiency.

Figure 2 illustrates the influence of concentration and pH on corrosion inhibition efficiency while maintaining a constant particle size. As both concentration and pH increase from 2 to 8, the inhibition efficiency initially improves, reaching its peak at an optimal midpoint. However, beyond this point, further increases in concentration and pH lead to a decline in efficiency. This decline is attributed to the alkaline nature of the solution and improper formation of the concentration coating.

These findings suggest that while specific concentration and pH levels enhance corrosion resistance, exceeding the optimal range diminishes the effectiveness.

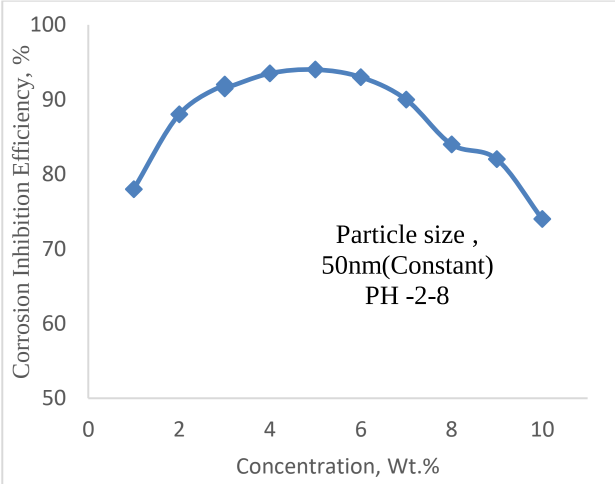



**Fig.2** Effect of Concentration (wt. %) and pH on Corrosion inhibition efficiency, %

### 3.1 Characterization of Product material

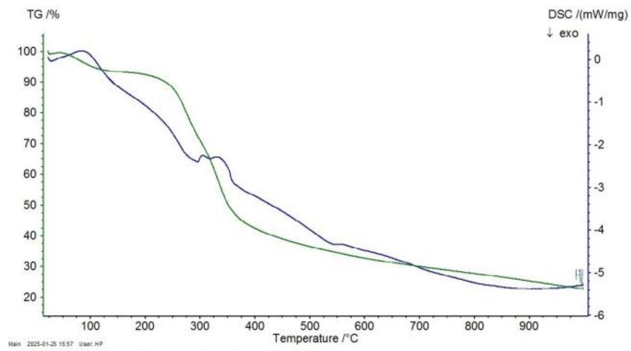



**Fig.3** TGA analysis of nano $SiO_2$ Coating for corrosion inhibition efficiency

Figure 3 illustrates that Thermogravimetric Analysis (TGA) is used to evaluate the thermal stability of $SiO_2$ in corrosion-resistant applications. This analysis helps assess moisture loss, organic residue decomposition, and structural stability at high temperatures. $SiO_2$ typically exhibits minimal weight loss, with water desorption below 200°C and organic additive decomposition between 200–650°C. Beyond 650°C, pure $SiO_2$ remains highly stable, confirming its effectiveness as a protective coating or corrosion inhibitor in high-temperature environments.

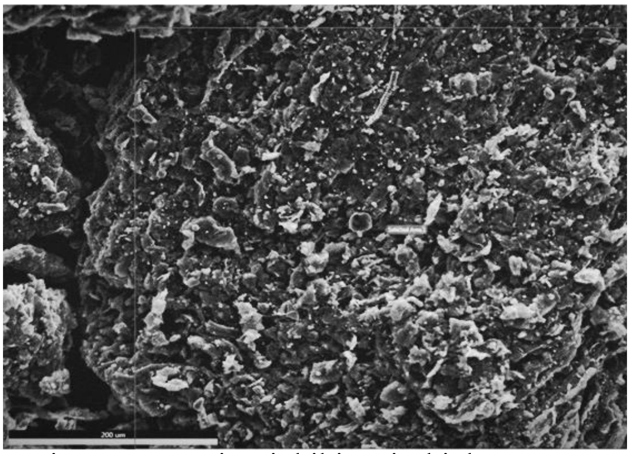


**Fig. 4** SEM analysis of nano $SiO_2$ Coating for corrosion inhibition efficiency

Figure 4 shows that SEM analysis of $SiO_2$ in corrosion studies helps evaluate oxide layer formation, surface degradation, and crack propagation. It reveals corrosion-induced morphological changes, including pitting, delamination, and the integrity of the $SiO_2$ layer. Energy Dispersive X-ray Spectroscopy (EDS) confirms the presence and elemental composition of $SiO_2$. SEM provides 200nm size structure insights into $SiO_2$'s function as a protective coating or corrosion byproduct, enhancing material durability assessments in harsh environments.

3.2. Analysis of corrosion efficiency by using RSM design and experiments using Minitab22

**Table 3.** The Box-Behnken design matrix was created using three variables and their corresponding response values.

| **Std Order** | **Run Order** | **Pt Type** | **Blocks** | **Cut off particle Size, nm ($X_1$)** | **Concentration %, $X_2$** | **PH, $X_3$** | **Corrosion inhibition efficiency, %, Y** |
|---|---|---|---|---|---|---|---|
| 7 | 1 | 2 | 1 | 10 | 5.5 | 8 | 70 |
| 6 | 2 | 2 | 1 | 100 | 5.5 | 2 | 82 |
| 10 | 3 | 2 | 1 | 55 | 10.0 | 2 | 84 |
| 3 | 4 | 2 | 1 | 10 | 10.0 | 5 | 76 |
| 12 | 5 | 2 | 1 | 55 | 10.0 | 8 | 82 |
| 2 | 6 | 2 | 1 | 100 | 1.0 | 5 | 86 |
| 15 | 7 | 0 | 1 | 55 | 5.5 | 5 | 94 |
| 11 | 8 | 2 | 1 | 55 | 1.0 | 8 | 85 |
| 4 | 9 | 2 | 1 | 100 | 10.0 | 5 | 78 |
| 9 | 10 | 2 | 1 | 55 | 1.0 | 2 | 83 |
| 13 | 11 | 0 | 1 | 55 | 5.5 | 5 | 94 |
| 5 | 12 | 2 | 1 | 10 | 5.5 | 2 | 72 |
| 14 | 13 | 0 | 1 | 55 | 5.5 | 5 | 94 |
| 8 | 14 | 2 | 1 | 100 | 5.5 | 8 | 80 |
| 1 | 15 | 2 | 1 | 10 | 1.0 | 5 | 74 |

The model is constructed based on the regression coefficients outlined in Table 3. In this formula, Y represents the increase in corrosion inhibition efficiency (%), while $x_1$, $x_2$, and $x_3$ correspond to particle size, concentration, and pH, respectively. Formula (1) estimates corrosion inhibition efficiency at approximately 94%, closely matching the experimental value of 97.11%, confirming the model's accuracy. Table 3 shows that the p-values for $x_1$, $x_2$, and $x_3$ are all below 0.001, highlighting their significant impact. The $R^2$ value of 98.97% indicates a highly precise prediction model, with minimal unnecessary elements. Experimental results confirm that silicon dioxide particle size and pH are key factors in enhancing corrosion inhibition efficiency.

**Table 4.** Output Calculation using Minitab for corrosion inhibition efficiency, % vs the Concentration, pH and Particle size

**Coded Coefficients**

| **Term** | **Coef** | **SE Coef** | **T-Value** | **P-Value** | **VIF** |
|---|---|---|---|---|---|
| Constant | 94.000 | 0.753 | 124.87 | 0.000 | |
| $X_1$, nm | 4.250 | 0.461 | 9.22 | 0.000 | 1.00 |
| $X_2$, wt% | -1.000 | 0.461 | -2.17 | 0.082 | 1.00 |
| $X_3$, pH | -0.500 | 0.461 | -1.08 | 0.328 | 1.00 |
| $X_1$, nm | -11.500 | 0.679 | -16.95 | 0.000 | 1.01 |
| $X_2$, wt% | -4.000 | 0.679 | -5.90 | 0.002 | 1.01 |
| $X_3$, pH* $X_3$, pH | -6.500 | 0.679 | -9.58 | 0.000 | 1.01 |
| $X_1$, nm * $X_2$, wt% | -2.500 | 0.652 | -3.83 | 0.012 | 1.00 |
| $X_1$, nm * $X_3$, pH | 0.000 | 0.652 | 0.00 | 1.000 | 1.00 |
| $X_2$, wt%* $X_3$, pH | -1.000 | 0.652 | -1.53 | 0.186 | 1.00 |

**Model Summary**

| S | R-sq | R-sq(adj) | R-sq(pred) |
|---|---|---|---|
| 1.30384 | 98.97% | 97.11% | 83.51% |

**Regression Equation in Uncoded Units**

| | | |
|---|---|---|
| Corrosion inhibition efficiency | = | 43.88+ 0.7870 ($X_1$, nm) + 3.000 ($X_2$, wt.%) + 7.463 ($X_3$, pH) - 0.005679 , ($X_1$, nm) ($X_1$, nm) ($X_1$, nm) * ($X_1$ , nm) - 0.1975 ($X_2$, wt.%) * ($X_2$, wt.%) - 0.7222 ($X_3$, pH) *($X_3$, pH) - 0.01235 ($X_1$, nm) *($X_2$, wt.%) - 0.0 ($X_1$, nm) *($X_3$, pH) - 0.0741 ($X_2$, wt.%) *($X_3$, pH) |

The predicted increase in corrosion inhibition efficiency depends on key variables, including particle size, silicon dioxide concentration, and process pH. The optimal leaching conditions 55 nm particle size, 5.5% concentration, and pH 5 demonstrate maximum efficiency in the corrosion inhibition process. These optimal conditions are detailed in Table 4.

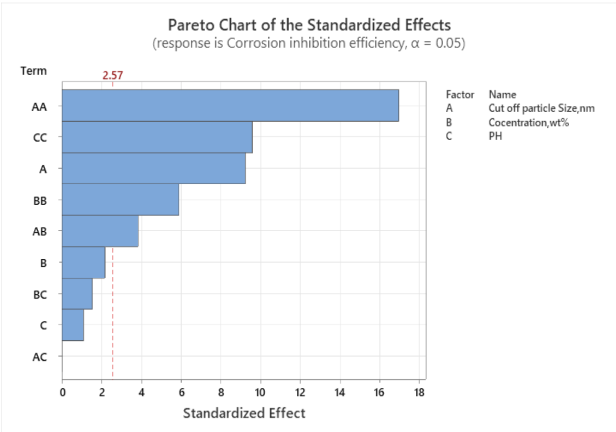



**Figure 5.** The effect of corrosion inhibition efficiency is illustrated using a Pareto chart with standardized effects

The Pareto chart in Figure 5 displays the effects of various factors, ranked from highest to lowest impact. A reference line marks statistically significant effects, based on a chosen significance level (α). This analysis helps quantify each variable's influence on the response. The chart indicates that corrosion inhibition efficiency and particle size are the most significant factors affecting $SiO_2$ particle size. These (RSM) with the Response Surface Methodology, experimental results and predictive models. This reinforces the reliability analysis, confirming the consistency between findings align of the statistical approach in understanding key factors influencing $SiO_2$ particle behavior.

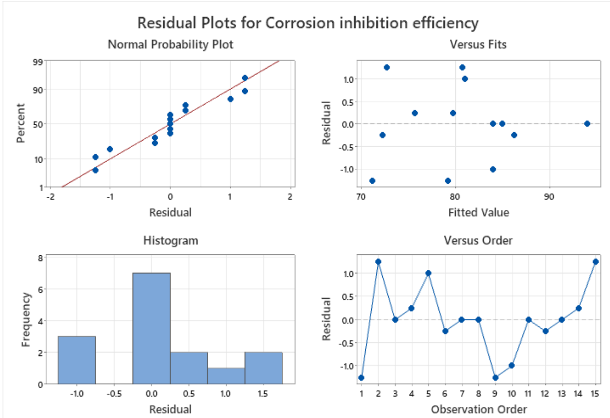
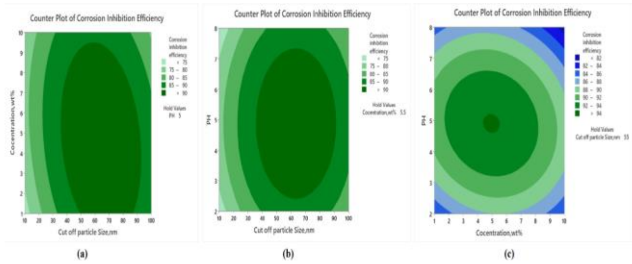



**Figure 6.** Diagnostic plots for corrosion inhibition efficiency: (a) Standardized residuals vs. normal % probability, (b) Predicted residuals vs. standardized residuals, (c) Histogram of residuals vs. frequency, (d) Residuals vs. observation order plot.

Figure 6. explores the relationship between corrosion inhibition efficiency quantity and key statistical measures to assess model reliability. With high $R^2$ (98.97%) and adjusted $R^2$ (97.11%), the model effectively explains data variability, demonstrating strong predictive capability.

Figure 6a examines whether errors follow a normal distribution, essential for statistical accuracy. Figure 6b evaluates scatter plots for homoscedasticity, ensuring consistent error variability. Figure 6c detects skewness or outliers that may affect predictions. Figure 6d confirms no systematic error patterns, validating model accuracy.



These analyses, based on the Box–Behnken design, affirm the model's robustness and reliability in predicting corrosion inhibition efficiency.

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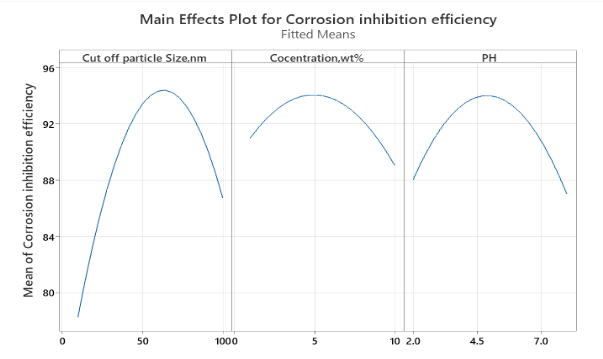



**Figure 7.** Responses using corrosion inhibition efficiency with the use of Conc. size and pH

Figure 7 show that particle size has the greatest impact on corrosion inhibition efficiency, surpassing the effects of pH and concentration. This emphasizes the crucial role of particle size in the removal process, highlighting its dominant influence over other factors in optimizing corrosion resistance.

**Figure 8.** Factorial Response for corrosion inhibition efficiency using different Process factors

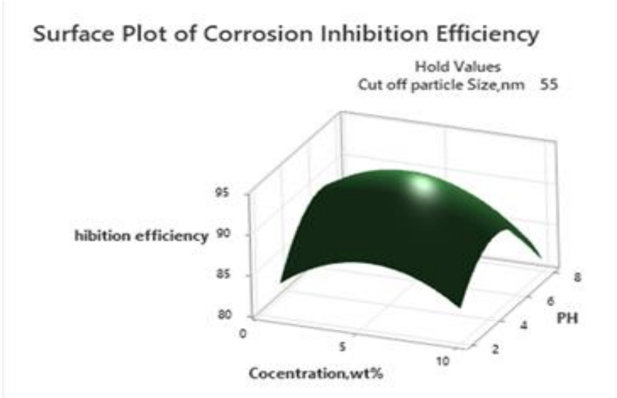
Figure 8. presents the average corrosion inhibition efficiency, calculated across various concentrations of a silicon dioxide mixture ranging from 1% to 10%. The experiment demonstrates that as the cutoff particle size increases from 10 nm to 100 nm, corrosion inhibition efficiency also improves. The graph visually represents this trend at three key cutoff particle sizes—10 nm, 100 nm, and across the full concentration range. Additionally, the results are analyzed under precisely specified pH conditions, highlighting the influence of particle size and concentration on inhibition efficiency, and offering valuable insights into optimizing conditions for enhanced corrosion resistance.

**Figure 9 A.** Contour Plot of Cut-off particle size, nm vs Concentration, % withhold value of pH 5

**Figure 9 B.** Contour Plot of Cut-off particle size, nm vs pH withholds value of Concentration, 5.5%.

**Figure 9 C.** Contour Plot of Conc., % vs pH withholds value of Cut-off particle size, 55nm.

Figures 9A, B, and C present contour plots that illustrate the interactions between initial concentration and cutoff particle size, cutoff particle size and pH, and concentration and pH. These plots reveal that a medium cutoff particle size significantly enhances corrosion inhibition efficiency. However, achieving this improvement requires maintaining a medium pH. The visual representation highlights the interdependence of these factors, emphasizing the need for balanced conditions to maximize efficiency. This analysis provides deeper insights into optimizing corrosion inhibition by adjusting key parameters, ensuring improved performance in various applications, particularly in industries where corrosion resistance is critical.



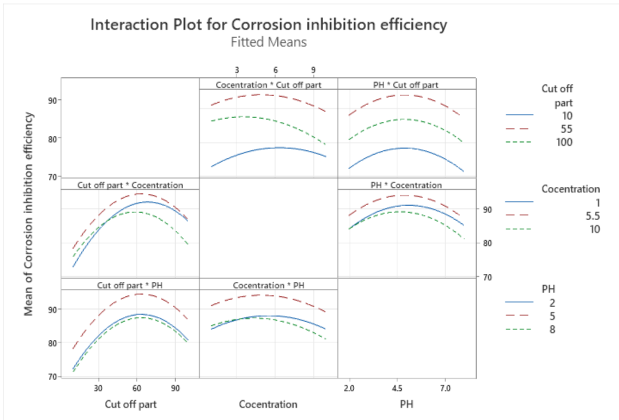




**Figure 10.** Surface Plot of corrosion inhibition efficiency percentage with different particle size, concentration, and pH 2-8.

Figure 10 indicates that as the concentration increases from 1% to 10%, the corrosion inhibition efficiency improves from 70% to 94%. This highlights the significant influence of both cutoff particle size and pH on enhancing corrosion inhibition, as supported by Equation 1 and the trends observed in the plot. Additionally, a higher concentration further boosts inhibition efficiency. The software identifies the optimal conditions as a 5.5% concentration, a pH of 5, and a cutoff particle size of 55 nm, achieving approximately 94% corrosion inhibition efficiency. These findings provide valuable insights into the interactive effects of these factors, helping to determine the most favorable conditions for applications in the painting industry.

## 4.0 Conclusion

The following conclusions are drawn from the study of using silica as a coating material to enhance corrosion resistance.

- Coatings containing nano silica particles applied on a galvanized steel plate to observe the effect of silica in corrosion prevention.
- Three process parameters; pH, particle size and concentration of silica have been varied over a range to assess their effect on corrosion inhibition efficiency.
- Applying RSM, it is found that at 5.5% concentration, pH value of 5, and a cutoff particle size of 55 nm, approximately 94% corrosion inhibition efficiency is achieved.
- Experimental results confirm that silicon dioxide particle size and pH are key factors in enhancing corrosion inhibition efficiency.
- The $R^2$ value achieved from the statistical model is 98.97%, which indicates a highly precise prediction model, with minimal unnecessary elements.

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