

EFFECT OF PROCESS VARIABLES ON THE CORROSION INHIBITION PERFORMANCE OF *AGERATUM CONYZOIDES* ON STRUCTURAL STEEL IN HCl - FUZZY LOGIC APPROACH

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Abstract The aim of this study is to optimize the process variables to achieve a more efficient *Ageratum Conyzoides* extract (ACE) inhibitive performance on structural steel in 1 M HCl acid, using the integrated Taguchi-fuzzy logic technique. Optimization of multiple performance characteristics of weight and corrosion rate; was achieved via a multiple response performance index (MRPI) from corrosion inhibition parameters of inhibitor concentration, temperature and exposure time. The predictive model determined that the setting of inhibitor concentration of 2 g/cm³, temperature of 30°C and exposure time of 2 days were the optimal setting for maximum inhibitive corrosion performance. The optimal setting was verified and validated by a confirmatory experiment, indicating a significant improvement of 0.634 in the actual MRPI value when the integrated Taguchi-Fuzzy logic optimization model was employed.

Keywords: Steel, Fuzzy logic, Corrosion inhibition, Optimization, Taguchi

I. INTRODUCTION

Our environment is getting progressively corrosive to all materials, including all metals and alloys. Contributing elements include contaminated air and water as well as a variety of industrial by-products such fuel gases, ammonia, sulphur dioxide, chlorine, and ammonia. Particularly corrosive are inorganic acids including nitric, sulphuric, and hydrochloric [1].

Structural steels are widely used in industry. Corrosion is caused by an unintentional yet harmful reaction with the exposed environment. Corrosion is a complex process that causes significant financial losses both directly and indirectly. The most promising and affordable way to combat corrosion is to use inhibitors.

Through their effective restriction of the active sites, inhibitors safeguard metals from corrosion in an environment [2].

The evaluation of weeds extracts and correlation in between their active constituents (having hetero atoms such as N, O, P and aromaticity in them) and the anti-corrosion property on several metals and their alloys have gained a popularity [3]. A lot of studies have used different green inhibitors, leading researchers to suggest that plant extracts contain certain antioxidants that made them good corrosion inhibitors. *Ageratum conyzoides* extract (ACE) contains several bioactive substances, including as tannins, terpenoids, chromenes, benzofurans, coumarins, alkaloids, and flavonoids [4].

Some of the studies on green inhibitor include: *Picralima nitida* leaves extract ([5], *Pomegranate peels* aqueous extract [6], Bitter kola leaf extract [7], *Euphorbia heterophylla* extract [8], *Azadirachta indica* seed extract [9], *Carica papaya* extract [10], Castor leaf extract [11], *Ficus thonningii* bark

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extract [12]. There is limited literature on the corrosion inhibition performance of *Ageratum conyzoides*. This study, investigates the evaluation of process variables on the corrosion inhibition performance of *Ageratum conyzoides* on structural steel in 1 M HCl using the integrated Taguchi-fuzzy logic approach. The fuzzy logic technique has proven to be a more accurate optimization technique than the traditional regression analysis using response surface methodology [13]. The study involves three input variables of inhibition concentration, temperature and exposure time, while the response (output) variables are weight loss and corrosion rate respectively.

II. MATERIALS AND METHODS

A. Material Preparation

The chemical composition of the structural steel (UNS G10170) utilized in this investigation, was acquired from a local vendor Donasulu steel limited Effurun, Delta state, Nigeria, and EDX analysis was carried out on the steel to determine its elemental composition, as shown in Table 1. The dimensions of the steel samples were 20 mm × 20 mm × 10 mm. After that, the steel samples were polished using emery paper with different grit levels, cleaned with a brush, fully rinsed in deionized water, allowed to air dry, and then preserved in a desiccator. After soaking in ethanol for three days, triple filtering, and evaporation, ACE leaves were dried and ground into a fine powder. This powder was then used to create the ACE extract, which will act as the study's inhibitor.

B. Method

i. Weight loss test

Weight loss measurements were performed by total immersion technique, using varied concentrations of ACE inhibitor in hydrochloric acid solution using matrix interactions generated according to Taguchi design of experiment. The test coupons'

Table 1: Result of the EDX Analysis on structural steel

Element	% Weight
Carbon	0.17
Silicon	0.31
Manganese	0.78
Phosphorus	0.03
Sulphur	0.03
Copper	0.51
Nickel	0.09
Chromium	0.05
Molybdenum	0.008
Aluminium	0.047
Nitrogen	0.007
Iron	97.968

weights were measured and noted before and after each exposure period. Equations (1) and (2) were used to compute the weight loss and corrosion rate, respectively.

$$W = W_1 - W_2 \quad (1)$$

In this case, W represents the weight loss, While W_1 and W_2 represent weight of steel coupon before and after immersion respectively.

$$CR = 87.6 \times \frac{W}{DAT} \quad (2)$$

Where CR = corrosion rate in mm/yr., D = density of metal in g/cm³, A = total exposed surface area of the steel in cm² and T is the Time in hours respectively

ii. Taguchi design of experiment

This study examined the various performance features in the inhibition corrosion performance of *Ageratum conyzoides* in 1 M HCl using the combined Taguchi-fuzzy logic technique.

MINITAB 19 computer software was used to generate the process variables interactions using the Taguchi design of experiment of L9 orthogonal array. Tables 2 and 3, respectively, exhibit the three-level process variables of inhibitor concentration, temperature, and exposure time as well as the Taguchi L9 orthogonal array.

The signal-to-noise ratio (S/N) is employed in the Taguchi method. Developing processes and products that are immune to noise, is the goal of employing the S/N ratio as a performance metric [14]. The S/N ratio shows how consistently a process or product performs in the presence of noise factors. Depending on the type of performance, Taguchi divided a system's performance characteristics into three categories according to [15]: 1) the nominal-the best; 2) the lower-the-better; and 3) the higher-the-better respectively. The least amount of weight loss and corrosion rate are required to get the best corrosion inhibition performance. Consequently, lower-the-better, was chosen as the preferable option in this study based on equation (3) according to [16].

Lower-is-better:

$$S/N = -10 \log \left(\frac{\sum_{i=1}^n y_i^2}{n} \right) \quad (3)$$

Where y is the observed data, n is the number of observations and y_i is the mean value of the observed experimental data.

iii. Fuzzy Logic

The linguistic variable, established by Zadeh [17], is the fundamental ingredient of fuzzy logic. A variable that has words as its values rather than numbers is called a linguistic variable. Because complex equations make many systems impossible to adequately model, traditional solution techniques are no longer practical in these systems.

A fuzzy logic unit is made up of a fuzzifier (Figure 1), membership functions (MFs) (shown in Figure 2), a fuzzy rule base (as depicted in Figure 3), an inference engine, and a defuzzifier (as displayed in Figure 4). The fuzzifier in the fuzzy reasoning system mainly uses MFs to fuzzify the S/N ratios. A MF is a graph that shows the mapping between each input value and a membership value, also known as the degree of membership that ranges from 0 to 1. The inference engine then executes a fuzzy interface in order to provide a fuzzy value based on the fuzzy rules and MF. Linguistic rule bases are developed based on experimental observations; for example, if inhibitor concentration is high, temperature is low and exposure time is high, then corrosion rate is low. Ultimately, the multiple response performance index (MRPI), a non-fuzzy value, is created from the fuzzy value by the defuzzifier. This study adopts the triangular MF which is the most widely used, to activate fuzzy rules.

iv. Optimization Technique

To maximize the effectiveness of corrosion inhibition, the following process was implemented:

1. Use the L9 orthogonal array from Taguchi to carry out the trials.
2. Calculate the signal-to-noise (S/N) ratio using the experimental results. The performance characteristics' divergence from the intended values can be quantified using the S/N ratio.
3. Create the fuzzy rules. After fuzzifying the signal-to-noise ratio for each performance metric, fuzzy reasoning based on the fuzzy rules yields a single MRPI. The corrosion inhibition process is optimized with the help of the MRPI.

Table 2: Factors for structural steel *Ageratum Conyzoides* induced corrosion inhibition.

Factor	Code	Unit	Level 1 (Low)	Level 2 (Medium)	Level 3 (High)
Inhibitor Concentration	A	(g/cm ³)	2	4	6
Temperature	B	°C	30	40	50
Exposure Time	C	Day	1	2	3

Table 3: Taguchi L9 Orthogonal array and experimental results for MRPI

Run	A	B	C	Weight loss (mg)	S/N (dB)	CR (mm/yr.)	S/N (dB)	MRPI	S/N (dB)
1	A ₁	B ₁	C ₁	0.0066	43.6091	0.00038	68.4043	0.789	-2.0585
2	A ₁	B ₂	C ₂	0.0086	41.3100	0.00022	73.1515	0.866	-1.2496
3	A ₁	B ₃	C ₃	0.0270	31.3727	0.00052	65.6799	0.496	-6.090
4	A ₂	B ₁	C ₂	0.0090	40.9151	0.00026	71.7005	0.756	-2.4296
5	A ₂	B ₂	C ₃	0.0145	36.7726	0.00028	71.0568	0.689	-3.2356
6	A ₂	B ₃	C ₁	0.0427	27.3914	0.00248	52.1110	0.0812	-21.8089
7	A ₃	B ₁	C ₃	0.0117	38.6363	0.00034	69.3704	0.654	-3.6884
8	A ₃	B ₂	C ₁	0.0177	35.0405	0.00103	59.7433	0.422	-7.4938
9	A ₃	B ₃	C ₂	0.0464	26.6696	0.00135	57.3933	0.218	-13.2309

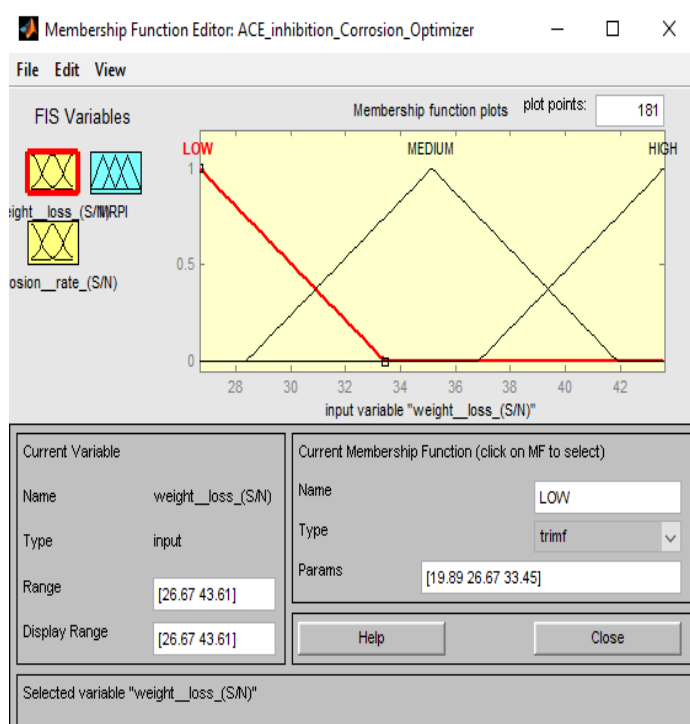
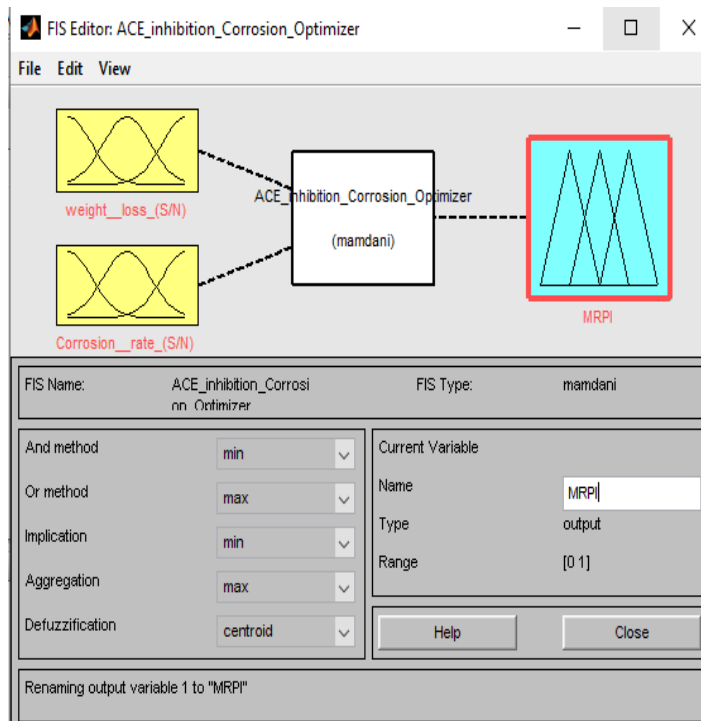


Fig. 1: Main Fuzzy logic interface system

Fig. 2: Fuzzy logic membership function editor

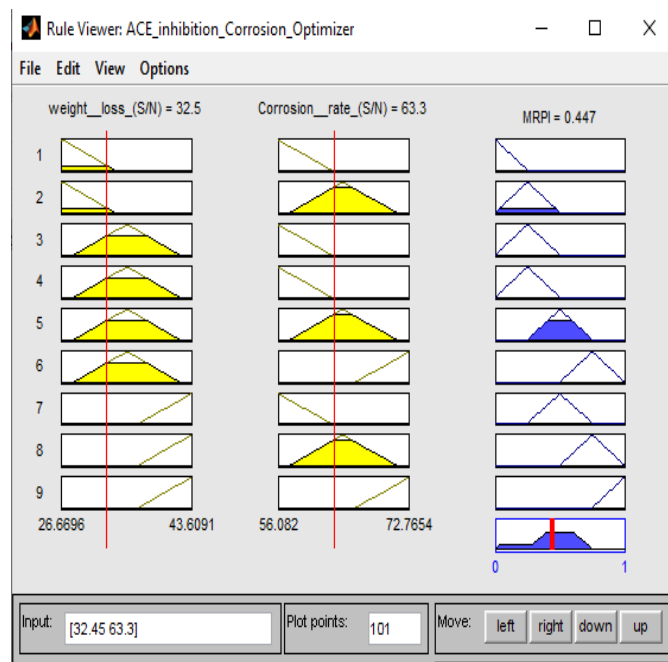
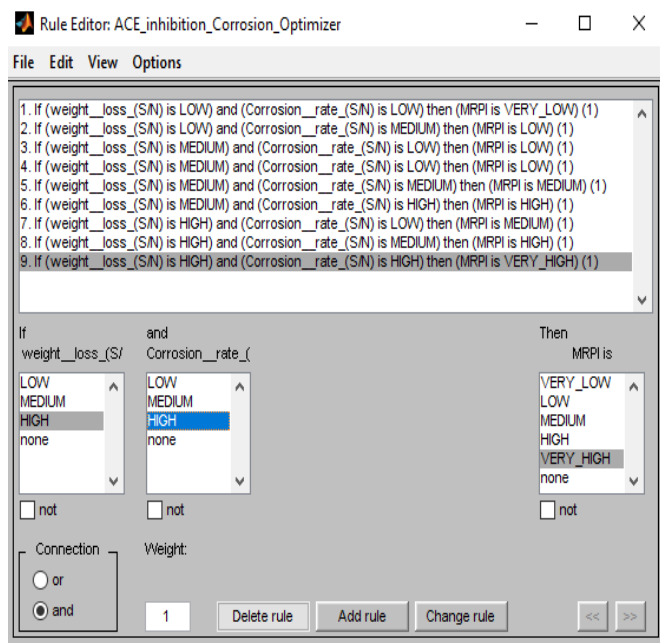


Fig. 3: Rule editor for process parameters

Fig. 4: Rule viewer for process parameter

4. Use statistical ANOVA and the MRPI to analyze the experimental data.
5. Choose the optimum levels of process parameters
6. Conduct an experiment to confirm the optimum parameters.

III. RESULTS AND DISCUSSION

Table 3 displays the experimental findings for the MRPI, S/N ratio, weight loss, and corrosion rate. The fuzzy logic unit was analyzed using the MATLAB 2007b computer software package to produce the MRPIs. The optimal inhibition corrosion parameters for the ACE corrosion inhibition performance may be found from the MRPI response table (Table 4) and the MRPI response plot (Figure 5). The multiple performance qualities, or the combined performance characteristics of weight loss and corrosion rate, are essentially higher-the-better MRPI. Experimental results from Table 4, show that the parameters combination for experiment 2 has the largest MRPI value of 0.866. Consequently, experiment 2 combination of corrosion inhibition parameters, is the optimum combination, for attaining multiple performances simultaneously for the nine runs of the experiments. Figures 6 (a-c), show the 3D surface plots of corrosion rate. From Figure 6a, with exposure time on hold at 2 days, corrosion rate increases with increasing temperature and inhibitor concentration. Figure 6b also shows that when temperature is held at 40°C, corrosion rate decreases with increasing inhibitor concentration with slight sensitivity to exposure time. It is deduced from Figure 6c that when inhibitor concentration is held constant at 4 g/cm³, corrosion rate increases at increasing levels of temperature and exposure time respectively. Contour plots of corrosion rate in

Figure 7, affirm the stated observations. Figure 7a clearly shows that corrosion rate increases with rising temperature and inhibitor concentration [18], maximum corrosion being attained at the temperature range of 47-50 °C. Figure 7b illustrates declining corrosion rate at longer exposure time and lower inhibitor concentration, perhaps as a result of the formation of corrosion products blocking the active cathodic and anodic sites [19]. Contour plot in Figure 7c, highlights the effect of temperature and exposure time on corrosion rate; showing that with decreasing temperature, corrosion rate diminishes with increasing time of exposure, attaining it lowest level at 30°C after 3 days of exposure time.

Similarly, Figure 8a shows that, increase in weight loss accompanies increasing temperature with little reaction to exposure time. Figure 8b demonstrated that, increasing exposure time leads to slight increase in weight loss followed by fairly stable loss of weight with inhibitor concentration. Surface plot of Figure 8c, indicates increasing weight loss at increasing temperature and inhibitor concentration. These assertions are further illustrated by Contour plots of Figure 9. Figure 9a of the contour plots, reveals that corrosion rate is more dependent on temperature than inhibitor concentration as it is more sensitive to changes in temperature. Figure 9b shows that there was an initial increase in weight loss which later became stable with increasing exposure time with respect to inhibitor concentration. The contour plot of Figure 9c, demonstrates that weight loss rises with reduction in exposure time and ascending temperature. It is obvious that elevating the environment temperature affects at the same time both the cathodic and anodic reactions. The temperature increase

catalyzes the reduction of protons and involves an increase of the passive current density [20]. Thus Figure 6c indicates that the metal sample underwent corrosion faster for decreasing period of exposure times, which agrees with earlier findings of [2].

The relative significance among the factors can be analyzed through an analysis of variance (ANOVA.). With the aid of MINITAB 19 computer software package, ANOVA was used to analyze which inhibition corrosion factors significantly affect the performance characteristics. From the results generated from ANOVA in Table 5, it is clearly determined that

temperature with 48.11%, was the most significant inhibition corrosion factors affecting corrosion rate followed by exposure time (30.13 %) and then inhibitor concentration (15.36 %). Larger values of the mean MRPI in the graph (Fig. 5) or in the MRPI table (Table 4) indicate that the smaller is the variance of the performance characteristics around the desired value, the greater the performance characteristics. Consequently, with respect to the mean MRPI response plot and table, the optimum factor combination for corrosion inhibition performance is $A_1B_1C_2$, that is, inhibitor concentration of 2 g/cm³ (level 1), temperature of 30 °C (level 1) and exposure time of 2 days (level 2) respectively.

Table 4: MRPI mean response values (higher is better)

Factor	MRPI Mean			Maximum
	Level 1	Level 2	Level 3	
Inhibitor concentration (A)	0.7170	0.5087	0.4313	0.7170
Temperature (B)	0.7330	0.6590	0.2651	0.7330
Duration (C)	0.4307	0.6133	0.6130	0.6133
Mean of the sum total of MRPI = 0.5524 dB				

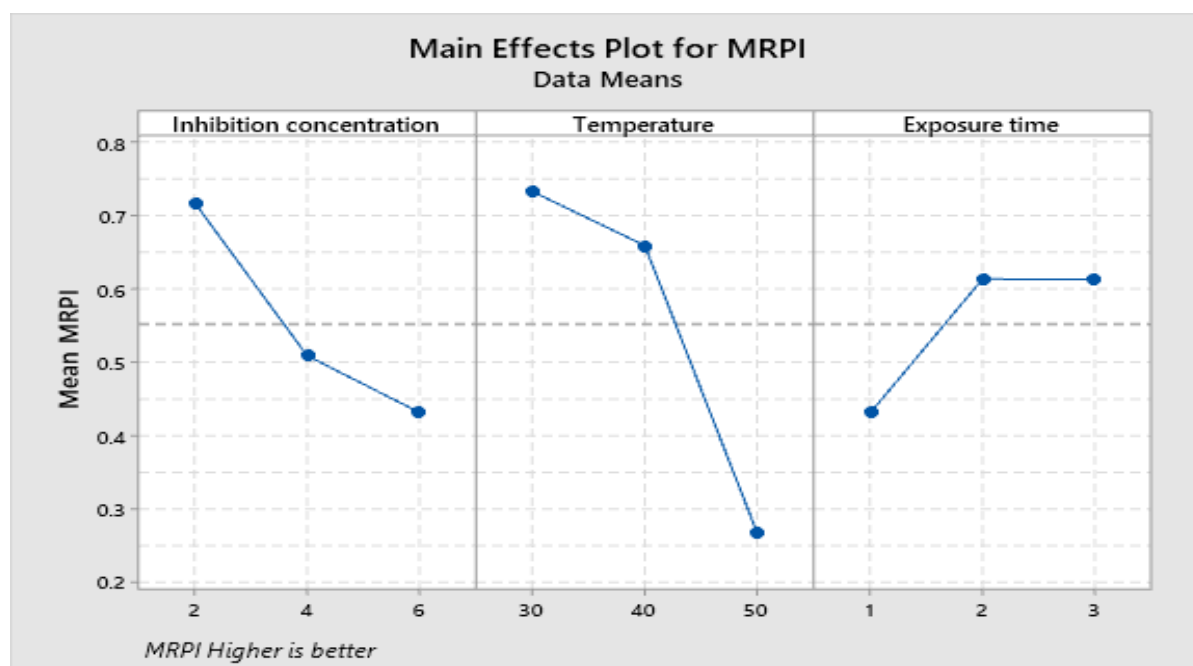


Figure 5: Main Effects plot for MRPI of inhibition parameters

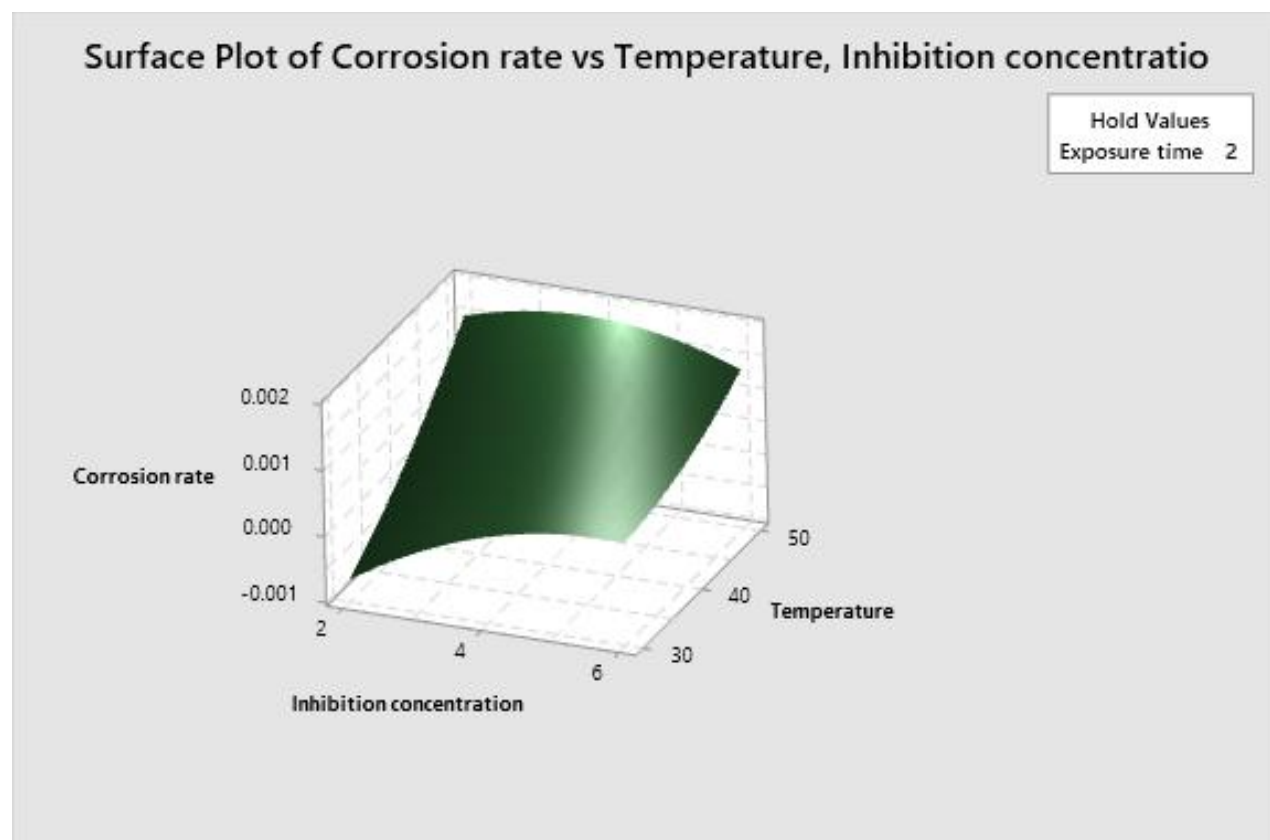


Figure 6a: Surface plot corrosion rate against temperature, inhibitor concentration

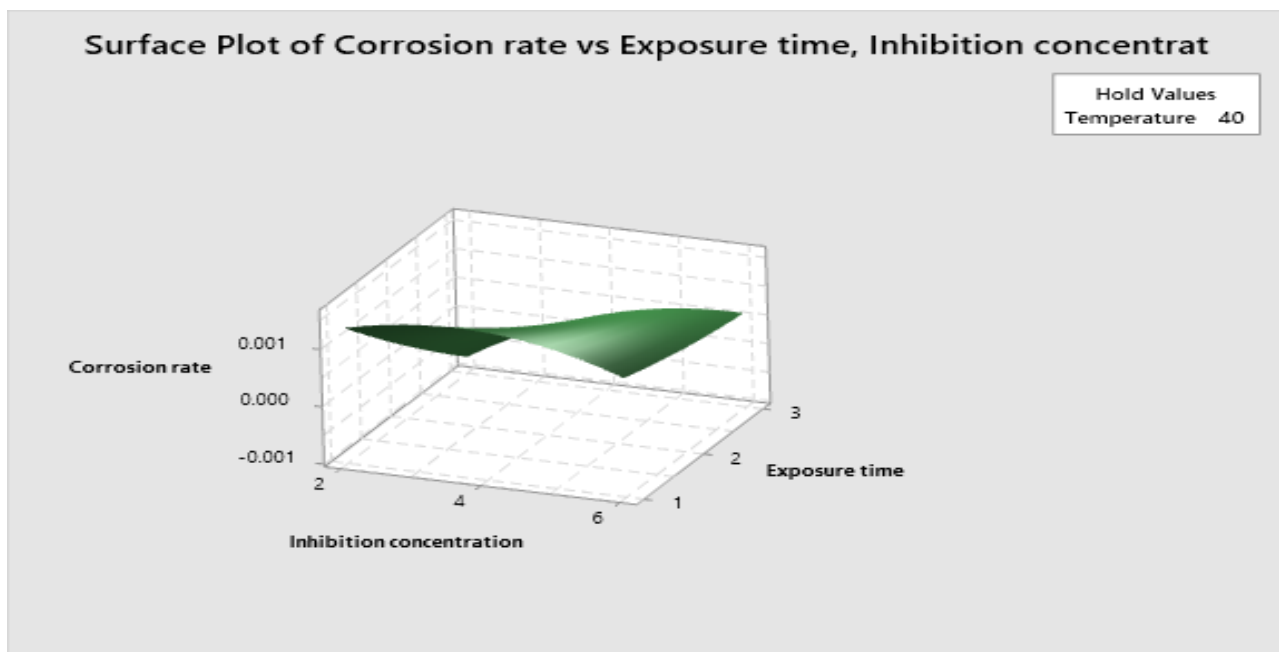


Figure 6b: Surface plot corrosion rate against inhibitor concentration, exposure time

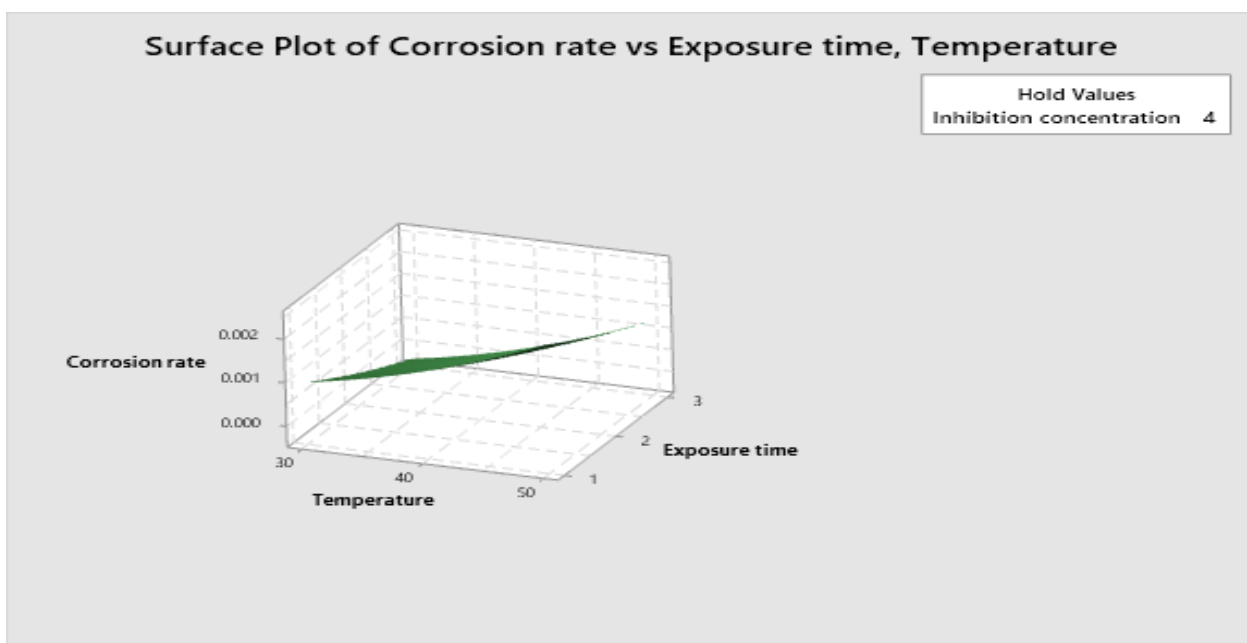


Figure 6c: Surface plot corrosion rate against temperature, exposure time

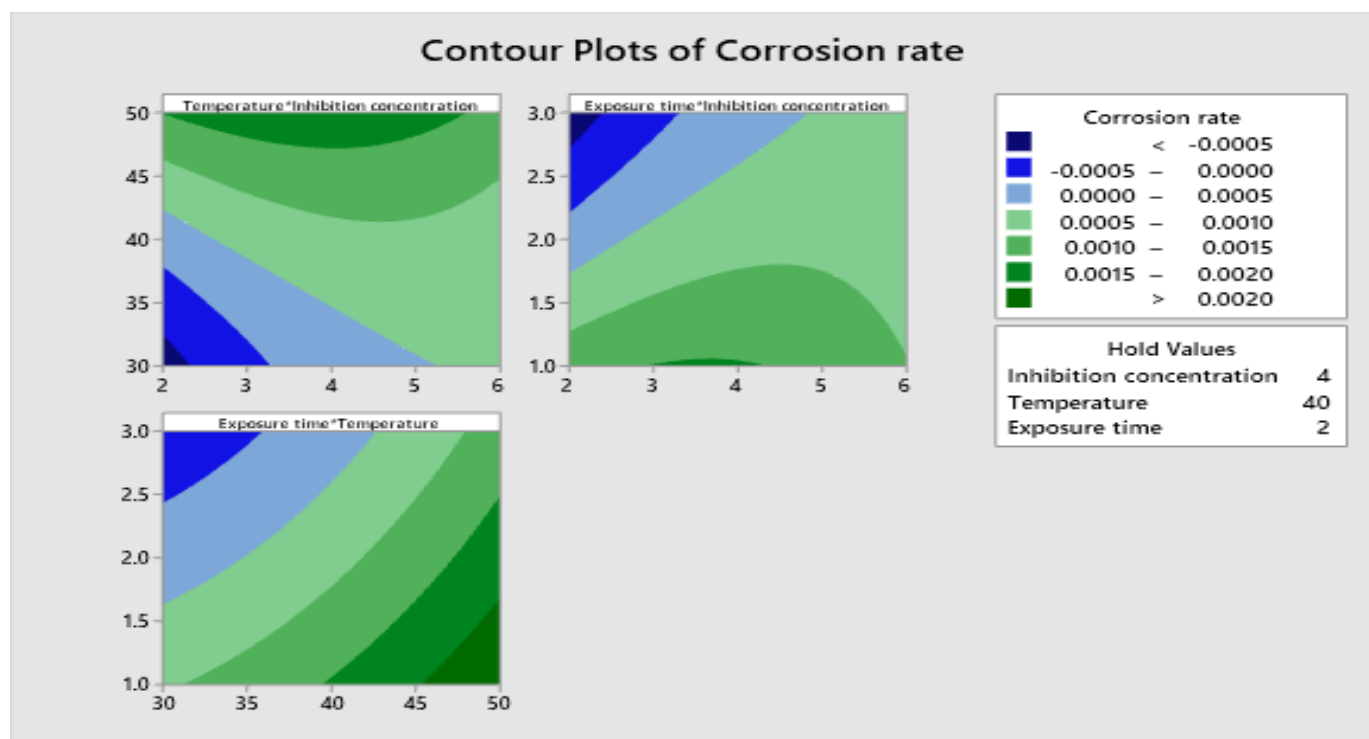


Figure 7: Contour plots of corrosion rate

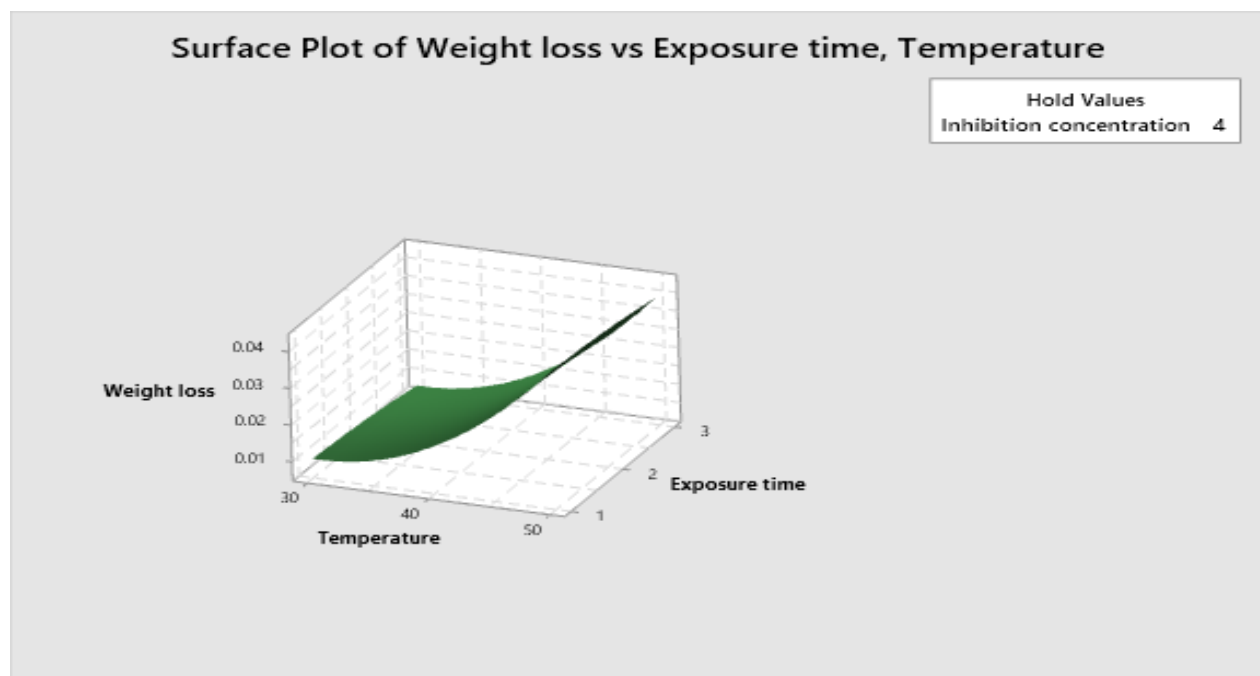


Figure 8a: Surface plot weight loss against temperature, exposure time

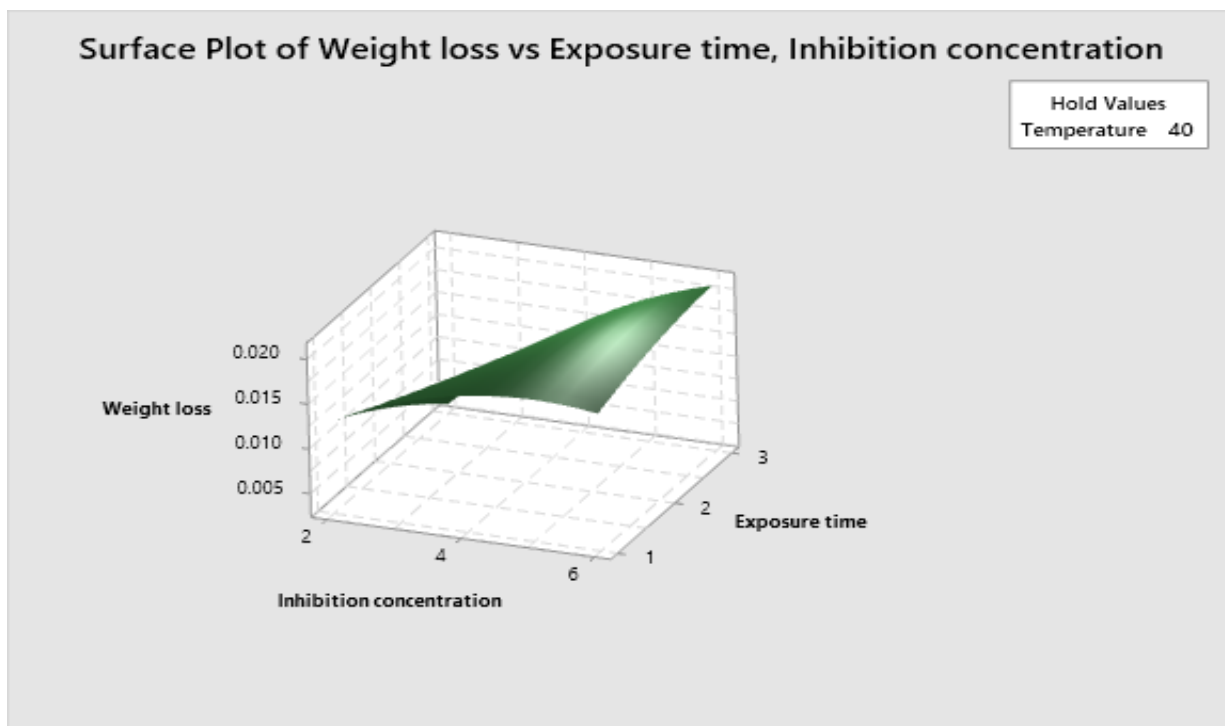


Figure 8b: Surface plot weight loss against inhibitor concentration, exposure time

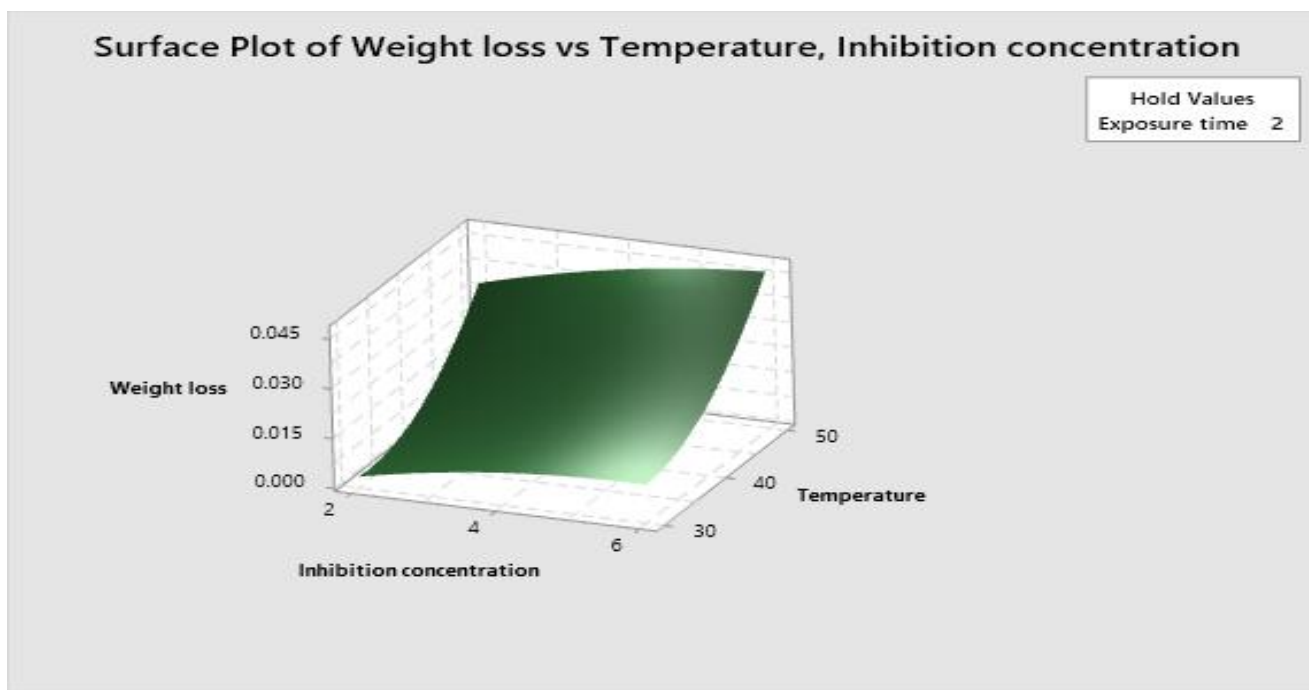


Figure 8c Surface plot weight loss against inhibitor concentration, temperature



Figure 9: Contour plots of weight loss

Table 5: Analysis of variance (ANOVA) for corrosion rate

Source	DF	Seq SS	Contribution	Adj SS	Seq MS	F-Value	P-Value
Inhibition concentration	2	0.000001	15.36%	0.000001	0.000000	2.39	0.295
Temperature	2	0.000002	48.11%	0.000002	0.000001	7.50	0.118
Exposure time	2	0.000001	30.13%	0.000001	0.000001	4.70	0.175
Error	2	0.000000	6.41%	0.000000	0.000000		
Total	8	0.000005	100.00%				

A. Confirmatory Test

After identifying the optimal level of the process parameters, the final step is to predict and verify the improvement of the multiple performance characteristic using the optimal level of the process parameters. The purpose of the confirmation test is to validate the deductions drawn during the analysis phase. The predicted or estimated MRPI value using the optimal level of the process parameters can be calculated according to equation (4). Consequently, a new experiment was carried out using the optimal levels of the corrosion inhibition parameters to validate the improvement of the multiple performance characteristics.

$$N = N_a + \sum_1^n (N_o - N_a) \quad (4)$$

Where N is the calculated or predicted MRPI,
 N_a is the average or mean of the sum total of the MRPIs of all the runs

N_o is the average of the MRPIs at optimal level of the process parameters

and n is the relevant corrosion inhibition parameters for the MRPI

The results from the confirmation test, are presented in Table 6. This table shows the predicted and actual experimental MRPI values. It is clearly seen from Table 6, MRPI is increased from 0.247 to 0.881, indicating a significant improvement of 0.634 in MRPI. Also, since the desired output for the corrosion inhibition process is lower weight loss and corrosion rate, from the results presented in Table 6, there was a significant improvement (reduction) in the weight loss and corrosion rate respectively.

Hence, based on the results of the confirmatory test, the optimum factor combination for corrosion inhibition performance is ($A_1B_1C_2$), that is, inhibitor concentration of 2 g/cm³ (level 1), temperature of 30 °C (level 1) and exposure time of 2 days (level 2) respectively was validated.

Table 6: Confirmation test results for predicted and actual MRPI

	Starting levels of corrosion inhibition factors	Optimal levels of corrosion inhibition factors	
		Prediction	Experiment
Levels combination	$A_1B_1C_1$	$A_1B_1C_2$	$A_1B_1C_2$
Weight Loss	0.207		0.0084
Corrosion Rate	0.00157		0.00024
MRPI	0.247	0.9585	0.881
Increase in MRPI = 0.634			

IV. CONCLUSION

This study was carried out to determine the optimal corrosion inhibition process factors required for a more efficient *Ageratum conyzoides* extract inhibitive performance on structural steel in 1 M HCl acid, using the integrated Taguchi-Fuzzy logic technique; and hence the following conclusions were arrived at:

1. The optimum factor combination for ACE corrosion inhibition performance is $(A_1B_1C_2)$, that is, inhibitor concentration of 2 g/cm³ (level 1), temperature of 30°C (level 1) and exposure time of 2 days (level 2)
2. Temperature with 48.11%, was the most significant factor affecting corrosion rate followed by exposure time (30.13 %) and then inhibitor concentration (15.36 %).
3. The integrated Taguchi-Fuzzy logic predictive model achieved an increase of 0.634 in MRPI, from an actual MRPI of 0.207 to predicted MRPI of 0.881 viz. weight loss and corrosion rate
4. The integrated Taguchi-Fuzzy logic is an effective predictive model for the optimization corrosion inhibition performance characteristics

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