Numerical analysis of the inhibition effect of *Commiphora myrrha* and *Cymbopogon nardus* plant extracts on low carbon steel corrosion in simulated industrial environment

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ABSTRACT

The corrosion inhibition properties of specific concentrations of *Commiphora myrrha* (CM), *Cymbopogon nardus* (CN) green chemical compounds and their combined admixture (CMCN) on low carbon steel in dilute H_2SO_4 and HCl solution was studied by weight loss analysis. Results show CM performed poorly at low concentrations (0.5% − 1.25% CM) with optimal inhibition value of 51.41% compared to CN which performed effectively at all concentrations with inhibition value generally above 85%. Performance of CM and CN compound in HCl solution were generally similar. Both compounds exhibited poor inhibition efficiency below 60% at low concentrations (0.5% − 0.75% concentration). At higher concentrations, their inhibition efficiencies were generally above 70%, with optimal values of 83.05% and 96.07% at 1.5% CM and 1.75% CN concentrations. Admixture of CM and CN inhibitor (CMCN) performed poorly in H_2SO_4 solution with inhibition value below 60% at all concentrations. This contrast the observation in HCl were it performed effectively at all concentrations with inhibition efficiency generally above 80%. Statistical analysis through ANOVA shows inhibitor concentration is the only statistically relevant variable influencing the performance outputs of the inhibitors with values of 92.29% and 88.48% for CM and CN in H_2SO_4, and 41.40% and 95.25% in HCl. Values for CMCN are 69.57% and 4.69% in H_2SO_4 and HCl solution. Standard deviation calculations show 33% and 98% at + 11.93% and + 3.24%% margins of error in H_2SO_4, and 25% and 53% at + 10.96% and ± 12.62% margins of error in HCl of CM and CN inhibition efficiency are above the 80% effective inhibition threshold value. Values for CMCN are 0% in H_2SO_4 and 100% in HCl which are above the 80% threshold.

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1. Introduction

The moderate cost of low carbon steels compared to other steel grades combined with their malleable metallurgical, mechanical and physical properties is accountable for their immense utilization in construction, pipelines, machine components, automobiles, marine, agricultural and petrochemical industries [1–3]. Despite their strong demand globally, carbon steels are highly vulnerable to the destructive activity of corrosive species in aqueous industrial conditions. This problem is excercebated by the heterogeneous metallurgical structure of carbon steels, presence of flaws and most importantly absence of passivating elements. As a results

the oxide formed on low carbon steels are porous leading to continuous surface degradation in the presence of reactive anions. Their useful service life is significantly impacted by this phenomenon hence limiting their application to specific environments containing certain thresholds of reactive anions. Secondly, industrial accidents and industry down time due to failure of carbon steels in service leads to significant loss of revenue which are eventually passed to consumers. The economic, environmental and industrial importance of corrosion has led to studies and research to properly understand its phenomenon and mitigate its effects [3]. It is the most prevalent destructive phenomenon limiting the performance and reliability of mechanical parts, machine components and structural columns [4]. Aqueous environments are prevalent in industry due to the peculiarity of industrial operations such as oil well acidizing, pickling, production of chemicals etc. which

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exposes carbon steels to corrosion [5]. There are effective corrosion control methods including anodic and cathodic protection, inhibitors, electroplating, electrodeposition etc. but they tend to be costly [6]. Corrosion inhibitors are chemical derivatives utilized for the prevention and control of carbon steel corrosion. The steel modifies the corrosive medium, hinders the electrochemical activities accountable for corrosion and protects the steel exterior through adsorption [7–13]. Research on corrosion inhibitors is important because the effective corrosion inhibitors in service are toxic to the environment, unsustainable and highly restrictive in use due to ever increasing government regulations [14,15]. Extracts from plants easily breaks down to non-harmful compounds due to their biodegradability. Preceding investigations has shown plant extracts to have very high applicability for corrosion prevention on carbon steels [16,17–19]. However, their performance is generally and severely limited by short shelf life, poor adsorption effect and average corrosion inhibition value. These can be properly addressed through adequate understanding of the corrosion inhibition performance of plant extracts and their threshold values for optimal performance with respect to exposure time. Research results for this manuscript evaluates the inhibition efficiency *Commiphora myrrha*, *Cymbopogon nardus* and their admixture on low carbon steel.

2. Experimental methods

2.1. Materials and methods

The *Commiphora myrrha* (CM), *Cymbopogon nardus* (CN) were evaluated separately and in the admixed form (CMCN) for their corrosion inhibition performance. In the admixed form they were combined in equal ratios and formulated in volumetric concentrates of 0%, 0.25%, 0.5%, 0.75%, 1%, 1.25% and 1.5% per 200 ml of 1.5 M H_2SO_4 and HCl solution. The acid electrolyte was prepared from standardized reagents with deionized water. Low carbon steel (MS) rod was cut into six test pieces for coupon measurement. Weighed samples of the steel were inserted into H_2SO_4 and HCl solution at fixed inhibitor concentrations for 288 h. The steels were weighed at 24 h interval with Ohaus weight instrument. Corrosion rate was estimated from the following equation;

$$\mathbf{CR} = \left[\frac{87.6\mathbf{WL}}{\mathbf{DAT}}\right] \tag{1}$$

WL signifies weight loss (g), D signifies density (g/cm^2), A signifies area (cm^2), and T signifies time of measurement (h). WL was estimated from the numerical contrast between the staring weight of the steel (sustained for 288 h) and the concluding weight every 24 h. Inhibition efficiency (IE) estimated as shown;

$$\mathbf{IE} = \left[\frac{\mathbf{WL}_1 - \mathbf{WL}_2}{\mathbf{WL}_1}\right] * 100 \tag{2}$$

WL$_1$ and WL$_2$ signifies weight-loss of the control and protected LCS in the electrolyte in relation to measurement time.

2.2. Statistical computation

Dual-factor single level experimental ANOVA test (F - test) was used to estimate the statistical importance of the inhibitor concentrations and measurement time on the inhibition performance of the oil extract on MS in both acid solutions. Estimation was executed at confidence level of 95% (i.e. a significance level of $\alpha = 0.05$) in accordance to the following equations. The summation of squares through columns (measurement time) was estimated from the equation below;

$$\mathbf{SS_c} = \frac{\sum \mathbf{T_c}^2}{\mathbf{nr}} - \frac{\mathbf{T}^2}{\mathbf{N}} \tag{3}$$

Aggregation of squares through rows (inhibitor concentration).

$$\mathbf{SS_r} = \frac{\sum \mathbf{T_r}^2}{\mathbf{nc}} - \frac{\mathbf{T}^2}{\mathbf{N}} \tag{4}$$

Total aggregation of squares.

$$\mathbf{SS_{Total}} = \sum \mathbf{x}^2 - \frac{\mathbf{T}^2}{\mathbf{N}} \tag{5}$$

3. Results and discussion

3.1. Coupon analysis

Corrosion rate data for CM and CN inhibitor in H_2SO_4 solution, in HCl solution, and the admixed CM and CN inhibitor (CMCN) in H_2SO_4 and HCl solution are displayed in Tables 1-3. Examination of the corrosion rate data in Table 1 shows CN inhibitor generally performed more effectively with respect to exposure time and inhibitor concentration in comparison to CM inhibitor. Secondly, change of MS corrosion rate with exposure time and inhibitor concentration was quite minimal in the presence of CM inhibitor compared to CN inhibitor. This signifies the performance of CN inhibitor is less dependent on exposure time and concentration. Hence, its inhibition mode is most likely attributed to anodic and cathodic inhibition behavior which strongly impacts their reaction processes on MS. The corrosion rate values for MS in the proximity of CN inhibitor generally peaked at 72 h and 96 h before gradually reducing to outputs between 1.41 mm/y and 5.50 mm/y. This shows inhibition performance of CN compound improves with time. The corrosion rate values of MS in the proximity of CM inhibitor is significantly concentration dependent while varying minimally with time. The observed concentration dependence of CM inhibitor performance shows its inhibition mode is anodic i.e. it suppresses the reaction mechanism on MS surfaces (due to the electrochemical activity of corrosive anions) by surface coverage. This phenomenon hinders the electrochemical diffusion of corrosive anions from getting to the steel surface. Hence, slowing down the rate of corrosion. Generally similar trend in variation of corrosion rate values was observed in Table 2 which compares the performance of CM and CN inhibitor in HCl solution. Although this trend is only applicable after 0.5% CM inhibitor concentration. Corrosion rate results of MS in the presence of CN inhibitor were generally similar to the corresponding values in the proximity of CM inhibitor. However, CM inhibitor compounds show strong signs of concentration dependent performance compared to CN inhibitor. The performance of CM inhibitor at 0.5% and 0.75% concentration was quite poor at 24 h of exposure.

Significant improvement in the performance of CM inhibitor was observed at 0.75% concentration with final value of 4.76 mm/y at 288 h of exposure. Corrosion rate of MS in H_2SO_4 and HCl solution without the presence of CM and CN inhibitor compounds is significantly higher than in the presence of the inhibitors. This is due to the corrosion reaction mechanism occurring on MS surface induced by the electrochemical activity of SO_4^{2-} and Cl^- anions in the acid solution. MS corrosion rate in H_2SO_4 is substantially greater than in HCl solution by reason of the higher dissociation constant of H_2SO_4 acid in H_2O and its diprotic nature. In the presence of the inhibitors, the reaction mechanism responsible for corrosion is suppressed when the inhibitor molecules protonate in the electrolyte and chemically combines with the corrosive anions while simultaneously forming a protective film over the steel exterior. This trend is observable in Table 3 where the combined admixture of CM and CN inhibitor compounds

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Table 1

Corrosion rate data for MS in H$_2$SO$_4$ solution at specific CM and CN inhibitor concentration with respect to exposure time.

CM & CN Conc. (%) Exp. Time (h)	CM H$_2$SO$_4$ 0% CM	0.5% CM	0.75% CM	1% CM	1.25% CM	1.5% CM	1.75% CM	CN H$_2$SO$_4$ 0.5% CN	0.75% CN	1% CN	1.25% CN	1.5% CN	1.75% CN
24	37.00	24.63	36.77	6.68	4.74	1.30	0.12	9.22	13.18	1.66	1.41	0.23	3.66
48	64.46	52.62	47.58	10.27	22.88	1.55	0.12	11.27	14.86	2.64	0.58	0.69	6.07
72	69.25	63.12	45.82	14.53	27.20	2.20	0.52	11.81	15.30	3.58	0.78	1.52	6.10
96	66.91	62.05	52.24	20.93	24.40	0.83	0.83	10.20	11.94	4.93	1.77	5.08	5.08
120	59.53	55.67	40.22	23.44	22.46	1.55	1.55	9.55	10.85	4.72	1.52	4.63	4.63
144	49.76	47.50	34.15	23.78	20.57	1.90	1.90	8.44	9.10	4.36	1.15	3.96	3.96
168	53.81	43.85	28.77	24.08	20.42	1.86	1.86	7.92	8.94	4.46	1.70	2.57	2.57
192	54.02	38.77	25.66	23.98	20.23	2.92	2.92	6.75	6.94	3.56	1.57	3.10	3.10
216	48.95	33.66	22.33	23.42	20.01	3.09	3.09	5.91	6.26	4.12	1.51	2.88	2.88
240	47.90	31.71	23.25	22.81	19.19	3.00	3.00	6.26	6.17	4.47	1.54	3.04	3.04
264	43.72	29.18	22.20	22.79	20.10	4.59	2.97	5.92	5.58	4.48	1.39	2.32	2.78
288	40.53	30.04	21.61	22.39	19.69	5.05	2.77	5.50	5.18	4.15	1.41	2.31	2.57

Table 2

Corrosion rate data for MS in HCl solution at specific CM and CN inhibitor concentration with respect to exposure time.

CM & CN Conc. (%) Exp. Time (h)	CM HCl 0% CM	0.5% CM	0.75% CM	1% CM	1.25% CM	1.5% CM	1.75% CM	CN HCl 0.5% CN	0.75% CN	1% CN	1.25% CN	1.5% CN	1.75% CN
24	49.37	48.29	20.12	3.45	5.99	0.90	8.00	10.28	10.44	0.82	6.62	10.81	9.21
48	30.71	25.79	10.93	2.62	4.32	2.76	1.78	5.60	5.59	0.46	6.11	5.57	3.82
72	25.40	18.45	8.05	3.27	3.45	3.08	2.64	4.51	4.17	0.47	5.24	3.30	3.02
96	24.26	15.18	6.47	3.52	2.96	2.39	2.39	3.00	3.76	0.69	5.91	2.71	2.71
120	16.04	13.78	5.78	2.03	2.50	2.07	2.07	2.23	2.06	0.41	2.89	1.73	1.73
144	16.38	12.32	4.98	2.99	2.44	2.00	2.00	2.68	2.06	0.53	2.56	1.72	1.72
168	14.78	11.37	4.53	2.79	2.46	1.19	1.19	2.99	1.98	0.62	2.26	1.65	1.65
192	12.94	10.59	4.29	2.95	2.49	1.06	1.06	3.38	2.13	0.74	2.09	1.83	1.83
216	11.23	10.01	4.10	3.09	2.30	1.03	1.03	3.66	2.16	1.12	1.93	1.61	1.61
240	11.49	10.10	4.08	3.09	2.24	0.89	0.89	4.79	2.70	1.82	2.26	1.86	1.86
264	10.60	10.11	4.33	3.14	2.08	2.03	0.22	4.71	2.91	2.20	2.16	1.47	1.76
288	11.61	11.16	4.76	3.01	1.96	1.91	0.46	5.50	4.75	2.99	2.60	1.97	2.00

Table 3

Corrosion rate data for MS in HCl solution at specific CMCN inhibitor concentration with respect to exposure time.

CMCN Conc. (%) Exp. Time (h)	H$_2$SO$_4$ 0% CMCN	0.5% CMCN	0.75% CMCN	1% CMCN	1.25% CMCN	1.5% CMCN	1.75% CMCN	HCl 0% CMCN	0.5% CMCN	0.75% CMCN	1% CMCN	1.25% CMCN	1.5% CMCN	1.75% CMCN
24	195.39	172.54	166.39	166.23	169.03	179.76	170.30	19.73	4.09	6.96	0.02	0.02	1.34	9.09
48	159.97	156.66	147.45	138.52	147.92	157.44	154.81	40.46	2.87	4.09	0.02	0.10	1.04	3.71
72	123.85	111.93	99.15	111.07	104.31	110.93	107.56	42.30	3.65	3.86	0.03	0.23	1.03	4.07
96	92.51	83.26	74.42	83.56	81.52	80.67	80.67	38.35	3.38	9.12	0.03	2.50	2.14	2.14
120	75.91	69.01	59.58	66.27	63.79	64.29	64.29	30.96	0.65	2.84	0.04	1.47	1.91	1.91
144	63.46	57.56	49.15	55.91	54.66	55.59	55.59	28.16	3.41	3.50	0.03	0.79	2.61	2.61
168	66.52	49.41	39.43	48.07	45.18	48.82	48.82	34.98	2.62	3.15	0.03	0.99	2.45	2.45
192	70.99	43.28	34.63	42.15	39.65	42.79	42.79	36.44	3.04	3.47	0.03	0.87	2.39	2.39
216	73.05	38.65	31.19	38.21	35.59	38.47	38.47	33.61	2.75	3.41	0.03	0.94	2.16	2.16
240	71.58	34.89	28.13	34.83	32.19	34.66	34.66	30.29	2.91	3.12	0.03	1.08	2.90	2.90
264	65.07	31.81	25.65	31.84	30.72	32.09	31.57	27.97	2.69	3.09	0.03	1.27	0.92	3.67
288	59.67	29.68	23.88	29.27	28.62	29.44	29.09	25.91	2.66	3.12	0.03	1.30	0.86	5.11

(CMCN) was applied to inhibit MS corrosion. Secondly, corrosion rate of MS in H$_2$SO$_4$ in the proximity of CMCN was significantly higher than in HCl for reasons earlier discussed. CMCN performance in H$_2$SO$_4$ was noticed to be independent of its concentration, but highly dependent on variation with exposure time. Hence, increase in molecular concentration do not impact the mechanism of corrosion on MS. However, decrease in corrosion rate value is synonymous with weakening of the H$_2$SO$_4$ electrolyte over time. The relationship between CMCN performance to its concentration and exposure time in HCl solution is non-linear which will be explore in the subsequent sub-sections. CMCN performed poorly in H$_2$SO$_4$ solution when compared to CM and CN in H$_2$SO$_4$ solution. Whereas, the performance of CMCN in HCl solution was slightly better than the individual performance of CM and CN in HCl solution.

Further understanding of the inhibition effect of CM, CN and CMCN inhibitor are gotten from Tables 4 to 6. Table 4 exhibits the inhibition performance of CM and CN inhibitor in H$_2$SO$_4$ solution, Table 5 presents the inhibition performance of CM and CM inhibitor in HCl solution while Table 6 shows the inhibition performance of CMCN inhibitor in H$_2$SO$_4$ and HCl solution. Insp of Table 4 shows that CM inhibitor performed poorly at 288 h with respect to 0.5% to 1.25% CM concentration with inhibition efficiency value ranging between 25.88% and 51.41%. At 1.5% and 1.75% inhibition value has increased significantly to 87.53% and 93.17%. Variation of inhibition value from lowest to highest CM concentration shows CM performance significantly depends on its concentration. With respect to time variation, inhibition value is limited although at 1% and 1.25% CM concentration, inhibition value initiated at 81.94% and 87.19% (24 h) and decreased significantly to 44.75%

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Table 4

Inhibition efficiency data for CM and CN inhibitor in H_2SO_4 solution at specific concentrations with respect to exposure time.

CM & CN Conc. (%)	CM H_2SO_4						CN H_2SO_4					
Exp. Time (h)	0.5% CM	0.75% CM	1% CM	1.25% CM	1.5% CM	1.75% CM	0.5% CN	0.75% CN	1% CN	1.25% CN	1.5% CN	1.75% CN
24	33.44	0.62	81.94	87.19	96.50	99.69	75.09	64.38	95.51	96.20	99.38	90.10
48	18.37	26.19	84.07	64.50	97.60	99.82	82.52	76.95	95.91	99.11	98.93	90.59
72	8.85	33.83	79.02	60.73	96.83	99.25	82.95	77.91	94.83	98.87	97.81	91.20
96	7.26	21.92	68.72	63.53	97.32	98.76	84.76	82.15	92.63	97.35	96.94	92.41
120	6.49	32.43	60.63	62.27	96.81	97.40	83.95	81.78	92.08	97.45	95.95	92.22
144	4.54	31.37	52.22	58.67	96.51	96.18	83.04	81.72	91.24	97.68	95.16	92.05
168	18.52	46.53	55.26	62.06	96.91	96.54	85.29	83.39	91.71	96.84	95.37	95.22
192	28.23	52.50	55.62	62.54	95.82	94.60	87.51	87.16	93.41	97.09	95.64	94.27
216	31.23	54.38	52.15	59.12	93.81	93.69	87.92	87.21	91.59	96.91	94.85	94.11
240	33.79	51.47	52.38	59.93	91.86	93.73	86.94	87.11	90.67	96.78	94.55	93.66
264	33.26	49.22	47.87	54.03	89.50	93.22	86.47	87.23	89.74	96.82	94.70	93.65
288	25.88	46.67	44.75	51.41	87.53	93.17	86.43	87.22	89.77	96.52	94.29	93.65

Table 5

Inhibition efficiency data for CM and CN inhibitor in HCl solution at specific concentrations with respect to exposure time.

CM & CN Conc. (%)	CM HCl						CN HCl					
Exp. Time (h)	0.5% CM	0.75% CM	1% CM	1.25% CM	1.5% CM	1.75% CM	0.5% CN	0.75% CN	1% CN	1.25% CN	1.5% CN	1.75% CN
24	79.18	78.85	98.33	86.59	78.10	81.35	2.20	59.25	93.02	87.87	98.17	83.79
48	81.76	81.81	98.51	80.11	81.87	87.57	16.04	64.42	91.45	85.92	91.00	94.20
72	82.24	83.60	98.14	79.39	87.00	88.10	27.34	68.32	87.13	86.43	87.86	89.62
96	87.62	84.50	97.17	75.66	88.79	88.82	37.43	73.34	85.49	87.80	84.47	90.14
120	86.08	87.18	97.44	82.00	91.79	89.23	14.13	64.00	87.37	84.43	79.33	87.11
144	83.62	87.42	96.75	84.35	92.26	89.47	24.78	69.62	81.76	85.08	82.70	87.81
168	79.77	86.62	95.83	84.73	91.99	88.81	23.03	69.37	81.13	83.34	81.89	91.93
192	73.87	83.57	94.32	83.83	90.91	85.83	18.22	66.84	77.20	80.75	80.73	91.85
216	67.41	80.73	90.05	82.82	89.19	85.70	10.89	63.46	72.48	79.52	79.11	90.83
240	58.35	76.53	84.14	80.35	88.29	83.86	12.11	64.51	73.08	80.52	81.27	92.25
264	55.61	72.52	79.22	79.63	86.16	83.39	4.60	59.14	70.37	80.36	80.84	97.88
288	52.63	59.11	74.25	77.59	83.05	82.75	3.93	59.03	74.08	83.11	83.54	96.07

Table 6

Inhibition efficiency data for CM and CN inhibitor in H_2SO_4 solution at specific concentrations with respect to exposure time.

CMCN Conc. (%) Exp. Time (h)	H_2SO_4						HCl					
	0.5% CMCN	0.75% CMCN	1% CMCN	1.25% CMCN	1.5% CMCN	1.75% CMCN	0.5% CMCN	0.75% CMCN	1% CMCN	1.25% CMCN	1.5% CMCN	1.75% CMCN
24	11.69	14.84	14.92	13.49	8.00	12.84	79.25	64.71	99.88	99.88	93.20	53.93
48	2.07	7.83	13.41	7.53	1.58	3.22	92.91	89.88	99.94	99.74	97.43	90.83
72	9.63	19.95	10.32	15.78	10.43	13.16	91.36	90.87	99.93	99.45	97.58	90.38
96	10.00	19.56	9.67	11.88	7.42	12.80	91.18	76.21	99.92	93.47	97.17	94.42
120	9.09	21.52	12.70	15.96	9.35	15.31	97.91	90.81	99.88	95.25	96.44	93.83
144	9.30	22.55	11.89	13.87	8.90	12.40	87.90	87.58	99.88	97.21	96.43	90.73
168	25.71	40.72	27.73	32.08	24.99	26.60	92.51	90.99	99.92	97.18	97.46	92.98
192	39.03	51.21	40.62	44.15	38.45	39.72	91.65	90.48	99.91	97.62	97.22	93.43
216	47.09	57.30	47.70	51.28	46.46	47.34	91.81	89.85	99.91	97.20	96.89	93.57
240	51.26	60.71	51.34	55.03	50.74	51.58	90.39	89.69	99.90	96.43	96.85	90.41
264	51.11	60.59	51.07	52.78	50.68	51.48	90.40	88.94	99.90	95.48	96.72	86.89
288	50.25	59.98	50.95	52.03	50.65	51.25	89.74	87.94	99.90	94.96	96.68	80.28

and 51.41%. CN compound displayed effective inhibition performance starting from the beginning of exposure hours (24 h) to culmination (288 h) at all concentrations. It must be noted that CN inhibition performance varied minimally with respect to its concentration. The performance of CM inhibitor significantly improved in HCl solution (Table 5) compared to its performance in H_2SO_4 solution. At initiation (24 h), the inhibition efficiency values varied between 78.10% and 98.33%. Whereas at culmination (288 h) inhibition performance varied between 74.25% and 82.75% (1% CM to 1.75% CM). CM performed poorly at 0.5% and 0.75% CM concentration. The final values at 288 h results from progressive decrease in inhibition efficiency values with respect to exposure time at all concentrations. The performance of CN inhibitor in HCl solution is quite poor in comparison to its performance in H_2SO_4 solution. CN inhibition performance varied non-linearly with respect to

exposure time. However, with respect to its concentration progressive increase in inhibition efficiency was observed with effective inhibition starting at 1% CN till 1.75% CN concentration. Inhibition efficiency outputs in Table 6 shows the admixture of CM and CN inhibitors (CMCN) did not improve the corrosion resistance of MS in H_2SO_4 solution as all the inhibition values at 288 h are lower than the value for potent corrosion inhibition. The values ranged between 50.25% and 59.98% at 288 h while the values at onset (24 h) were significantly lower. Comparing these values to CM and CN inhibitor at 288 h in H_2SO_4 solution it is clearly visible that admixture of CM and CN increases the lateral repulsion effect among the inhibitor molecules which invariably impacts the inhibition output of the inhibitors. CMCN significantly improved the corrosion resistance of MS in HCl solution from inspection of the inhibition efficiency outputs analogous to concentration and expo-

sure time. At 24 h, the inhibition values at all concentrations initiated at values between 64.71% and 99.88% whereas at 288 h, the inhibition values ranged between 87.94% and 99%. In HCl CMCN exhibited limited concentration and time dependent inhibition performance, achieving inhibition performance greater than the individual performance of CM and CN inhibitors in HCl solution.

3.2. Statistical analysis

Analysis of variance (ANOVA) was utilized to enumerate the statistical importance of inhibitor concentration and exposure time on the inhibition output of CM, CN and CMCN inhibitor extracts [20]. Results from ANOVA test is depicted from Tables 7 to Table 9. Table 7 depict the ANOVA results for CM and CN in H_2SO_4 solution, Table 8 shows the statistical ANOVA results for CM and CN in HCl solution while Table 9 depict the ANOVA results for CMCN in HCl and H_2SO_4 respectively. The statistical relevance, theoretical significance factor and mean square ratio are the determinant parameters that establishes the statistical importance and influence of inhibitor concentration and exposure time on the inhibition output of CM, CN and CMCN inhibitors. The statistical relevance factor is the numerical value of the effect of the exposure time and inhibitor concentration. The theoretical significance factor is the value wherewith the mean square ratio must be higher than for the statistical relevance factor to be valuable. Tables 7-9 shows the value of the mean square ratio for both inhibitor concentration and exposure time are significantly below the corresponding value of the theoretical significance factor. Hence, the statistical relevance fac-

tor in Tables 7, 8 and 9 are statistically irrelevant and do not significantly influence the performance output of CM, CN and CMCN inhibitors in H_2SO_4 and HCl solution. Performance of the inhibitors is determined by inherent factors associated with the molecular configuration and behavior of cationic inhibitor molecules in interaction with the steel surface in the acid medium. Observation of the Tables shows the statistical relevance factor for inhibitor concentration quite high compared to exposure time despite being statistically irrelevant. This shows the behavior of the inhibitor molecules from the statistics point of view is independent of its concentration and time of exposure.

3.3. Standard deviation, mean and margin of error

Data for standard deviation (SD), average data values and margin of error for CM, CN and CMCN inhibition performance from H_2SO_4 and HCl media at definite inhibitor concentration are presented from Tables 10-12. The SD data for CN in H_2SO_4 solution (Table 10) are significantly lower than the corresponding values for CM inhibitor. Secondly, the SD data for CN in H_2SO_4 varies minimally with concentration compared to the values for CM inhibitor. This shows the variation of CN inhibitor values from average data values and with respect to time is minimal i.e. CN inhibition performance is thermodynamically stable over time and effective. However, for CM inhibitor in H_2SO_4 solution, it is clearly evident that lower SD values occurred at higher CM concentration analogous to higher average data values. The lower SD values shows the deviation of inhibition performance values from average data

Table 7
ANOVA data for CM and CN inhibition performance in H_2SO_4 solution.

H_2SO_4							
CM				**CN**			
Source of Variation	**Mean Square Ratio (F)**	**Theoretical Significance Factor**	**Statistical Relevance Factor, F (%)**	**Source of Variation**	**Mean Square Ratio (F)**	**Theoretical Significance Factor**	**Statistical Relevance Factor, F (%)**
Inhibitor		Concentration	1.72	2.42	92.29	Inhibitor concentration	0.03
2.42	88.48						
Exposure Time	−4.92	2.15	−475.22	Exposure Time	−5.00	2.15	−31689.56

Table 8
ANOVA data for CM and CN inhibition performance in HCl solution.

HCl							
CM				**CN**			
Source of Variation	**Mean Square Ratio (F)**	**Theoretical Significance Factor**	**Statistical Relevance Factor, F (%)**	**Source of Variation**	**Mean Square Ratio (F)**	**Theoretical Significance Factor**	**Statistical Relevance Factor, F (%)**
Inhibitor		Concentration	0.05	2.42	41.40	Inhibitor Concentration	1.11
2.42	95.25						
Exposure Time	−4.96	2.15	−7683.17	Exposure Time	−4.97	2.15	−769.79

Table 9
ANOVA data for CMCN inhibition performance in H_2SO_4 and HCl solution.

HCl				H_2SO_4			
CM				**CN**			
Source of Variation	**Mean Square Ratio (F)**	**Theoretical Significance Factor**	**Statistical Relevance Factor, F (%)**	**Source of Variation**	**Mean Square Ratio (F)**	**Theoretical Significance Factor**	**Statistical Relevance Factor, F (%)**
Inhibitor		Concentration	0.02	2.42	69.57	Inhibitor Concentration	0.10
2.42	4.69						
Exposure Time	−5.00	2.15	−37315.85	Exposure Time	−3.89	2.15	−332.47

Table 10
Data for mean, SD and margin of error for CM and CN inhibitor in H_2SO_4 solution.

Inhibitor	H_2SO_4						CN					
	CM											
Conc. (%)	0.5%	0.75%	1%	1.25%	1.5%	1.75%	0.5%	0.75%	1%	1.25%	1.5%	1.75%
SD	12.04	11.17	10.23	3.91	3.51	2.30	1.80	3.35	1.58	0.68	1.11	1.23
Mean	19.81	42.03	56.86	59.43	94.29	95.65	85.53	84.29	91.77	97.23	95.53	93.24
Margin of Error	±11.93%%	Result above 80% Inhibition	33%	Margin of Error	±3.24%	Result above 80% Inhibition	98%					

Table 11
Data for mean, SD and margin of error for CM and CN inhibitor in H_2SO_4 solution.

Inhibitor	HCl						CN					
	CM											
Conc. (%)	0.5%	0.75%	1%	1.25%	1.5%	1.75%	0.5%	0.75%	1%	1.25%	1.5%	1.75%
SD	13.30	8.83	8.59	3.03	2.96	2.61	10.61	4.62	6.41	2.82	2.62	3.35
Mean	72.72	80.18	90.73	81.04	88.94	86.60	17.65	65.76	79.01	83.13	82.17	91.55
Margin of Error	±10.96%	Result above 80% Inhibition	25%	Margin of Error	±12.62%	Result above 80% Inhibition	53%					

Table 12
Data for mean, SD and margin of error for CMCN inhibitor in H_2SO_4 and HCl solution.

Inhibitor	H_2SO_4						HCl					
	CMCN						CMCN					
Conc. (%)	0.5%	0.75%	1%	1.25%	1.5%	1.75%	0.5%	0.75%	1%	1.25%	1.5%	1.75%
SD	19.38	18.63	18.79	18.48	19.48	17.77	2.60	4.43	0.02	1.68	0.40	4.32
Mean	30.25	41.41	31.40	34.48	29.81	32.16	91.49	88.34	99.91	96.43	96.94	90.69
Margin of Error	±0%	Result above 80% Inhibition	0%	Margin of Error	±0%	Result above 80% Inhibition	100%					

values with respect to time is limited. i.e. inhibition performance of the inhibitor is stable over time. This indicates thermodynamic equilibrium of the inhibitor molecules and increased lateral attraction effect among the inhibitor molecules. The effect is synonymous with higher inhibitor concentration and higher average data values. CN inhibitor in H_2SO_4 demonstrated stable surface protection characteristics in H_2SO_4 at all concentrations compared to CM which exhibited stability at higher concentration. Observation of Table 11 shows the SD values for CM and CN inhibitor in HCl solution are comparable at all inhibitor concentrations. However, the higher the inhibitor concentration, the lower the SD values and the higher the average data value. This assertion is more evident for CN inhibitor in HCl, while the average data value for CM inhibitor tends to be relatively stable with respect to inhibitor concentration. The average data value for CM inhibitor in HCl is significantly higher than in H_2SO_4 solution, while the corresponding values for CN in HCl is generally lower than its values in H_2SO_4 solution. In Table 12, the average data values for CMCN in H_2SO_4 solution is significantly poor ranging between 29.81% and 41.41% throughout. The corresponding SD values for CMCN in H_2SO_4 solution are significantly higher, indicating significant variation of CMCN inhibition performance data with respect to exposure time. It shows CNCM performed poorly in H_2SO_4 in an unstable manner on the steel surface. This observation contradicts the performance of CMCN in HCl solution where the average data values are quite high ranging between 88.34% and 99.91%. The corresponding SD values are significantly low indicating stable protection behavior over MS surface with respect to exposure time. Tables 10-12 shows the margin of error of the inhibition performance data of the inhibitors in H_2SO_4 and HCl solution. In H_2SO_4 solution, the percentage data above 80% inhibition efficiency for CM and CN compound are 33% and 98%, in HCl the values are 25% and 53%. Whereas, the combined admixture of CMCN compound in H_2SO_4 and HCl solution gave values of 0% and 100%.

4. Conclusion

Commiphora myrrha and *Cymbopogon nardus* plant extracts, and their combined admixture effectively inhibited low carbon steel corrosion in H_2SO_4 and HCl solution. Performance of *Commiphora myrrha* in H_2SO solution was marginal at low concentrations but highly effective at higher concentrations in comparison to *Cymbopogon nardus* whose performance was highly effective at all concentrations studied. Both extracts exhibited generally similar performance in HCl solution with poor inhibition efficiencies at very low concentrations of the compounds and effective inhibition efficiencies at higher concentrations. The admixed extracts performed very poorly in H_2SO solution at all concentrations, but effectively in HCl at all concentrations. Statistical analysis through ANOVA shows inhibitor concentration is the only statistically relevant variable influencing the performance outputs of the inhibitor compounds. Standard deviation calculations show 33% and 98% of *Commiphora myrrha* and *Cymbopogon nardus* in H_2SO_4, 25% and 53% of *Commiphora myrrha* and *Cymbopogon nardus* in HCl, and 0% and 100% of the admixed plant extracts in H_2SO_4 and HCl are above the 80% effective inhibition efficiency threshold.

CRediT authorship contribution statement

Victor David: Supervision, Conceptualization, Writing – original draft, Visualization, Investigation, Validation, Methodology, Data curation. **Chinazom Iroanyanwu:** Supervision, Conceptualization, Writing – original draft, Visualization, Investigation, Validation, Methodology, Data curation. **Bilkisu Suleiman Atane:** Supervision, Conceptualization, Writing – original draft, Visualization, Investigation, Validation, Methodology, Data curation. **Roland Tolulope Loto:** Supervision, Conceptualization, Writing – original draft,

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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