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SOLVENT-DEPENDENT KINETICS OF DL-METHIONINE OXIDATION BY BENZIMIDAZOLIUM FLUOROCHROMATE

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ABSTRACT
DL-Methionine undergoes BIFC-mediated oxidation in DMSO solvent to yield its sulfoxide derivative as the predominant product. Kinetic analysis reveals Michaelis–Menten-type behaviour for methionine and a first-order dependence on BIFC concentration. The oxidation process is accelerated under acidic conditions. The rate of methionine oxidation was investigated in a variety of organic solvents, and analysis using solvatochromic parameters shows that, while the solvents' anion- and cation-solvating characteristics have an impact on the reaction, cation-solvation has the most influence. The protonated form, $BIFCH^+$, functions as the reactive oxidant. There has been a suggested mechanistic route.
Keywords: Kinetics, Methionine, Benzimidazolium Fluorochromate, Solvent Effect, Mechanism.
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INTRODUCTION

Methionine is a sulfur-containing amino acid that is necessary for cellular development, protein synthesis, and metabolic control. Through S-adenosylmethionine (SAM), which is involved in DNA methylation and other biochemical processes, it acts as a crucial methyl group donor. Methionine may be oxidised to produce methionine sulfoxide, which is important for comprehending redox control, ageing, and oxidative stress associated with illness and serves as a biomarker of protein oxidation and cellular oxidative damage.[1] A key advancement in organic synthesis is the development of selective oxidation methods for organic substrates in non-aqueous media; accordingly, numerous Cr(VI) compounds have already been designed and synthesized.[2-5] Benzimidazolium fluorochromate (BIFC), composed of a benzimidazolium cation and a fluorochromate anion ($C_7H_7N_2^+[CrO_3F]^-$), is a chromium(VI)-based oxidizing reagent. It is non-hygroscopic and insensitive to light, making it more stable and easier to store than many previously reported Cr(VI) oxidants. This reagent was first reported by Sivamurugan *et al.*[6] in 2005. Our work focuses on investigating the processes and dynamics of oxidations involving more recent Cr(VI) derivatives. Because of its electron-rich, easily oxidizable sulphur atom, methionine, an amino acid that contains a thioether, has unique reactivity towards a variety of oxidising agents.[7-9] A review of the literature indicates that the oxidation of methionine by BIFC has not yet been investigated from a mechanistic standpoint. The kinetics and mechanism of methionine oxidation by BIFC in dimethyl sulfoxide (DMSO) under acidic conditions are presented in this paper, along with a detailed discussion of the related mechanistic characteristics.

EXPERIMENTAL

Materials

Iodometric analysis was used to confirm the purity of BIFC, which was developed using the described method.[6] DL-Methionine (Merck, India) was utilized as supplied, requiring no further purification. The hydrogen-ion source was p-toluenesulfonic acid (TsOH). Every solvent was purified using accepted, previously published procedures.[10]

Product Analysis

Kinetic conditions with an excess of methionine over BIFC were used for product analysis. The oxidant BIFC (0.005 mol) and methionine (0.05 mol) were combined in 20 mL of the solvent DMSO. This mixture was left undisturbed for a full day to ensure the success of the reaction. Then, under reduced

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pressure, most of the solvent was removed. Chloroform (3 × 50 mL) was used to remove the residue after it had been diluted with water. The solvent was evaporated after the mixed chloroform extracts were dried over anhydrous $MgSO_4$. When the residue was examined using infrared spectroscopy, the spectrum matched that of methionine sulfoxide. The sulfoxide production was 89 ± 2%. IR spectroscopy was also employed to characterise methionine sulfoxide, formed by the oxidation of methionine, which has a unique strong IR band about 1032 (1/cm) which corresponds to the S=O stretching vibration, and another prominent peak around 1585 1/cm, which arises from NH_2 bending. The O–H stretch of the carboxylic acid group is responsible for the wide absorption at 3000(1/cm) and the CH/NH bending bands in the 1420-1500 (1/cm) regions.

Stoichiometry

At room temperature, stoichiometric studies were performed when BIFC was in excess of methionine. Solutions of BIFC (0.015 mol) and methionine (0.003 mol) were prepared in DMSO (100 mL) containing 0.1 mol dm^{-3} TsOH. The unreacted BIFC was measured using spectrophotometry after the reaction mixture was allowed to stand for 12 hours to ensure completion. A stoichiometric ratio of 2:3, meaning that two moles of BIFC are used for every three moles of methionine, was established by a series of tests using different amounts of BIFC and methionine.

Kinetic Measurements

A UV-Vis spectrophotometer (UV5704, ECIL) was used to examine the rate of methionine oxidation by BIFC in different solvents. The reduction in BIFC absorbance at its analytical wavelength of 364 nm was used to track the course of the reaction. By altering their concentrations in the reaction mixture, the effects of [BIFC] and [methionine] on the reaction rate were investigated. Over the course of 45 minutes, kinetic measurements were performed at multiple temperatures. Absorbance values were taken every three minutes. Equation (1) was used to get the first-order rate constants (k_{obs}).

$$k_{obs} = \left(\frac{2.303}{t}\right) \log \left(\frac{A_0}{A_t}\right) \qquad (1)$$

Here, A_0 and A_t denote the absorbance at zero time and at time t, respectively. The reported rate constants represent the average of three independent measurements and carry an experimental error of ±4.0%. The activation parameters, namely $\Delta G^{\#}$, $\Delta H^{\#}$ and $\Delta S^{\#}$, were evaluated from temperature-dependent kinetic data. The quality of linear correlations was assessed using Exner's isokinetic criterion[11] (Ψ), supplemented by the coefficient of determination (R^2 or r^2) and standard deviation (SD).

RESULT AND DISCUSSION

Methionine is oxidised to its equivalent sulfoxide as the primary product, according to stoichiometric studies and product analysis. The whole reaction can be expressed as:

$$3\ R{-}S{-}CH_3 + 2\ Cr_2O_7^{-2} + 22\ H^+ \longrightarrow 3\ R{-}\underset{\underset{O}{\|}}{S}{-}CH_3 + 4\ Cr^{+3} + 11\ H_2O \qquad (2)$$

Where R = $CH_2CH_2CH(NH_2)COOH$

Oxidation experiments performed under a nitrogen atmosphere yielded no evidence of acrylonitrile polymerization, ruling out the generation of radical intermediates. In the absence of substrate, BIFC concentration remained unchanged throughout the observation period. Furthermore, including acrylonitrile in the reaction mixture did not perturb the observed rate constants (Table-1), and no reduction of mercury(II) chloride[12] was detected. These control results are collectively inconsistent with a radical chain mechanism. In the case of 0.01 mol dm^{-3} acrylonitrile, a one-electron oxidation route is implausible since neither increased polymerization of acrylonitrile nor reduction of Mercury(II) chloride was seen. Furthermore, there was no noticeable decrease in the BIFC concentration in control tests conducted without the substrate.

Rate Laws

In the present study, the reaction shows a fractional order with respect to methionine. The reaction is first order in BIFC, as the pseudo-first-order rate constant remains unchanged with variation in the oxidant

(BIFC). Linear plot of log(absorbance) versus time, which stays linear up to around 80% reaction completion, lends additional support to this view.

Table-1: Observed Rate Coefficients (k_{obs}) for the Oxidation of Methionine by BIFC at 30 °C

[Methonine] (mol/dm^3)	10^3 [BIFC] (mol/dm^3)	[H^+] (mol/dm^3)	$10^4\,k_{obs}$ (1/sec)
0.01	1.0	0.3	0.75
0.03	1.0	0.3	1.79
0.05	1.0	0.3	2.72
0.08	1.0	0.3	3.42
0.1	1.0	0.3	3.92
0.3	1.0	0.3	5.81
0.5	1.0	0.3	6.42
1.0	1.0	0.3	6.98
0.1	2.0	0.3	3.89
0.1	3.0	0.3	3.76
0.1	0.5	0.3	4.08
0.1	1.0	0.3	4.02[a]

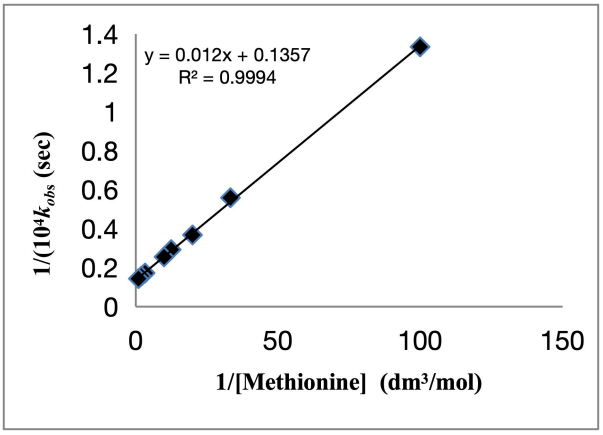


Fig.-1: Plot of 1/(10^4 k_{obs}) vs 1/[Methionine] at 30°C
[H^+] = 0.3 mol/dm^3, 10^3[BIFC] = 1.0 mol/dm^3

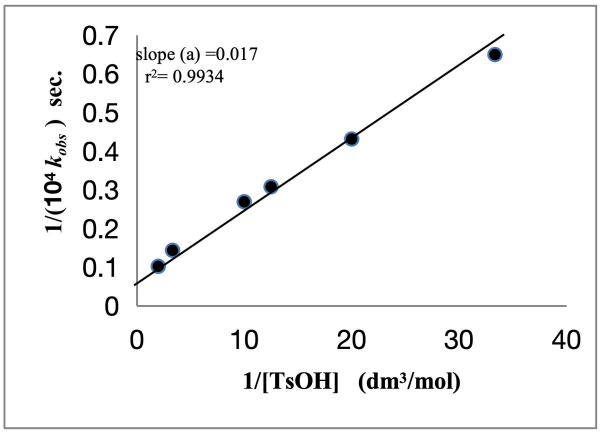


Fig.- 2: Plot of 1/(10^4 k_{obs}) vs 1/[TsOH] at 30°C
[Methionine] = 1.0 mol/dm^3, 10^3[BIFC] = 1.0 mol/dm^3

Prior to the rate-determining step, the reaction proceeds through the initial generation of an oxidant–substrate complex. The products are then produced by the breakdown of this complex (Eq. 3 and Eq. 4):

$$\text{Methionine} + \text{BIFC} \underset{k_{-1}}{\overset{k_{+1}}{\rightleftharpoons}} [\text{Complex}] \qquad (3)$$

$$[\text{Complex}] \xrightarrow{k_2} \text{Product} \qquad (4)$$

Equation (5) displays the rate expression that may be determined by using the steady-state approximation.[13] The predicted linear relationship between 1/k_{obs} and 1/[Methionine], with a positive intercept on the rate-constant axis, is indeed observed (Fig.-1), thereby validating the proposed scheme.

$$\text{Rate} = -\frac{d[\text{Complex}]}{dt} = k_2\,[\text{Complex}]$$

$$\text{Rate} = \frac{K\,k_2\,[\text{Methionine}]\,[\text{BIFC}]_t}{1 + K\,[\text{Methionine}]}$$

$$\text{Rate} / [\text{BIFC}]_t = k_{obs} = \frac{K\,k_2\,[\text{Methionine}]}{1 + K\,[\text{Methionine}]}$$

$$(\text{Rate}/[\text{BIFC}]_t^{-1}) = 1/k_{obs} = 1/K\,k_2\,[\text{Methionine}] + 1/k_2 \qquad (5)$$

Where $K = k_1/k_{-1}$, and the total oxidant concentration of the oxidant is given by

$[\text{BIFC}]_t = [\text{Complex}] + [\text{BIFC}]$

Effect of Temperature

The dependence of k_{obs} on methionine concentration was examined over the temperature range of 20°C-50°C. Using Equation (5), double-reciprocal plots (Fig.-1) were used to determine both the complex-formation constant (K) and the complex-decomposition constant (k_2). The thermodynamic and activation parameters for methionine were then calculated (Tables-2 and 3). The activation enthalpy and entropy values indicate that rate variations are governed by contributions from both thermodynamic quantities. The relatively modest activation energy is consistent with a reaction facilitated by prior complex formation. Markedly negative $\Delta S^{\#}$ values are indicative of a highly ordered, charge-separated transition state requiring substantial solvent reorganization around the developing ionic centers.

Table-2: Formation Constant (K) and Associated Thermodynamic Parameters for the [Methionine-BIFC] Complex

K(dm^3/mol)				ΔH	ΔS	ΔG (25°C)
20°C	30°C	40°C	50°C	(kJ/mol)	(J/mol K)	(kJ/mol)
13.26	10.54	7.36	4.58	-30.3±2.4	-73±7.8	-8.6±1.9

Table-3: Rate Data (k_2) and Activation Parameters for the Decomposition of the [Methionine–BIFC] Complex

$10^4\,k_2$(1/sec)				$\Delta H^{\#}$	$\Delta S^{\#}$	$\Delta G^{\#}$(25°C)	E_a
20°C	30°C	40°C	50°C	(kJ/mol)	(J/mol K)	(kJ/mol)	(kJ/mol)
4.82	7.65	12.78	21.4	36.6±0.9	-184±3.2	91.3±0.	39.16

Effect of TsOH Concentration

systematic increase in TsOH concentration produces a progressive enhancement of the reaction rate. A logarithmic plot of k_{obs} against [TsOH] yields a line with slope ≈ 0.64, signifying a fractional order (<1) in acid, consistent with a pre-equilibrium protonation mechanism (Table-4). Plotting $1/k_{obs}$ against 1/[TsOH] gives a straight line with a finite positive intercept (Fig.-2), leading to the empirical expression:

$$1/k_{obs} = 1/k_o + a/[\text{TsOH}] \qquad (6)$$

In Equation (6), k_o designates the rate constant for the uncatalyzed pathway and 'a' represents the slope of the linear fit. Qualitatively similar acid-dependent rate profiles have been documented for the oxidation of alcohols and related substrates by various Cr(VI) reagents, including isoquinolinium dichromate.[14]

Table-4: Dependence of the Reaction Rate on TsOH Concentration

[TsOH] (dm^3/mol)	0.03	0.05	0.08	0.1	0.3	0.5
$10^4 k_{obs}$(1/sec)	1.54	2.32	3.25	3.72	6.98	9.81

[Methionine]=1.0 mol/dm^3, 10^3[BIFC] = 1.0 mol/dm^3, Temperature = 30°C

Effect of the Reaction Medium

Kinetic studies were extended to nineteen organic solvents selected on the basis of reagent solubility. No evidence of direct interaction between BIFC and any of the solvents employed was found spectroscopically. Rate constants (k_2) across all media are compiled in Table-5; uniform kinetic behavior was preserved throughout, with solvent polarity modulating the reaction rate.

Conductimetric measurements in DMSO indicated that addition of BIFC raised the background conductance only marginally, consistent with predominantly non-ionized BIFC under reaction conditions. Corroborating this, the presence of exogenous benzimidazolium ion exerted no discernible effect on the

oxidation rate, confirming that dissociation into CrO_3F^- and $BIH^+$is negligible at the concentrations employed.

Table-5: Impact of Solvent Variation on Methionine Oxidation by BIFC at 30°C

Solvent	K (dm^3/mol)	10^4 k_2 (1/sec)	Solvent	K (dm^3/mol)	10^4 k_2 (1/sec)
Acetone	11.2	2.61	Butanone	10.2	2.21
1,2-Dichloroethane	9.7	2.85	Toluene	10.2	0.89
Dichloromethane	10.8	2.76	Benzene	10.1	1.05
DMSO	10.5	7.67	Tetrahydrofuran	9.5	1.45
Chloroform	11.8	2.42	Ethyl acetate	11.1	1.18
Carbon disulfide	10.6	0.46	Dioxane	11.0	1.48
Acetic acid	9.4	0.58	1,2-Dimethoxyethane	11.8	0.86
Dimethylformamide	9.8	4.31	*Tert*-butyl alcohol	10.4	1.09
Acetophenone	11.6	3.52	Cyclohexane	9.3	0.16
Nitrobenzene	11.5	3.32			

While the rate constant for complex decomposition (k_2) exhibits significant solvent dependency, the equilibrium constant (K) is rather immune to solvent variation, according to the data shown in Table-5. The oxidation of methionine by tetraethylammonium chlorochromate has shown similar behavior.[15] To quantify these solvent effects, the Kamlet–Abboud–Taft linear solvation energy relationship (LSER) model[16] was applied to the k_2 dataset collected in nineteen solvents:

$$\log k_2 = A + p\pi^* + a\alpha + b\beta \quad (7)$$

In this multi-parameter model, π* encodes the dipolarity/polarizability of the solvent and captures non-specific electrostatic contributions to solvation, α quantifies the capacity of the solvent to donate a hydrogen bond (HBD acidity), and β reflects the ability of the solvent to accept a hydrogen bond (HBA basicity); A is a regression constant. Notably, thirteen of the eighteen solvents in the analysis have α = 0, reducing the effective dimensionality of the correlation. Both full three-parameter and reduced two-parameter equations were therefore evaluated at 30°C (n denotes the number of solvents included):

$$\log k_2 = -4.73 + 1.42{+}0.18\,\pi^* - 0.28{+}0.15\,\alpha + 0.19{+}0.15\,\beta \quad (8)$$
$$R^2 = 0.8571,\ \psi = 0.41,\ \mathrm{SD} = 0.17,\ n = 18,$$

$$\log k_2 = -4.81 + 1.52{+}0.19\,\pi^* + 0.10{+}0.16\,\beta \quad (9)$$
$$R^2 = 0.8204,\ \psi = 0.45,\ \mathrm{SD} = 0.18,\ n = 18$$

$$\log k_2 = -4.76 + 1.55{+}0.18\,\pi^* \quad (10)$$
$$r^2 = 0.8484,\ \psi = 0.41,\ \mathrm{SD} = 0.17,\ n = 18$$

$$\log k_2 = -3.92 + 0.37{+}0.34\,\beta \quad (11)$$
$$r^2 = 0.0685,\ \psi = 0.99.\ \mathrm{SD} = 0.41,\ n = 18$$

Equation (8) accounts for approximately 86% of the variance in the observed solvent effect; however, by Exner's criterion[11] the overall correlation quality remains unsatisfactory. The dominant solvatochromic descriptor is π*, while contributions from α and β are marginal. No meaningful collinearity between β and π* was identified among the solvents tested. To further interrogate the ionic character of the transition state, the complementary framework of Swain *et al.*[17] was employed, in which the parameter 'A' quantifies the anion-solvating capacity and 'B' captures the cation-solvating power of the solvent; the sum (A + B) provides an index of net solvent polarity, and C is the regression intercept:

$$\log k_2 = aA + bB + C \quad (12)$$

Results of the regression analysis using Swain's equation, examined individually for A, B, and the composite term (A + B), for nineteen solvents are summarized below:

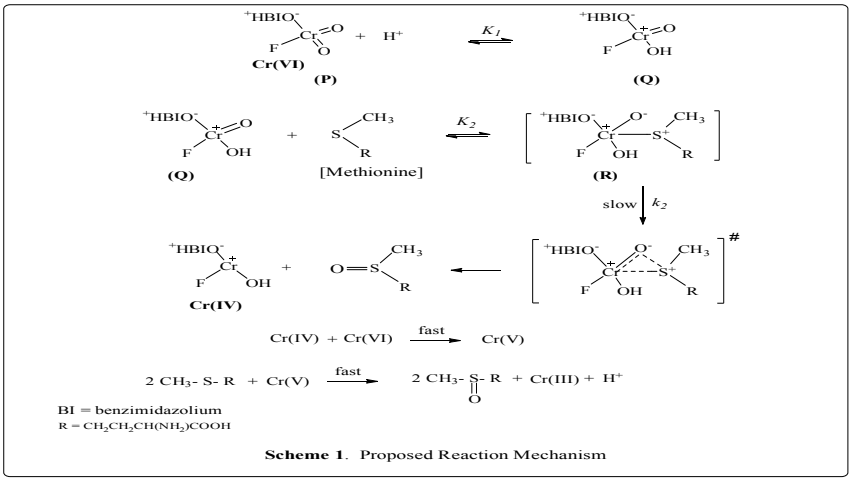
$$\log k_2 = 0.54{\pm}0.01\ A + 1.51{\pm}0.01\ B - 4.94 \quad (13)$$
$$R^2 = 0.9988,\ \mathrm{sd} = 0.0147,\ \psi = 0.036$$

$$\log k_2 = 0.32\pm0.49\ A - 3.90 \quad (14)$$
$$r^2 = 0.024,\ sd = 0.4038,\ \psi = 1.015,$$
$$\log k_2 = 1.47\pm0.09\ B - 4.76 \quad (15)$$
$$r^2 = 0.9327,\ sd = 0.1060,\ \psi = 0.266$$
$$\log k_2 = 1.19\pm0.12\ (A + B) - 4.91 \quad (16)$$
$$r^2 = 0.8418,\ sd = 0.1625,\ \psi = 0.41$$

The near-perfect fit to eqn.-13 ($R^2 = 0.9988$) demonstrates that solvent-induced rate variation is governed by both ionic solvation modes. Critically, the regression coefficient for B exceeds that for A by nearly three-fold, establishing cation solvation as the predominant factor, accounting for roughly 93% of the observed variation. No significant inter-correlation between A and B was detected across the nineteen solvents ($r^2 = 0.0108$; SD = 0.27), validating their independent use as regressors. The combined polarity index (A + B) captures approximately 84% of the variance, and the substantial co-variation of π* with (A + B) ($r^2 = 0.8418$) confirms that these two parameters encode essentially equivalent solvation information. An attempt to correlate log k_2 with the inverse of the solvent's relative permittivity did not produce a satisfactory linear relationship ($r^2 = 0.5315$), indicating that simple dielectric models are inadequate to describe these solvent effects. The observed patterns collectively point to a transition state bearing greater polarity than the reactant ground state, arising from nucleophilic attack of the methionine sulfur on the electrophilic chromium centre of BIFC with concomitant partial positive charge development on sulfur and negative charge on oxygen in the rate-limiting step. Solvents with higher ionising power preferentially stabilise this polar transition state, thereby accelerating the reaction.

Mechanism

Several lines of evidence preclude a single-electron radical mechanism: (i) acrylonitrile, a sensitive radical trap, caused no acceleration of polymerisation when added to the reaction mixture; (ii) mercury(II) chloride remained unreacted throughout, confirming that one-electron oxidation is not formed in the primary step. Taken together, these results favour a heterolytic mechanism initiated by protonation of the BIFC oxidant to generate the electrophilically activated species $BIFCH^+$, a conclusion supported by the dominant role of cation-solvating power in the LSER analysis.The Michaelis–Menten-type kinetic response to methionine concentration points to the rapid, reversible formation of a 1:1 encounter complex via a SN_2-type attack of the methionine sulfur on the protonated chromate centre. Subsequent rate-limiting oxygen transfer from the activated oxidant to the sulfur atom of the substrate delivers the sulfoxide product (Scheme-1).



Scheme 1. Proposed Reaction Mechanism

The mechanistic picture is self-consistent: the highly negative entropy of activation ($-\Delta S^{\#} = 184$ J mol^{-1}K^{-1}) reflects the extensive organisational constraints imposed on both the transition state and the surrounding solvent shell, a hallmark of concerted oxygen-atom transfer processes (Scheme-1). The proposed pathway is fully consistent with precedents established for other Cr(VI)-mediated sulfoxidations and with the SN_2-

like character of the transition state implied by the solvent sensitivity data. The role of solvent polarity in modulating reactivity can additionally be rationalized by noting that in low-permittivity media (e.g., cyclohexane), the oxidant and the intermediate complex likely exist as tight ion pairs, whereas polar solvents promote dissociation and thereby facilitate charge development in the transition state. Consistent with established Cr(VI) redox chemistry[18], the reaction begins with a two-electron reduction to Cr(IV). The resulting Cr(IV) then disproportionates with unreacted Cr(VI) to generate Cr(V), which is rapidly consumed, ultimately yielding the thermodynamically stable Cr(III) as the final product.

CONCLUSION

The study presents a kinetic and mechanistic analysis of DL-methionine oxidation by benzimidazolium fluorochromate in dimethyl sulfoxide, yielding sulfoxide as the sole product. The reaction is first order in oxidant and fractional order in methionine, indicating formation of a transient complex, and is acid-catalysed with $BIFCH^+$ as the active species. A large negative entropy of activation suggests a highly ordered transition state. Solvent effect studies using Kamlet–Taft and Swain correlations show that cationic solvation governs the rate, supporting a mechanism involving nucleophilic sulfur attack and charge development at the chromium–oxygen–sulfur interface.

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CONFLICT OF INTERESTS

No documented financial or personal conflict of interest exists that might have affected the study's findings.

AUTHOR CONTRIBUTIONS

The present work is related to *SDG-12: Responsible Consumption and Production*. All the authors contributed significantly to this manuscript, participated in reviewing/editing and approved the final draft for publication. The research profile of the authors can be verified from their ORCID ids, given below:

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REFERENCES

1. B.C. Lee and V.N. Gladyshev, *Free Radical Biology and Medicine*, **50(2),** 221(2011), https://doi.org/10.1016/j.freeradbiomed.2010.11.008
2. C.P. Saini, A. Ali and D. Panday, *Theoretical and Experimental Chemistry*, **60(4),** 255(2024), https://doi.org/10.1007/s11237-025-09830-2
3. S. Ghammamy, S. Khorsandtabar, A. Moghimi and H. Sahebalzamani, *The Journal of the Mexican Chemical Society,* **53(2)**, 41(2009), https://doi.org/10.29356/jmcs.v53i2.1003
4. S. Priyadarshinia, P.S. Gurua, R. DS and S. Dash, *Kinetics and Catalysis*, **60(2),**147(2019), https://doi.org/ 10.1134/S0023158419020083
5. A. Singadiya, R. Jangir, P. Bishnoi and Om Prakash, *Rasayan Journal of Chemistry*, **15(4),** 2512 (2022), https://doi.org/10.31788/RJC.2022.1547088
6. V. Sivamurugan, G.A. Rajkumar, B. Arabindoo, V. Murugesan, *Indian Journal of Chemistry,* **44B,** 144(2005).
7. M. Patel, L. Mathur, K. Jha, A. Kothari, I. Shastri and P. K. Sharma, *Asian Journal of Chemistry*, **25(5),** 2779(2013), https://doi.org/10.14233/ajchem.2013.13887

8. D. Pandey and S. Kothari, *Progress in Reaction Kinetics and Mechanism*. **34**, 199(2009), https://doi.org/10.3184/146867809X466221
9. B. K. Satsangi, S. Kothari and K. K. Banerji, *Transition Metal Chemistry*, **20**, 288(1995) https://doi.org/10.1007/BF00143494
10. D. D. Perrin, W. L. F. Armarego and D. R. Perrin, *Purification of Laboratory Chemicals*, Pergamon Press, Oxford (1966).
11. O. Exner, *Collection of Czechoslovak Chemical Communications,* **31**, 3222(1966), https://doi.org/10.1135/cccc19663222
12. J. S. Littler and W. A. Waters, *Journal of Chemical Society,* 1299(1959), https://doi.org/10.1039/JR9590001299.
13. K. J. Laidler, *Chemical Kinetics*, 2nd ed., McGraw-Hill, New York (1965), p. 327.
14. R. Kalal and D. Panday, Journal of the Indian Chemical Society, **98(2)**, 100009(2021), https://doi.org/10.1016/j.jics.2021.100009
15. S. S. Mansoor and S. S Shafi, *Arabian Journal of Chemistry*, **8**(4), 480(2015), https://doi.org/10.1016/j.arabjc.2011.01.031
16. M. J. Kamlet, J. L. M. Abboud, M. H. Abraham and R. W. Taft, *Journal of Organic Chemistry,* **48**, 2877(1983), https://doi.org/10.1021/jo00165a018
17. C. G. Swain, M. S. Swain, A. L. Powell and S. Alumni, *Journal of the American Chemical Society,* **105**, 502(1983), https://doi.org/10.1021/ja00341a033
18. F. A. Cotton, G. Wilkinson, C. A. Murillo and M. Bochmann, *Advanced Inorganic Chemistry*, 6th ed., Wiley-Interscience, New York (1999).

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